Center for Biological Diversity

Comments on the 2022 Scoping Plan Update – Engineered Carbon Removal Technical Workshop

References Cited

List of References

California Energy Commission, "California Energy Commission's R&D Activities in CCS for California" (Feb. 12, 2016), https://www.arb.ca.gov/cc/ccs/meetings/cec_presentation_2-12-16.pdf

CAN Position: Carbon Capture, Storage, and Utilization, Climate Action Network Int'l (2021), https://climatenetwork.org/resource/can-position-carbon-capture-storage-and-utilisation/

CARB, Accounting and Permanence Protocol for Carbon Capture and Geologic Sequestration under Low Carbon Fuel Standard (Aug. 13, 2018), https://ww2.arb.ca.gov/sites/default/files/2020-03/CCS_Protocol_Under_LCFS_8-13-18_ada.pdf

Center for Biological Diversity, Forest Bioenergy Briefing Book (March 2021), https://www.biologicaldiversity.org/campaigns/debunking_the_biomass_myth/pdfs/Forest-Bioenergy-Briefing-Book-March-2021.pdf

Center for International Environmental Law, "Carbon capture is not a climate solution" (July 19, 2021), https://www.ciel.org/wp-content/uploads/2021/07/CCS-Letter_FINAL_US-1.pdf

Center for International Environmental Law, "Confronting the Myth of Carbon Free Fossil Fuels," https://www.ciel.org/wp-content/uploads/2021/07/Confronting-the-Myth-of-Carbon-Free-Fossil-Fuels.pdf

Conley. S. et al., Methane emissions from the 2015 Aliso Canyon blowout in Los Angeles, CA, Science (March 18, 2016), https://science.sciencemag.org/content/351/6279/1317

Frontiers in Energy Research, Bearing the Cost of Stored Carbon Leakage (May 15, 2018), https://www.frontiersin.org/articles/10.3389/fenrg.2018.00040/full

Gan, Wei and Cliff Frohlich, Gas injection may have triggered earthquakes in the Cogdell oil field, Texas, 110 PNAS 18786 (2013).

IEEFA, Carbon Capture and Storage Is About Reputation, Not Economics at 4 (2020), https://ieefa.org/wp-content/uploads/2020/07/CCS-Is-About-Reputation-Not-Economics_July-2020.pdf

International Aluminium Institute, Aluminum Sector Greenhouse Gas Pathways to 2050 (Mar. 2021), https://www.world-aluminium.org/media/filer_public/2021/03/16/iai_ghg_pathways_position_paper.pdf

IPCC, Summary for Policymakers in Global Warming of 1.5°C: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (2018)

IPCC, Mitigation Pathways Compatible with 1.5° C in the Context of Sustainable Development, Ch. 2 in Global Warming of 1.5°C: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (2018)

IPCC, Mitigation Pathways Compatible with 1.5° C in the Context of Sustainable Development, Ch. 2 Supplementary Material in Global Warming of 1.5°C: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (2018)

IPCC, Sustainable Development, Poverty Eradication and Reducing Inequalities, Ch. 5 in Global Warming of 1.5°C: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (2018)

IPCC, Transport of CO2, Ch. 4 in Special Report on Carbon Dioxide Capture and Storage (2005)

Jacobson, Mark Z., The health and climate impacts of carbon capture and direct air capture, 12 Energy Envt. Sci. (Aug. 24, 2019), https://pubs.rsc.org/en/content/articlelanding/2019/ee/c9ee02709b/unauth#!divAbstract

Mac Dowell, N. et al., The role of CO2 capture and utilization in mitigating climate change, 7 Nature Climate Change 243 (2017), https://www.nature.com/articles/nclimate3231

Psarras, P. et al., Cost analysis of carbon capture and sequestration from U.S. natural gas fired power plants, 54 Envtl. Sci. Tech. 6272 (2020), https://users.wpi.edu/~jlwilcox/documents/Part%201_NG.pdf

Searchinger, Timothy D. et al., Europe's renewable energy directive poised to harm global forests, 9 Nature Comms. 3741 (2018)

Stanford Center for Carbon Storage, "An Action Plan for Carbon Capture and Storage in California: Opportunities, Challenges, and Solutions" (Oct. 22, 2020), https://static1.squarespace.com/static/58ec123cb3db2bd94e057628/t/5f9739146a54d17debd6808f/1603746076400/EFI-Stanford-CA-CCS-Slides-ForWeb-10.26.20vF.pdf

Sterman, John D. et al., Does replacing coal with wood lower CO2 emissions? Dynamic lifecycle analysis of wood bioenergy, 13 Envtl. Research Letters 015007 (2018)

WHEJAC, Interim Final Recommendations at 55, 58 (May 13, 2021), https://www.epa.gov/sites/default/files/2021-05/documents/whejac_interim_final_recommendations_0.pdf

Zoback, Mark D. and Steven M. Gorelick, Earthquake triggering and large-scale geologic storage of carbon dioxide, 109 PNAS 10164 (2012)

California Energy Commission's

R&D Activities in CCS for California

February 12, 2016

Mike Gravely
Deputy Division Chief
Energy Research and Development Division
California Energy Commission

PIER CCS R&D and Techno-Economic Summaries of Key Activities

- California Carbon Capture and Storage Review Panel (2010), including Technical Advisory Team
- WESTCARB – West Coast Regional Carbon Sequestration Partnership (2003−2015); collaborative R&D with DOE NETL, state agencies, national labs/universities, EPRI, industry, and others
- PIER projects on potential for induced seismicity, groundwater impacts, etc., from CO_2 injection (some ongoing)
- *Geologic Carbon Sequestration Strategies for California: Report to the Legislature* (2008) and *Assessment of the Barriers and Value of Applying CO_2 Sequestration in California* (2015)
- Staff workshop on CCS for natural gas power plants (2015)
- CEC Siting Division-siting activities with HECA

California Agencies Convene Expert Panel to Examine CCS Policy

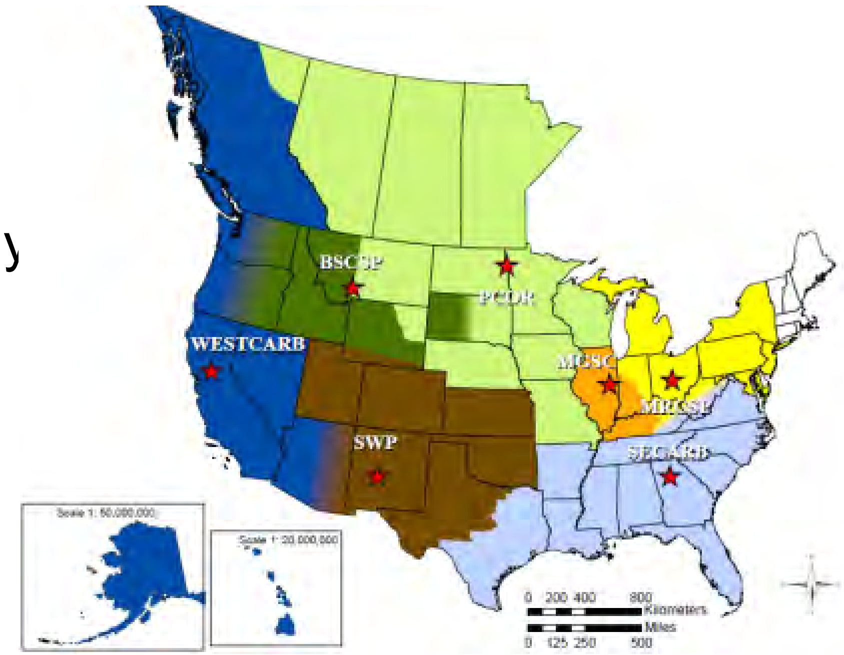
- California Carbon Capture and Storage Review Panel was created in 2010 by the Energy Commission, CPUC, and ARB, with involvement of DOGGR, Dept. of Water Resources, and others
- Panelists included experts from academia, NGO, utilities, industry associations, law firms, and a former state legislator. Chaired by Carl Bauer, former Director of DOE's National Energy Technology Laboratory
- Five public meetings held; Energy Commission team developed topical white papers for panelists
- Panel developed recommendations to guide CCS policy formulation and regulatory role coordination in California
- http://www.climatechange.ca.gov/carbon_capture_review_panel/index.html

Key Recommendations of CCS Review Panel

- Determine and coordinate permitting and regulatory authority for CCS projects including CEQA lead, site operations, and CO_2 pipelines
- Establish GHG "accounting protocols" for sequestered CO_2 to facilitate inclusion in AB 32 compliance programs
- Develop performance standards for the design and operation of CCS sites for environmental, health, and safety protection
- Clarify ownership and use of subsurface pore space for CO_2 storage
- Assign financial responsibility for long-term stewardship of CO_2 storage sites
- Establish cost allocation mechanisms and/or incentives to support early CCS projects
- Develop public education materials and programs

West Coast Regional Carbon Sequestration Partnership (WESTCARB)

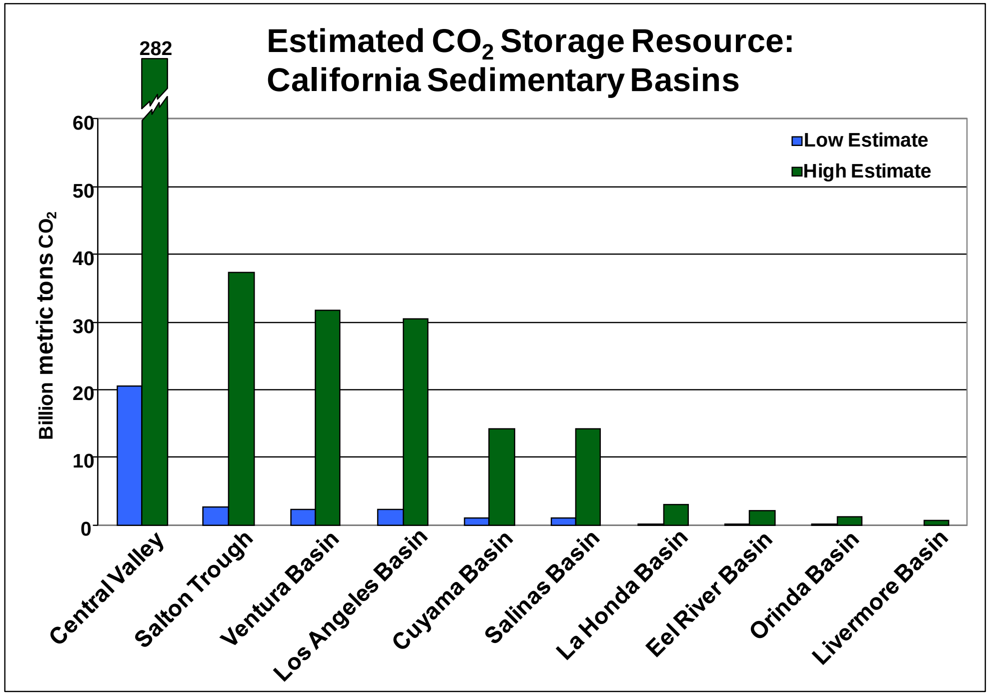
- Collaborative R&D team with >100 partners, led by Energy Commission
- One of 7 DOE “regional partnerships,” each charged with conducting regionally focused research and public outreach
- Basic questions answered for geologic and terrestrial carbon storage:
  - Is there ample, affordable, widely distributed storage capacity for the types of emission sources in the region?
  - Will storage be secure given the region’s seismicity (geologic storage) and history of wildfires (terrestrial storage)?
  - Does geologic storage pose any risk to hydrocarbon or groundwater resources?
  - California applications are promising
- Pilot-scale field tests validate technology



WESTCARB territory includes AK, AZ, BC, CA, HI, NV, OR, and WA

California's Geologic CO_2 Storage Capacity Is Very Large

- On-shore sedimentary basins conducive to storage represent capacity for roughly 1000 years of current point source CO_2 emissions
- Central Valley's Sacramento and San Joaquin Basins have the largest capacity
- Opportunities for CO_2 storage also exist in the state's oil and natural gas fields – many have potential for CO_2-enhanced oil recovery
- Off-shore basins identified and partially characterized



30–460 Gt onshore saline formation capacity
3.3–5.7 Gt natural gas reservoir capacity
1.4–3.7 Gt oil reservoir capacity

WESTCARB Drilled Wells to Validate Formation Permeability at Promising Sites (CA and AZ)

- Site screening and selection
- Project planning; industry host engagement
- Subsurface modeling and injection simulation
- Risk assessment
- Monitoring plan
- Permitting
- Community outreach
- Safety plan and training
- Field measurements, laboratory analysis of core samples
- Site closure and restoration

Rock core collected at Citizen Green well (above) sent to LBNL scientists for laboratory analysis of CO_2 behavior in pore spaces (below)

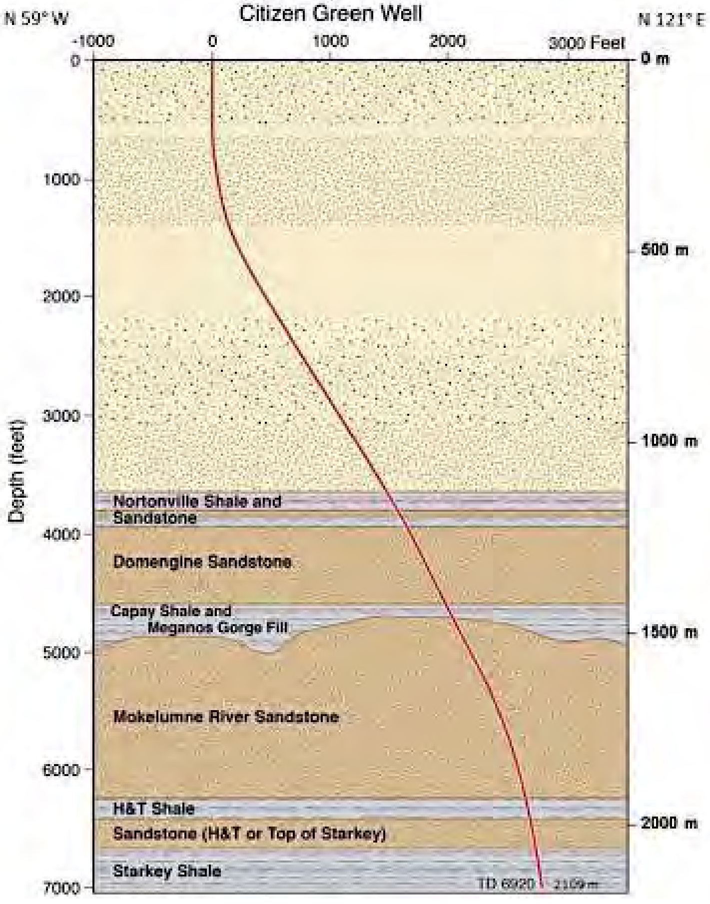
WESTCARB Criteria for Site Selection

- Well-defined stratigraphy or geologic structure to confine CO_2 to target strata
- No impact on low-salinity (<10,000 mg/L TDS) aquifers
- Location unlikely to cause public nuisance (noise, traffic, dust, etc.)
- Proximity to large CO_2 point sources (future commercial potential)
- Available hydrogeologic, well log, seismic, and rock/fluid properties to inform site suitability and initial modeling
- Major faults understood for evaluating potential leakage pathways
- Depth of storage greater than ½ mile to keep CO_2 in dense (low buoyancy) phase

Characterization Well Results for the Sacramento Basin

Citizen Green well on King Island near Lodi

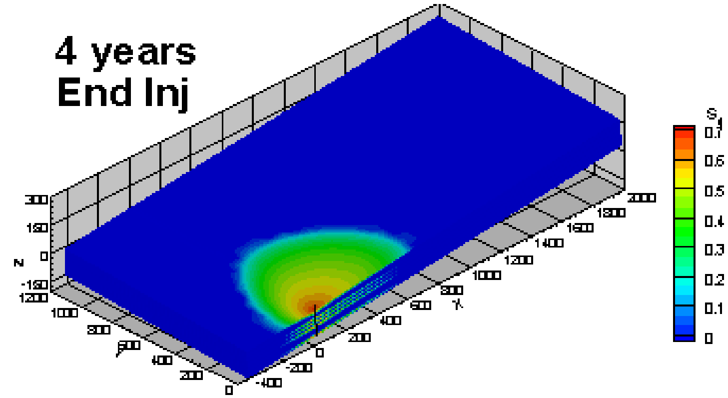
- Location in northern California's natural gas producing region allowed use of experienced local drillers, mudloggers, etc.
- Reuse of pad and surface casing from an inactive natural gas well saved money and simplified CEQA
- Deviated well drilled to 7000 foot depth
- Core samples and logging data showed unconsolidated sands with high permeability in primary target formation, as well as good sealing properties in the shales
- Laboratory analyses of core samples at LBNL indicated good CO_2 injectability

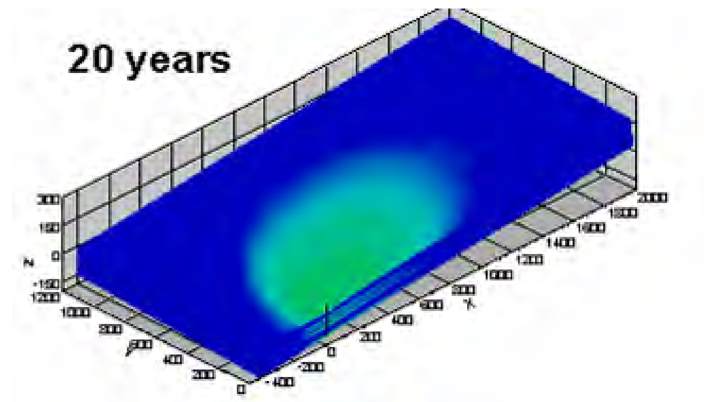


Modeling and Simulation Results for the San Joaquin Basin

Kimberlina Power Plant north of Bakersfield

- Site of Clean Energy Systems' 5 MW oxy-combustion power plant with inherent CO_2 separation; on-site injection well planned but not drilled
- 85-square-mile geologic model developed by Lawrence Livermore; regionally continuous Vedder Formation at a depth of 8000 feet appears best storage site
- Lawrence Berkeley simulation of a 4-year, 1 million-ton CO_2 injection showed plume stabilization within 20 years with little migration

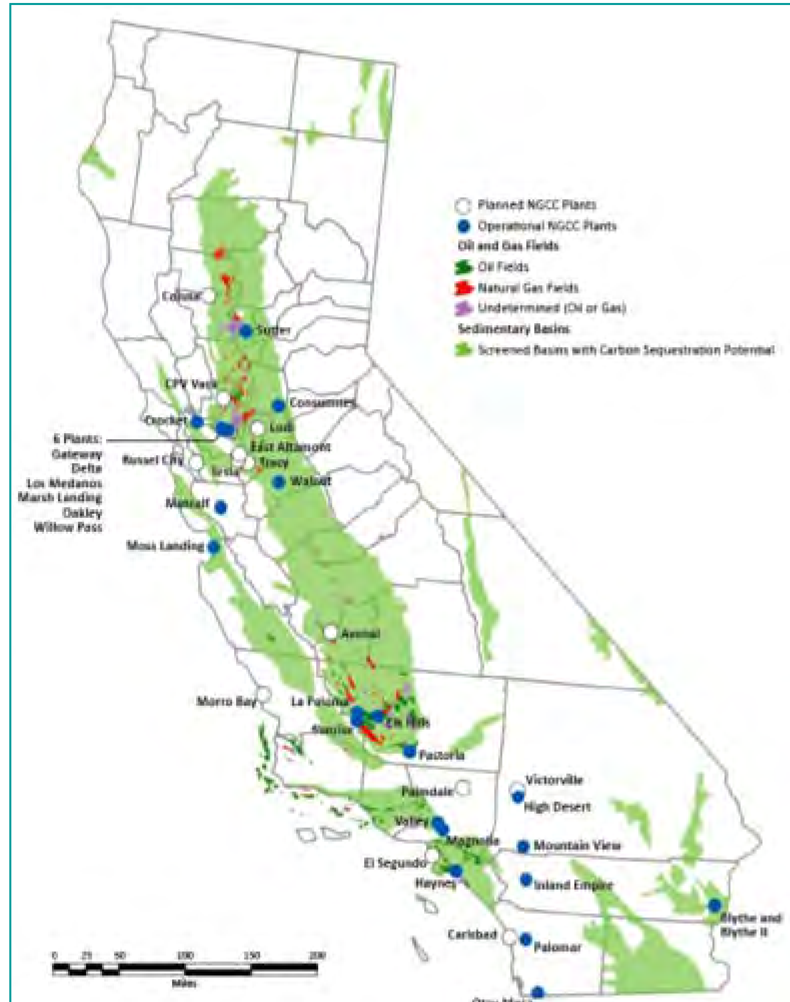




Initial LBNL simulation of CO_2 plume in the Vedder formation at end of the 4-year, 1 million ton injection period (top) and after 20 years (bottom)

California NGCC Plants Align Well with Sedimentary Basins Screened for CO_2 Storage

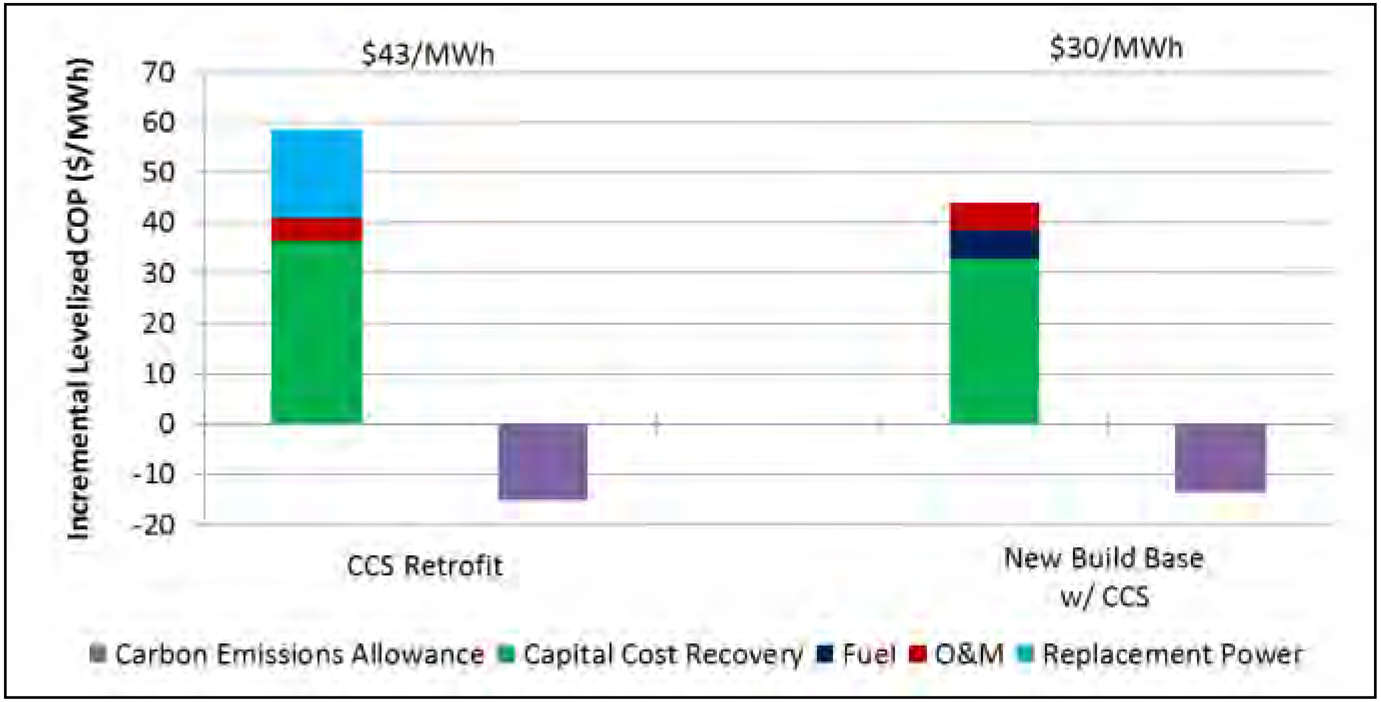
- Initial review of geology beneath 42 NGCC plant sites found 33 with underlying sedimentary basins having sand thickness and depth suitable for CO_2 storage
- About 20 sites also had oil and gas fields within 12 miles
- Most are in flat, rural terrain, suggesting CO_2 pipeline construction may be feasible
- Similar result expected for cement, biofuels, and ag processing plants



Source: Lawrence Livermore National Lab and California Geological Survey

Capital Cost Is the Most Significant Economic Variable for Adding CCS to NGCC Plants

- Adding CO_2 capture and compression reduced net output by 11% and increased net heat rate by 12%
- Cost for full CCS system is $900 million for 600 MW plant; for retrofits, replacement power is also costly



Source: CB&I

CO_2 Storage Integrity and Seismicity

- Could earthquakes release CO_2 or could CO_2 injection cause earthquakes? Both have been studied.
- California Geological Survey issued seismic hazard map classifying faults according to age since last activity
- WESTCARB analyzed the risk of induced seismicity from small-scale CO_2 injection in the Montezuma Hills of Solano County. Results yielded an approach to risk assessment for induced seismicity as part of the permitting process.
- LBNL examined the potential for induced seismicity in the San Joaquin Valley from geologic CO_2 storage and historic basin pressure changes

Active faults in the vicinity of a proposed pilot CO_2 injection well in the Montezuma Hills were identified and the pressure change effects simulated by LBNL

WESTCARB Outreach to California Communities

- Thornton – pilot-scale CO_2 injection proposed; CEQA declaration published
- Rio Vista – pilot-scale CO_2 injection proposed; draft permit issued
- Bakersfield – 1 million ton CO_2 injection proposed; permit application developed
- Well attended public meetings in all three communities; no formal comments to CEQA or draft permit
- WESTCARB also conducted public official and business/civic/EJ group briefings, science teacher training, opinion surveys, media interviews, etc.
- Citizen Green well videos at http://www.westcarb.org/videos.html

How WESTCARB Results Can Support ARB Storage Protocol Development

- Project site geologic characterization procedures
- Risk, EHS, and surface and subsurface monitoring plans
- Geologic models and CO_2 injection simulations
- Data from permit applications and CEQA declarations
- Stakeholder network and engagement experience

- For more information, contact Mike Gravely at (916) 327-1370 or Mike.Gravely@energy.ca.gov

Climate Action Network

Position: Carbon Capture, Storage and Utilisation

January 2021

Climate Action Network (CAN) is the world's largest network of civil society organizations working together to promote government action to address the climate crisis, with more than 1300 members in over 120 countries.
www.climatenetwork.org

Introduction[1]

Climate change is one of the biggest challenges facing humankind in this century. The Paris Agreement seeks to respond to the climate crisis by providing a collective framework for nationally determined actions with the goal of limiting global average temperature increase to 1.5°C above pre-industrial levels. The aim is to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century. In practice, achieving this goal means greenhouse gas emissions must decrease to as close to zero as possible by mid-century at the latest.

CAN's vision for a safe climate centers on rapid and deep economy-wide decarbonisation of all countries and a transition to a just, equitable, and sustainable future. A range of solutions and climate mitigation tools can help achieve this vision, including, renewable energy, energy efficiency, forest conservation, ecosystem restoration, sustainable reforestation, and reduced meat consumption as well as shifting to sustainable consumption patterns by the global rich and middle classes. CAN urges a global Just Transition to 100% renewable energy, supported by ambitious energy conservation and efficiency measures by mid-century at the latest, conducted earlier by richer countries and essential to meet the Paris Agreement goal.

Carbon Capture and Storage (CCS) is a technology promoted by some as essential to limiting global average temperature increase to 1.5°C. Many climate models produce scenarios, including CCS in the power and industrial sectors, bioenergy with CCS (BECCS), direct air capture with CCS (DACCS), and carbon capture and utilisation (CCU), to either limit warming and/or account for overshooting of the 1.5°C target through the removal of carbon dioxide emissions from the atmosphere. Other scenarios model ways to limit warming without overreliance on or any CCS.

[1] Environmental Defense Fund (EDF) does not support all aspects of this document. EDF believes we cannot afford to a priori reject the CCS potential.

The Integrated Assessment Model scenarios with low or no CCS deployment require considerable increases in energy efficiency and near-term rapid fall in energy demand to meet commitments under the Paris Agreement.[2] Climate models show that if the current pace in global energy demand growth and emission reductions continue, the pathway to limit warming at 1.5°C without CCS will be out of reach within some years. The path we take is a societal choice, with significant implications for intergenerational equity, social and economic justice, land use rights, access to energy, sustainable development, and our ultimate effectiveness in decarbonising our economies.

As detailed in this paper, CAN prioritizes ambitious climate mitigation to meet targets under the Paris Agreement. CAN is concerned that CCS risks distracting from the need to take concerted action across multiple sectors in the near-term to dramatically reduce emissions. Overall, to meet the 1.5°C limit, richer parts of society must consume less, and all must consume efficiently, and sustainably. This will provide space for the globally poorer parts of society to ensure their legitimate space ensuring social and economic well-being for all.

Carbon Capture and Storage (CCS) types and deployment

CCS encompasses a range of carbon capture, storage applications. This paper focuses on the following: CCS in the power and industrial sectors, BECCS, DACCS. Additionally, this section considers related issues concerning Enhanced oil and gas recovery [EOR/EGR] and carbon capture and utilization (CCU).

Fossil Fuel/Industrial CCS

Whilst in different stages of development, as further discussed in Appendix 1, many CCS applications are still largely unproven at scale. Despite billions in public support over the past decade,[3] there are 51 large-scale CCS projects across the globe, of which 19 are operating and most are pilot-scale projects that demonstrate only a part of CCS (e.g., capture but not storage).[4] These figures include operational carbon capture projects in the power and industrial sectors but do not include BECCS or DACCS facilities in operation, which are briefly discussed below.

Collectively, currently operational CCS projects (excluding EOR operations) are injecting and storing less than 5 million tonnes of CO_2 ($MtCO_2$) per year.[5] The International Energy Agency (IEA), which counts only two large-scale CCS projects operating in the power sector with a combined capture capacity of 2.4 million tonnes of CO_2 per year,[6] notes the technology remains well off track to reach the 760 $MtCO_2$ by 2030 and about 2.8 Gt CO2 by 2050 storage rate outlined in IEA's own Sustainable Development Scenario.[7]

BECCS

[2] Grubler, A., Wilson, C., Bento, N. *et al.* A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nat Energy* **3,** 515–527 (2018). https://doi.org/10.1038/s41560-018-0172-6

[3] *See* Appendix 2.

[4] Global CCS Institute (2019). Facilities Database, available at: https://co2re.co/FacilityData (accessed 19 September 2019).

[5] Calculation based on figures provided on by Global CCS Institute (2019). Facilities Database, available at: https://co2re.co/FacilityData (accessed 19 September 2019).

[6] Boundary Dam and Patra Nova, located in Canada and the US, respectively. Both projects involve EOR.

[7] IEA's Sustainable Development Scenario holds temperature rise to below 1.8 °C with a 66% probability without reliance on global net-negative CO_2 emissions; this is equivalent to limiting the temperature rise to 1.65 °C with a 50% probability. Global CO_2 emissions fall from 33 billion tonnes in 2018 to less than 10 billion tonnes by 2050 and are on track to net zero emissions by 2070. *See* International Energy Agency (2020a). CCUS in power, available at: https://www.iea.org/reports/tracking-power-2019/ccus-in-power#abstract (accessed 1 February 2020); *see also* International Energy Agency (2020b). World Energy Model, available at: https://www.iea.org/reports/world-energy-model/sustainable-development-scenario (accessed 1 February 2020).

BECCS still remains in the very early stages of development and has yet to be demonstrated at a commercial scale: Globally, there is one large scale BECCS facility currently capturing and storing 1MtCO_2 p.a., and four small scale plants (all combined with EOR) in operation – all ethanol plants. A single pilot project in the UK has been demonstrating capturing of about a ton of CO_2 (but not storing) per day from 100% biomass feedstock combustion, starting in 2019 at the Drax Power Station.[8]

DACCS

Very few DACCS projects are operating globally at any scale although several companies are working to commercialise the technology.[9]

CCU

CCU covers a range of technologies at differing levels of maturity, cost, and market size, with many applications still in the research and development (R&D) phase.[10]

Technological maturity aside, CCS applications face myriad deployment barriers and raise a number of environmental, economic, and social concerns. As summarised in Appendix 1, the CCS applications discussed in this paper are currently expensive to deploy, may not result in substantially lower or negative emissions, and/or raise significant sustainability and environmental justice concerns in light of their potential energy, water, land use, and other resource demands. CAN therefore remains unconvinced of the many aspects and value of CCS applications and their value as climate mitigation tools.

Conclusions on CCS

Based on current global trends and an analysis of existing literature and reports, as discussed in Appendix 1, CAN concludes about CCS and its potential to serve as a climate mitigation tool as follow:

1. **CCS at scale remains largely unproven and its potential to deliver significant emission reductions by mid-century is currently limited.** Current evidence supporting CCS as an effective and scalable climate mitigation tool is largely theoretical, and still under debate. Furthermore, for CCS to play a significant role in achieving the Paris Agreement goal, gigatonnes (Gt) of CO_2 would need to be captured and permanently stored. This would require the financing and construction of CO_2 transport infrastructure roughly equivalent in scale to today's oil and gas pipeline and marine transport networks. The political, social, economic, and technical barriers to achieving this cannot be understated. Equity, cost-effectiveness, and abatement potential are all important factors in determining whether CCS should be considered a technology solution.
2. **Safe, permanent, and verifiable storage of CO_2 is difficult to guarantee.[11]** Well-selected, fully characterised, properly designed, and appropriately managed CO_2 storage sites are likely to have

[8] Drax Group plc (2019). Carbon dioxide now being captured in first of its kind BECCS pilot. Press Release issued 7 February 2019. Available at: https://www.drax.com/press_release/world-first-co2-beccs-ccus/.
[9] Fasihi, M., et al (2019). Techno-economic assessment of CO2 direct air capture plants. Journal of Cleaner Production, Vol. 224: 957-980. 1 July 2019. Available at: https://doi.org/10.1016/j.jclepro.2019.03.086
[10] IOGP (2019). The potential for CCS and CCU in Europe. Report to the 32nd meeting of the European Gas Regulatory Forum 5-6 June 2019. Available at: https://ec.europa.eu/info/sites/info/files/iogp_-_report_-_ccs_ccu.pdf.
[11] *See* Appendix 1.

a low risk of leakage.[12] Such storage sites, however, are expected to be a limited resource and will not be evenly distributed across the globe.[13] It is therefore likely that some CO_2 storage will occur in lower quality sites, and it is reasonable to assume not all sites will be properly managed, thereby increasing leakage risk.[14] At the same time, it is very difficult to detect CO_2 leaks, which can occur in different timescales.[15] The implications for climate mitigation as well as other environmental and public health risks makes governance and the risk of leakage, even at very low rates, a serious concern.

3. **The climate impact of CCS should consider all emissions and costs from concomitant processes**. The costs and emission of greenhouse gases and some pollutants from processes associated with CCS need to be carefully factored in. Power plants and industries intended to sequester CO_2 will use additional energy to compress, transport to suitable reservoir and pump into the ground the captured CO_2. Studies calculate that 15-25% more energy would be required, depending on particular CCS technology used.[16]

4. **CCS is not needed in the power sector.** Faster, cleaner, safer, more efficient, and cheaper means exist to reduce CO_2 emissions, such as phasing out fossil fuels and replacing them with renewable energy, energy efficiency, and energy conservation.

5. **EOR/EGR is dangerously at odds with any climate action,[17]** and will not lower emissions in comparison to renewable energy and energy efficiency. To meet the Paris Agreement target, the majority of fossil fuel reserves must be left in the ground.

6. **A suite of strategies and technologies already exist to cut emissions in the industrial sector, without CCS .[18]** Emissions in the industrial sector can be significantly reduced by increasing process efficiency, but there is a need also to increase the speed of development and/or deployment of low or zero carbon processes and materials, replacing fossil fuels with renewable energy, increasing recycling rates, and designing alternative materials with lower emission footprints than steel, conventional cements, plastics and aluminum. CAN strongly supports further and internationally coordinated research, development and deployment into CO_2-free processes and alternative materials with the objective that these can ensure that energy-intensive industries eliminate all emissions by mid-century at the latest.

---

[12] Anderson, S. (2017). Risk, Liability, and Economic Issues with Long-Term CO2 Storage—A Review. Natural Resources Research 26, 2017, pp. 89-112. https://doi.org/10.1007/s11053-016-9303-6; In such reservoirs, the IPCC noted in 2005 that the fraction of CO_2 retained in such geological reservoirs is "very likely [above 90% certainty] to exceed 99% over 100 years and is likely [above 60% certainty] to exceed 99% over 1000 years." IPCC (2005). IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H. C. de Coninck, M. Loos, and L. A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp.

[13] Center for International Environmental Law (2019). Fuel to the Fire: How geoengineering threatens to entrench fossil fuels and accelerate the climate crisis. February 2019. Available at: https://www.ciel.org/reports/fuel-to-the-fire-how-geoengineering-threatens-to-entrench-fossil-fuels-and-accelerate-the-climate-crisis-feb-2019/.

[14] *See* Appendix 2, which discusses how mismanagement of the In Salah CO_2 storage project in Algeria led to fracturing of a storage formation's caprock.

[15] Hvidevold, H.K., Alendal, G., Johannessen, T., Ali, A., Mannseth, T., Avlesen, H. (2015). Layout of CCS monitoring infrastructure with highest probability of detecting a footprint of a CO_2 leak in varying marine environment. International Journal of Greenhouse Gas Control Vol. 3, June 2015, pp. 274-279. https://doi.org/10.1016/j.ijggc.2015.03.013.

[16] European Environment Agency, "Carbon capture and storage could also impact air pollution", last modified 10 December 2019, see: https://www.eea.europa.eu/highlights/carbon-capture-and-storage-could

[17] *See* Appendix 1.

[18] *See* Appendix 1.

7. **Large-scale deployment of BECCS would result in unacceptable negative impacts on food security, land use rights, and biodiversity given its land use, water, and resource requirements.**[19] CAN also concludes there is no definitive evidence that large scale BECCS will deliver on its negative emissions promise. It should also be emphasized that CAN has already agreed to focus the need for negative emissions primarily, and as much as possible, on increased carbon sequestration in the biosphere, including primarily the protection and restoration of forests and other carbon- and biodiverse rich natural ecosystems, and sustainable agricultural practices. Whilst bioenergy is already playing a role in the energy transition in some countries, its use must be strictly limited and regulated to avoid social and environmental harm. Displacement of communities due to land grabs for massive cultivation of bioenergy crops is a key concern for many developing countries. There are also serious concerns on permanence and food security around afforestation in many countries, as well as on the overall net benefits of carbon sequestration when converting unutilized grasslands/savannahs and other lands for energy crops.

8. **DACCS is in its infancy and is very costly and energy intensive, with serious doubts about its effectiveness.** DACCS poses significant challenges for energy use and there is currently insufficient evidence that it provides a feasible climate mitigation solution. Recent research revealed that for DAC removal in the US of about 850 Mt CO_2, (2% of global energy-related CO_2 emissions annually), the equivalent of almost all global present wind power would be needed,[20] or about 1000 TWh electricity representing *4% of all global electricity produced.* That approximates about 550 Mt CO_2 in the global electricity mix.[21]Using present global power mix, DACCS would require about two third of a ton of CO_2 emissions to sequester one ton of CO2. Or if using only renewables, it would significantly undermine renewable-based power sector decarbonization. Therefore, the potential larger expansion of DACCS in the near term runs counter to CAN`s climate vision and would significantly delay efforts to achieve and maintain a 100% renewable energy system. DACCS is also not immune to the same CO_2 storage problems and concerns as other CCS applications. Any future consideration of DACCS as a potential means to reduce CO_2 emissions must address energy requirement concerns and alignment with the UN's Sustainable Development Goals.

9. **Long-term CO_2 storage creates financial, liability, and climate risks that are highly likely to be transferred from the private sector to the public sector.** Liability questions for CO_2 storage have yet to be answered in many places, and most countries lack a governance structure to maintain and ensure the long-term fiscal integrity of CO_2 storage sites. Some proponents of CCS have sought to relieve private sector parties engaged in CCS of financial and legal liability by transferring risk to governments and/or incorporating liability limits into law. Even with strong financial security mechanisms in place, there is a risk that governments will ultimately be responsible for the long-term monitoring, management, and remediation of CO_2 storage sites.

10. **Continued pursuit of CCS, for example in the power sector, risks diverting attention and resources from proven, cost effective solutions.**[22] CCS is expensive, resources are limited, and

[19] *See* Appendix 1.
[20] Larsen, J et al., Rhodium Group (2019). "Capturing Leadership: Policies for the US to Advance Direct Air Capture Technology", p. 45. Available at: https://rhg.com/research/capturing-leadership-policies-for-the-us-to-advance-direct-air-capture-technology/
[21] International Energy Agency *(2019). World Energy Outlook 2019*, p. 680.
[22] *See*, *e.g.,* Center for International Environmental Law (2019). Fuel to the Fire: How geoengineering threatens to entrench fossil fuels and accelerate the climate crisis. February 2019. Available at: https://www.ciel.org/reports/fuel-to-the-fire-how-geoengineering-threatens-to-entrench-fossil-fuels-and-accelerate-the-climate-crisis-feb-2019/; *see also* Ash, K. (2015). Carbon

time is of the essence. There is a risk that public and private monies spent supporting CCS may decrease funding available for solutions that can deliver safe and permanent emission reductions. This means the fossil fuel industry may adopt CCS as a strategy to maintain business as usual or expand operations, and potentially access climate subsidies.

11. **CCS raises significant intergenerational equity concerns as well as environmental and social justice concerns.** CCS deployment would result in resource allocation decisions likely to undermine efforts to secure a just, equitable, and sustainable future. CCS also passes the responsibility for today's climate pollution onto future generations by requiring them to maintain and ensure the long-term integrity of CO_2 storage sites.

Climate Action Network position statement

CAN fully endorses a transition to 100% renewable energy for all energy use by mid-century at the latest[23] and adopts the following positions:

1. CAN strongly supports the Paris Agreement's goal to limit global average temperature rise to 1.5°C above pre-industrial levels, and believes that all sustainable solutions and strategies need to be implemented to achieve this goal. **CAN does not consider currently envisioned CCS applications as proven sustainable climate solutions.** It is therefore imperative that actions to reduce emissions are maximised.

2. **CAN calls upon all governments to phase out all fossil fuel production and use, and phase in 100% renewable energy, as quickly as possible but no later than mid-century.** Achieving the 1.5°C goal requires transformational change based on a managed phase-out of fossil fuel production, increased deployment of renewable energy, dramatic reductions in energy consumption, and greater efficiency along with substantial changes in production and consumption patterns at a much faster rate than what particularly governments of richer countries have pursued or committed to thus far.

3. **All government subsidies, loans, grants, tax credit, incentives, and financial support for fossil fuels and technologies that use or otherwise support the continued used of fossil fuels, including CCS, should be phased out as soon as possible**. CAN opposes government support to the fossil fuel industry. CAN affirms that renewable energy, energy efficiency, smart grid technologies, and electricity storage provide the best value route to reducing emissions from electricity generation. Governments should rule out new fossil fuel investments, in line with a just transition and consistent with carbon budgets identified by the IPCC, to not exceed 1.5°C average global warming by the end of this century.

4. CAN believes and reiterates that radical action needs to be taken to reduce greenhouse gas emissions as quickly as possible. In terms of negative emissions approaches, absolute priority should be given to increasing the capacity of natural carbon sequestration through the protection and restoration of forests and other natural ecosystems that maximise the co-benefits to people

---

Capture Scam: How a False Climate Solution Bolsters Big Oil. Greenpeace USA. July 2015. Available at: https://www.greenpeace.org/usa/research/carbon-capture-scam/.

[23] http://climatenetwork.org/sites/default/files/can_position_energy_ambition_in_ndcs_june2019.pdf

and biodiversity. **CAN cannot and will not support any effort to promote negative emissions or offsets as an alternative to stringent emission reductions**.

5. **CAN does not recognise BECCS as a proven large-scale mitigation option that delivers negative emissions, and does not support its deployment at any scale if it results in food insecurity, resource and land use conflicts, and detrimental biodiversity impacts.** Respect of human rights, which underpins the Paris Agreement, must not be compromised through the use of BECCS or any other climate mitigation tool.

6. **CAN supports proven sustainable strategies to address carbon emissions in the industrial sector**.[24] CAN sees no definitive evidence that CCS is the fastest, cheapest, cleanest and most durable way to decarbonise the industrial sectors, including the cement, iron ore-based steel and other metals, and chemical industries. For some of these industries, alternative technologies and solutions already exist and should be rapidly deployed. The promise of CCS must not delay necessary action in the present. Governments should start and expand R&D programs for these industries to have the solutions needed to adapt.

7. EOR/EGR combined with CCS utilises captured CO_2 to improve and enhance the exploitation of oil and gas fields. Such activities do not lower overall CO_2 emissions and contradict the need to keep the majority of remaining fossil fuel reserves in the ground. **CAN opposes such an practice.**

8. **CAN does not believe DACCS will be able to contribute to significant emission reductions in the coming years**, thus it has no place in decarbonisation scenarios focusing on early and steep CO2 emissions reductions.

9. While certain CCU applications theoretically have the potential to mitigate climate emissions at scale (e.g., carbon fibers as substitute for steel), there are concerns regarding cost-effectiveness and environmental impacts. **At present, without additional mitigation incentives, further R&D, and a comprehensive review of potential environmental impacts, CCU is a mere detour for decarbonisation and unlikely to deliver mitigation in the order of gigatons of CO_2 needed to address climate change.**

[24] *See* Appendix 1.

Appendix 1- Carbon Capture, Storage, and Use Applications

This appendix provides a summary overview of the carbon capture, storage, and use applications discussed in this paper based on CAN's review of existing literature and reports. It provides detail on various potential applications for CCS technology, including limitations likely to prevent their safe, efficient and cost-effective deployment as a carbon mitigation or carbon removal technology. Whilst not exhaustive, this overview summarises the main issues associated with CCS and its deployment.
The following CCS applications are the subject of this paper:

- CCS in the power sector
- CCS in industry to capture process and smokestack emissions (also known as "industrial CCS")
- Bioenergy with carbon capture and storage (BECCS)
- Direct air carbon capture and storage (DACCS)
- Carbon capture and utilisation (CCU), which is distinct to CCS due to the different end-of-life use for the captured CO_2: rather than sequestered in geological formations, captured CO_2 is converted into a new product.
- While not a type of CCS, EOR/EOG can be applied alongside CCS, having significant implications on its potential as a climate technology and is also discussed below.

CCS is an integrated process comprised of three distinct parts: carbon capture, transport, and storage (including measuring, monitoring, and verification).

- Capture technology collects CO_2 from a point source (e.g., power station smokestack) that can be compressed, transported, and stored.
- Transport of captured CO_2 is mostly likely to take place via pipelines, but could also be moved via ships, rail, and road.
- CO_2 storage is most likely to occur underground in geological sites on land or below the seabed of at least 800 meters (up to more than three kilometers) under a caprock. Whilst CO_2 disposal at the seafloor (ocean carbon sequestration) has previously been proposed by certain governments, this method has been largely discounted by UN-fora or even banned by many nations due to the significant impacts it would have on the ocean ecosystem and legal constraints that effectively prohibit it.[25]

CCS Applications

A. CCS in the Power Sector

Fossil fuel power stations, particularly those that burn coal provide a large point sources of CO_2. Some power stations emit as much as 10 $MtCO_2$ or more per year, creating an economy of scale for capture, transport, and storage. CCS has a limited commercial track record in the power sector

[25] For example, the United Nations Convention on the Law of the Sea (UNCLOS), the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention), the Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Protocol, which will eventually replace the London Convention), and regional agreements such as the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention).

and associated costs for different capture technologies (e.g., amine-based post-combustion capture and oxyfuel combustion) remain high.[26]

Power sector applications of CCS have several drawbacks, including increasing overall energy demand (which means burning more fossil fuels to produce the same amount of energy) and reducing power plant efficiency. For example, the energy penalty for pulverized coal power stations fitted with carbon capture can be 25% or more, whilst the efficiency penalty can be as high as 15%.[27] Such penalties mean more fuel has to be burned to produce the same amount of power, which has a host of implications related to energy costs, non-CO_2 air pollutants, and power station resource demands. In short, using capture technology on power stations increases costs, emissions of non-CO_2 air pollutants, power station water demand, and impacts associated with the mining, extraction, and transport of fossil fuels.[28]

Even more importantly, from a climate perspective, carbon capture does not eliminate CO_2 emissions from fossil fueled power stations. Theoretically, CCS has the potential to reduce power station CO_2 emissions by as much as 90%. In practice, however, capture rates on most of the power stations fitted with capture technology have been much lower.[29] CCS also results in additional upstream or downstream emissions, including those generated upstream through the mining and transport of fossil fuels and the transport and storage of CO_2. When such emissions are accounted for, CCS results in even lower net capture rates over the life of a project.[30]

Large-scale fossil fuel CCS power stations also risk running counter to and could hinder the transition to a 100% renewable energy system. Some argue that CCS can provide a climate solution while renewable energy is deployed worldwide, while others note the risk this strategy will incentivize or justify prolonged fossil fuel use. In general, coal-fired power plants have a limited technical ability to balance variable renewable energy resources like wind and solar. Coal CCS would therefore not improve this ability and could even constrain other fossil fuel power plants' capacity to serve as a flexible resource for technical and/or economic reasons.[31]

One of the crucial environmental impacts is enhanced water consumption by carbon capture applications in power plants. Freshwater is a scarce resource, a precondition for all life on Earth, and needs to be protected much more particularly in times of enhanced global warming and

---

[26] *See, e.g.,* Lazard Ltd (2018). Lazard's Levelized Cost of Energy Analysis—Version 12.0. Lazard Ltd. November 2018. Available at: https://www.lazard.com/media/450784/lazards-levelized-cost-of-energy-version-120-vfinal.pdf, which shows the cost of CCS power stations relatives to other energy technologies. Note that the Lazard LCOE analysis does not includes costs for CO_2 transport, storage, and monitoring.

[27] Budinis, S., Krevor, S., MacDowell, N., Brandon, N., Hawkes, A. (2018). An assessment of CCS costs, barriers and potential. Energy Strategy Reviews, Vol. 22, November 2018, pp. 61-81. https://doi.org/10.1016/j.esr.2018.08.003.

[28] *See, e.g.*, Newcastle University, Institute for Sustainability, Impact of carbon capture & storage on water, available at: https://www.ncl.ac.uk/sustainability/ourresearch/excellence/water/ccs/ (accessed 1 February 2020).

[29] *See, e.g.,* Schlissel, D. (2019). IEEFA op-ed: Reality of carbon capture not even close to proponents' wishful thinking. Guest editorial in Denver Post. 8 August 2019. Available at: https://ieefa.org/reality-of-carbon-capture-not-even-close-to-proponents-wishful-thinking/.

[30] Jacobson, M. (2019). The health and climate impacts of carbon capture and direct air capture. Energy & Environmental Science, 12, 2019, pp.3567-3574. https://doi.org/10.1039/C9EE02709B.

[31] Domenichini, R., Mancuso, L., Ferrari, N., Davison, J. (2013). Operating Flexibility of Power Plants with Carbon Capture and Storage (CCS). Energy Procedia vol. 37, pp.2727-2737. https://doi.org/10.1016/j.egypro.2013.06.157.

biodiversity decline. Carbon capture in coal and gas power plants can result in increased water consumption by 20% to 60% in the absence of water recovery options.[32]

Economics is one of the primary reasons why CCS hasn't been more extensively deployed in the power sector. Outfitting new or existing fossil fuel power stations with CCS is very expensive, requires considerable space near the power plant for the capture device, and costs significantly more than zero emission renewable energy technologies per tonne of CO_2 avoided.[33] To-date, only few coal power plants capturing CO_2 emissions exist worldwide and a handful of gas power plant CCS projects are under development. Significantly, there is not a single commercial-scale power plant capturing and sequestering emissions for the purpose of climate mitigation at-scale anywhere in the world.[34]

Considering the costs, especially without CO_2 restrictions or without a considerable CO_2-price well above €50-70 per ton of CO_2 which is two to three times the present carbon price in the European Emissions Trading System, no power producer would consider building a new fossil fuel power plant with CCS or retrofit an existing power plant for CCS. The economic case for CCS in the power sector, in the absence of public support and revenue from captured carbon sales to EOR/EGR operations, therefore rests on carbon pricing or government support. Studies have suggested that even a very high carbon price (e.g., greater than US$50 MWh) would not guarantee that CCS is able to overcome current cost barriers.[35]

Based on operational experience in the past decade, it is likely that CCS will not advance substantially in the power sector in the coming decade.[36] This leaves only niche applications for the technology, which would have to carry the full R&D, deployment, and infrastructure development costs.

I. Enhanced Oil and Gas Recovery

In its application with CCS, EOR describes the process of captured CO_2 being injected underground extract otherwise unreachable of oil and gas. EOR/EGR is not a new process,

[32] *Magneshi et al. (2017). Available at: https://reader.elsevier.com/reader/sd/pii/S1876610217319720?token=C460FDDC1C312BAFF5F2A4D447B5C7B7FE2981C45134C3B7DC842DBFC272B610EADC2405A8E9414C2EDE03E9D266406B*

[33] Jacobson, M. (2019). The health and climate impacts of carbon capture and direct air capture. Energy & Environmental Science, 12, 2019, pp.3567-3574. https://doi.org/10.1039/C9EE02709B.

[34] The Boundary Dam project in Saskatchewan, Canada is often touted as the world's first coal-fired CCS project. The project is a post-combustion retrofit of a single coal-fired unit that cost more than US$1 billion; a large part of the project's cost was paid for with government funding. Boundary Dam has been plagued by operating difficulties and has had difficulty maintaining a high capture rate. What's more, captured CO_2 is sold to a nearby EOR operation rather than stored in a standalone geological formation. Schlissel, D. (2018). Holy Grail of Carbon Capture Continues to Elude Coal Industry. Institute for Energy Economics and Financial Analysis. November 2018. Available at: https://ieefa.org/wp-content/uploads/2018/11/Holy-Grail-of-Carbon-Capture-Continues-to-Elude-Coal-Industry_November-2018.pdf.

[35] Cost estimates for CCS often focus on the level of carbon price needed to make a power station fitted with carbon capture technology economic whilst discounting or ignoring the cost of transport, injection, storage, and storage site monitoring. *See, e.g.,* Lazard Ltd (2018). Lazard's Levelized Cost of Energy Analysis—Version 12.0. Lazard Ltd. November 2018. Available at: https://www.lazard.com/media/450784/lazards-levelized-cost-of-energy-version-120-vfinal.pdf, which shows the cost of CCS power stations relatives to other energy technologies. Note that the Lazard LCOE analysis does not includes costs for CO_2 transport, storage, and monitoring.

[36] "…as far as the power sector is concerned the overall message seems to be that for the moment it is 'game over' for CCS, in the EU especially, with renewables offering a cheaper option." Elliott, D. (2018). Whatever happened to carbon capture? PhysicsWorld. 5 September 2018. Available at: https://physicsworld.com/a/whatever-happened-to-carbon-capture/.

and has been in commercial use since the 1970s. At present, EOR/EGR is one key aspect to the economic viability for CCS projects – most notably in the United States.[37]

Estimates of the amount of CO_2 remaining underground when used in EOR/EGR operations vary widely. Nevertheless, the risk of leakage in such underground storage sites can also be significantly higher due to the existence of multiple wells that may or may not have been properly sealed.[38] Sound independent and scientific monitoring and verification activities at such sites, if they occur at all, are usually not transparent and information is rarely shared with the public. However, more than three quarters of the reportedly stored all CO_2 from CCS is based on EOR.

Lifecycle analyses of the CO_2 mitigation potential of CCS linked with EOR/EGR vary in their results primarily due to differing boundary definitions, which makes comparisons between studies difficult. Cradle-to-grave analyses that assess the net lifecycle emissions of CO_2-EOR projects from coal mining to product combustion conclude that CO_2-EOR projects have historically emitted more CO_2 than they have removed through geologic storage[39]. In this way, EOR/EGR could perhaps be described as a CO_2 capture and release strategy whereby CO_2 captured from power station smokestacks is used to recover fossil fuel resources that may have otherwise remained underground that, when burned, release CO_2 back into the atmosphere. While EOR/EGR makes business sense for the fossil fuel industry, it is not a winning strategy for the climate.

B. Industrial CCS

Energy-intensive Industries and some **with CO_2 process emissions** are a large source of CO_2 emissions in some countries and are part of global supply chains. For example, the iron and steel industries use pure carbon-rich coking coal for reduction of iron ore (oxide) to metal and emits about 2 Gt CO_2 worldwide. Graphite electrodes for the electrolysis used in the production of aluminum are transforming to CO_2. The cement industry has to heat limestone, which then as process emissions emits vast amounts of CO_2. The entire cement making emits about 2.5 Gt CO2 worldwide. Chemical and fertilizer industries produce polyethylene and Ammonia, respectively, two very energy-intensive processes from fossil fuels. - Other high-emitting industries include paper and pulp production and oil refineries.

While industrial CCS is promoted by some as a key feasible strategy to decarbonize industry, a wide range of solutions for net zero industry are emerging including increased material efficiency, material recirculation and new production processes. Different approaches, alternative materials, and R&D, particularly into new processes have the potential to eliminate the need for CCS in this

[37] Center for International Environmental Law (2019). Fuel to the Fire: How geoengineering threatens to entrench fossil fuels and accelerate the climate crisis. February 2019. Available at: https://www.ciel.org/reports/fuel-to-the-fire-how-geoengineering-threatens-to-entrench-fossil-fuels-and-accelerate-the-climate-crisis-feb-2019/.

[38] *See* Appendix 1.

[39] *See, e.g.,* Jaramillo, P., Griffin, W. M., McCoy, S. T. (2009). Life cycle inventory of CO_2 in an enhanced oil recovery system. Environmental Science & Technology, vol. 43, pp.8027–8032. https://doi.org/10.1021/es902006h. Other lifecycles analyses have indicated that CO_2-EOR may reduce carbon emissions, or result in net negative emissions, for all or some portion of a CO_2-EOR project's life but the boundaries for these analyses are usually not cradle-to-grave. For a gate-to-grave lifecycle analysis along these lines, see Núñez-López, V., Gil-Egui, R., Hosseini, S. A. (2019). Environmental and operational performance of CO_2-EOR as a CCUS technology: a Cranfield example with dynamic LCA considerations. Energies, vol.12(3), p 448. https://doi.org/10.3390/en12030448.

sector. Iron ore, for example, can be mined less with better recycling and recovery methods. Alternative production processes are also being trialed, which could eliminate the need for coal, such as the iron ore reduction using renewably-produced hydrogen obtained through the electrolysis of water.

Aluminum can also be produced either with renewably-produced hydrogen or with inert electrodes instead of graphite electrodes. For the cement industry, alternative binders such as geopolymers (clays), pozzolanic (volcanic ash, ash from coal combustion), slag and magnesium-based cements can be used instead of CO_2-emitting Portland cement to make concrete. A greater focus on waste prevention, alternative sustainable bio-based materials, along with reuse and recycling, can reduce or eliminate the need to incinerate household and other wastes that contain a large fraction of plastics.

Further, district heating plants, steel mills, paper mills, and industrial heating plants are far from ideal for CCS. Such facilities tend to be much smaller in size than power stations and can be widely dispersed. Capture and transport costs will therefore be proportionally higher. A typical district combined heat and power or industrial heating plant is between 1 and 100 MW; and each plant would require a separate engineering design, environmental impact assessment, permitting, and financing process.

Given that current CCS costs make the economics for a single 2 GW coal power plant producing 10 $MtCO_2$ per year challenging, CCS is even less likely to be economically feasible for 100 smaller plants located anywhere from 10 to 100 (or more) kilometers apart. Proponents of CCS clustering in Europe have asked for grants, subsidies, and loan guarantees for projects that would share infrastructure and costs to make them economically viable and financeable.[40]

C. Bioenergy with Carbon Capture and Storage

BECCS envisions the use of plants, such as trees or agricultural crops, to naturally remove CO_2 from the atmosphere; the subsequent burning of such plants to produce electricity (or heat); and the capture and storage of any emissions produced in connection with energy transformation activities. It has gained attention in recent years as a potential negative emissions strategy, and features prominently in a number of decarbonisation pathways.[41] Some studies question the carbon neutrality claim of biomass[42] as well as the negative emissions claims of BECCS.[43]

[40] *See* Duruset, E. (2017). Deployment of an Industrial CCS Cluster in Europe: A Funding Pathway. i24c. 7 August 2017. Available at: http://i2-4c.eu/wp-content/uploads/2017/10/Deployment-of-an-industrial-CCS-cluster-in-Europe_v2.2_final_web.pdf.

[41] As noted by Carbon Brief, "[i]n little more than a decade, BECCS had gone from being a highly theoretical proposal for Sweden's paper mills to earn carbon credits to being a key negative emissions technology underpinning the modelling, promoted by the IPCC, showing how the world could avoid dangerous climate change this century." CarbonBrief (2016). Timeline: How BECCS became climate change's 'saviour' technology. Carbon Brief. 13 April 2016. Available at: https://www.carbonbrief.org/beccs-the-story-of-climate-changes-saviour-technology.

[42] *See, e.g.,* Southern Environmental Law Center (2019). Fact Sheet: New Report Shows Wood Pellets from Drax's U.S. Mills Increase Carbon Emissions During the Timeframe Necessary to Address Climate Change. Southern Environmental Law Center. 8 August 2019. Available at: https://www.southernenvironment.org/uploads/publications/2019-08-08_FINAL_Biomass_Factsheet_Drax_SIG_Report_Updated1.PDF.

[43] Harper, A.B., Powell, T., Cox, P.M. et al. Land-use emissions play a critical role in land-based mitigation for Paris climate targets. Nature Communications 9, 2938 (2018). https://doi.org/10.1038/s41467-018-05340-z.

Furthermore, many experts and scientists have highlighted ecological, water and resource constraints and competition with food production which would limit its deployment.[44]

A single BECCS pilot project which is burning 100% biomass feedstock exists globally and has been capturing about a tonne of CO_2 (but not storing) per day since 2019 at the Drax Power Station in the UK.[45] The Drax Power Station is a coal- and biomass-fired power station, and the UK's largest source of CO_2 emissions. The power station is also the world's single biggest burner of biomass (burning more wood than the UK produces annually).[46] The company that owns the Drax Power Station receives more than >£2.1 million in public subsidies per day to support its wood burning activities.[47] Whilst the company has signaled its intent to expand its use of BECCS at the power station, such plans are contingent on the continuation of public subsidies as well as "an effective negative emissions policy and investment framework."[48]

Whilst biomass is an abundant resource, its use in the energy section should be limited given concerns about potential climate benefits as well as competing demands on land and water, especially for food production and the protection of forests and natural ecosystems. In many parts of the world, biomass production often involves land use conflict between many different interests from food to biodiversity, transport fuels, industry, as building material, power, and heat.[49] Combining biomass with CCS at a large scale is likely to exacerbate existing issues.[50]
Studies on deploying BECCS at scale envisioned raises significant concerns related to land use, food security, water use, and biodiversity impacts:

- ***Land use***. Estimates vary, but models have estimated millions to a billion (or more) hectares would be needed to produce sufficient biomass to achieve BECCS's share of emission reductions in many climate pathways.[51]

---

[44] *See, e.g.*, Smith, P., Davis, S., Creutzig, F. et al. Biophysical and economic limits to negative CO_2 emissions. Nature Clim Change 6, pp.42–50 (2016). https://doi.org/10.1038/nclimate2870; *see also* Smith, L.J., Torn, M.S. Ecological limits to terrestrial biological carbon dioxide removal. Climatic Change 118, pp.89–103 (2013). https://doi.org/10.1007/s10584-012-0682-3.

[45] Drax Group plc (2019). Carbon dioxide now being captured in first of its kind BECCS pilot. Press Release issued 7 February 2019. Available at: https://www.drax.com/press_release/world-first-co2-beccs-ccus/.

[46] Biofuelwatch (2019a). Drax Plc: Harming Forests, Climate and Communities. April 2019. Available at: https://reclaimthepower.org.uk/uncategorized/drax-power-station-burning-all-the-things/.

[47] Biofuelwatch (2019b). Campaigners Call on Government to Stop Drax from Fuelling Environmental Injustice, Forest Destruction and Climate Breakdown. Press Release issued 9 October 2019. Available at: https://www.biofuelwatch.org.uk/2019/drax-protest-pr-2/.

[48] Fawthrop, A. (2019). Drax to deploy BECCS technology to become carbon-negative by 2030. NS Energy. 10 December 2019. Available at: https://www.nsenergybusiness.com/news/company-news/drax-carbon-negative/.

[49] *See, e.g.,* European Environment Agency (2016). Land use conflicts necessitate integrated policy, available at: https://www.eea.europa.eu/highlights/land-use-conflicts-necessitate-integrated-policy (accessed 1 February 2020).

[50] The Illinois Industrial Carbon Capture and Storage Project in Decatur, Illinois which involves capture of CO_2 from ethanol production and storage in Mount Simon Sandstone Reservoir, for example, involves massive industrial monocropping that could compete with food production and add pressure on land and water resources when adopted at scale globally as a mitigation approach. *See* Greenberg, S. (2018). Illinois Basin Decatur Project - Sharing practical lessons learned about moving from pilot to large-scale demonstration. Presentation, available at: http://conference2018.co2geonet.com/media/28835/10-greenberg.pdf.

[51] For example, "[i]n the Integrated Assessment Model scenarios consistent with a 2 °C target, a median of 3.3 GtC yr^{-1} was removed from the atmosphere through BECCS by 2100, equivalent to one-third of present-day emissions from fossil fuel and industry. This median amount of BECCS would result in cumulative negative emissions of 166 GtC by 2100 and would supply ~170 EJ yr^{-1} of primary energy. The bioenergy crops to deliver such a scale of CO_2 removal could occupy an estimated 380–700 Mha of land, equivalent to up to ~50% of the present-day cropland area." Harper, A.B., Powell, T., Cox, P.M. et al. Land-use emissions play a critical role in land-based mitigation for Paris climate targets. Nature Communications 9, 2938 (2018). https://doi.org/10.1038/s41467-018-05340-z.

- ***Food security.*** The demand for land area for BECCS deployment at scale corresponds to globally converting approximately 50% of arable land and permanent crops for biomass.[52] Some studies have shown that as a result of decreasing land availability, BECCS could increase food prices and increase conflict for land, biomass, and water by putting pressure on limited natural resources.[53]
- ***Water use.*** If implemented at scale, BECCS could more than double the amount of water currently used for irrigation in food production to support the growth of biomass for combustion.[54]
- **Biodiversity.** If implemented at scale, BECCS has the potential to reduce biodiversity, especially if land areas are converted to monoculture plantations and/or use non-native plant species.[55]

Like CCS as applied to fossil fuel power stations, BECCS also has to grapple with the same energy demand associated with CO_2 capture technology, transport issues, and identifying appropriate and permanent storage sites within reasonable proximity to the bioenergy facility.

D. Direct Air Carbon Capture and Storage

DACCS involves filtering CO_2 from ambient air which represents 0.04% of air by volume. This approach, whilst technically feasible, is in its infancy. As with BECCS, DAC is promoted by some for its potential to delivery negative emissions. Several companies are currently working to advance the technology, including Climeworks, Carbon Engineering, Skytree, and Antecy. Climeworks has advanced the farthest with a small-scale demonstration including in Switzerland, where captured CO_2 is used for various applications rather than stored.[56] In 2019, Carbon Engineering and Occidental Petroleum announced plans to build the world's first large-scale direct air capture plant, where captured CO_2 would be used for EOR.[57]

Two key barriers to DACCS commercialisation are cost and energy demand. DACCS is currently very energy intensive and expensive because massive volumes of air must be filtered to capture any reasonable amount of CO_2. One study examining the potential of DACCS to help meet the Paris Agreement goal found that widescale deployment of DACCS would account for a full one-quarter of global energy demand for heat and power by the end of this century.[58] Cost estimates

---

[52] *Ibid.*

[53] Stokstad, E. (2019). Bioenergy plantations could fight climate change—but threaten food crops, U.N. Panel warns. Science. 8 August 2019. Available at: https://www.sciencemag.org/news/2019/08/bioenergy-plantations-could-fight-climate-change-threaten-food-crops-un-panel-warns.

[54] Yamagata, Y., Hanasaki, N., Ito, A. et al. Estimating water–food–ecosystem trade-offs for the global negative emission scenario (IPCC-RCP2.6). Sustainability Science 13, pp.301–313 (2018). https://doi.org/10.1007/s11625-017-0522-5.

[55] Smith, P., Price, J., Molotoks, A., Warren, R., and Malhi, Y. (2018). Impacts on terrestrial biodiversity of moving from a 2°C to a 1.5°C target. 376. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences. https://doi.org/10.1098/rsta.2016.0456.

[56] National Academies of Sciences, Engineering, and Medicine (2019). Negative Emissions Technologies and Reliable Sequestration: A Research Agenda, Chapter 5 Direct Air Capture. Washington, DC: The National Academies Press. https://doi.org/10.17226/25259.

[57] Rathi, A. (2019). Carbon Engineering is doubling its CO_2-capturing machine even before it's built. Quartz. 21 September 2019, available at: https://qz.com/1713529/carbon-engineering-and-occidental-will-capture-1-million-tonnes-of-carbon-dioxide/.

[58] Realmonte, G., Drouet, L., Gambhir, A. et al. An inter-model assessment of the role of direct air capture in deep mitigation pathways. Nature Communications10, 3277 (2019). https://doi.org/10.1038/s41467-019-10842-5.

vary widely and span an order of magnitude, from US$100 to US$1,000 per ton of CO_2, not including associated transport and storage costs.[59]Critically, these estimates represent the cost of CO_2 captured rather than the cost of net CO_2 removed from the atmosphere. Factoring in this cost tends to make DACCS the most expensive atmospheric CO_2 removal approach.[60]

Overall, there are serious doubts about the effectiveness of DACCS given the tension between the need for high capture rates and the very low concentration of CO_2 in the atmosphere. Another potential barrier to widescale DACCS deployment is pollution concerns associated with the chemical sorbent manufacture at "vast scales" to capture CO_2 from the atmosphere.[61] Also a point of concern is the fact that DACCS has attracted attention and investment from the oil and gas sector, which views the technology as a potential source of CO_2 for EOR/EGR operations.[62]

E. Carbon Capture and Utilisation

CCU covers a variety of processes which involve the absorption or conversion of CO_2 during the manufacture of usable product. For example, CO_2 can be utilised as a chemical feedstock or input to produce products, like synthetic fuels. CO_2 could be also used to fertilise algae or increase CO_2 levels in greenhouses to boost plant growth. It is also possible to use CO_2 to produce carbon fibers as a substitute for many materials and applications containing other mineral fiber components[63].

Theoretically, CCU is a promising technology which, depending on its application, may support achieving the 1.5°C target. However, many CCU applications are in the early research phase and very far from commercialisation. Costs and market size are also difficult to assess at this stage.[64] However, it is clear that the volume of CO_2 that would need to be captured far outpaces potential uses in industrial and other applications, including EOR/EGR operations.[65]

Because CCU typically results in the re-release of captured GHG emissions, its potential is limited to a carbon neutral technology. Further, some processes that use CO_2 as a chemical intermediary, such as the production of synthetic fuels have limited or no value from a climate mitigation perspective. Only CCU processes that integrate and permanently store CO_2 would have the

[59] Ishimoto, Y., M. Sugiyama, E. Kato, R. Moriyama, K. Kazuhiro Tsuzuki, and A. Kurosawa (2017). Putting costs of direct air capture in context. Forum for Climate Engineering Assessment Working Paper Series: 002. Washington, DC: American University School of International Service.

[60] National Academies of Sciences, Engineering, and Medicine (2019). Negative Emissions Technologies and Reliable Sequestration: A Research Agenda, Chapter 5 Direct Air Capture. Washington, DC: The National Academies Press. https://doi.org/10.17226/25259.

[61] Realmonte, G., Drouet, L., Gambhir, A. et al. An inter-model assessment of the role of direct air capture in deep mitigation pathways. Nature Communications 10, 3277 (2019). https://doi.org/10.1038/s41467-019-10842-5.

[62] Center for International Environmental Law (2019). Fuel to the Fire: How geoengineering threatens to entrench fossil fuels and accelerate the climate crisis. February 2019. Available at: https://www.ciel.org/reports/fuel-to-the-fire-how-geoengineering-threatens-to-entrench-fossil-fuels-and-accelerate-the-climate-crisis-feb-2019/.

[63] The problem with light weight carbon fibers is their very high energy need when produced from virgin materials but they presently have very low re-cyclability. Since they hardly decompose because of their physio-chemical inertness, products with carbon fibers end mostly in landfills. The opportunity for carbon fibers lies in the reusability of the product in case the physical shape does not change, like plane and car envelopes.

[64] IOGP (2019). The potential for CCS and CCU in Europe at 3. Report to the 32nd meeting of the European Gas Regulatory Forum 5-6 June 2019. Available at: https://ec.europa.eu/info/sites/info/files/iogp_-_report_-_ccs_ccu.pdf.

[65] Group of Chief Scientific Advisors (2018). Novel carbon capture and utilization technologies. European Commission Directorate-General for Research and Innovation. May 2018. Available at: https://ec.europa.eu/research/sam/pdf/sam_ccu_report.pdf.

potential to mitigate and or remove CO_2 emissions albeit with varying concerns associated in specific applications.[66]

Carbon Dioxide Storage

Globally, experience with the long-term underground/sub-seabed storage of CO_2 though CCS applications is limited. The longest running CO_2 storage project in the world, the marine Sleipner oil field in Norway, has only been operational since 1996 and is still actively injecting CO_2.[67] The IPCC noted in 2005 that the fraction of CO_2 retained in such geological reservoirs is "very likely [above 90% certainty] to exceed 99% over 100 years and is likely [above 60% certainty] to exceed 99% over 1000 years."[68] Whilst the existence of naturally occurring carbon dioxide deposits provides an indication on the permeance of storage through CCS, issues concerning CO2 leakage risks, governance and storage capacity inform on the challenges of CCS technologies. While a 2005 special report from the IPCC[69] assessed the CO2 storage as safe, some scientists[70] and some NGOs (footnote) seeing large risk with storage facilities like Sleipner and in the North Atlantic in general.

A. CO_2 Leakage

For CCS to serve as a safe, effective mitigation tool, captured carbon must be injected and stay underground permanently.[71] The IPCC had shown in its Fifth Assessment Report in 2013 that up to 40% of atmospheric CO2 stays there for at least 1000 years. Therefore, even very low leakage rates over long periods of time could negate the climate benefits of CCS. For example, a leakage rate of 0.1% per year would release 73% of stored CO_2 from a storage site over 1,000 years.

As long as CO_2 is present in geological formations, there is a risk of leakage. In contact with water, CO_2 becomes a weak but permanent acid and therefore corrosive and can compromise the integrity of caprocks, well casings, and cement plugs. Undetected fractures and abandoned, improperly, or unsealed wells (in the case of depleted oil and gas fields) can also provide an avenue for CO_2 to escape. Remediation for CO_2 leaks may be possible but there is no track record or cost estimate for such measures.

Whilst leakage rates in appropriately selected and maintained storage sites particularly in the sub-seabed[72] are likely to be limited, such sites are a limited resource and will not be distributed evenly

---

[66] For example, CO_2 can be used to "cure" cement, or in the manufacture of aggregates. Doing so stores some CO_2 for the long term and could displace emissions-intensive conventional cement but does not offset all emissions from the cement production process.

[67] *See* Appendix 2 for a discussion of potential leakage risk in the Sleipner formation.

[68] IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H. C. de Coninck, M. Loos, and L. A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp.

[69] The IPCC noted in 2005 that the fraction of CO_2 retained in such geological reservoirs is "very likely [above 90% certainty] to exceed 99% over 100 years and is likely [above 60% certainty] to exceed 99% over 1000 years; IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H. C. de Coninck, M. Loos, and L. A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp.

[70] https://www.airclim.org/acidnews/myths-about-carbon-storage-%E2%80%93-sleipner-case

[71] Therefore, national CCS laws (e.g., Germany) assume zero leakage. If leakage occurs - in contrary to this assumption - the operator of the storage site has to start measures to stop this.

[72] Vielstädte, L. et al, "Footprint and detectability of a well leaking CO2 in Central North Sea: Implications from a field experiment and numerical modeling", International Journal of Greenhouse Gas Control, Vol 84, May 29, pp. 190-203 https://doi.org/10.1016/j.ijggc.2019.03.012, available in: https://www.sciencedirect.com/science/article/pii/S1750583618304857

across the globe.[73] Moreover, significant uncertainty remains in estimates of potential leakage risk.[74] Depleted oil and gas fields, including those used in EOR/EGR operations, are one type of storage site used by CCS applications. These storage sites tend to be very well characterised but the multiple bore holes and wells drilled in them to find and extract oil and gas increase the risk of leakage.

The increased risk is due, in part, to what may be labeled as a lack of diligence on the part of the oil and gas industry to clean up after itself. Many wells in oil and gas fields are improperly sealed or not sealed at all. For example, an investigation conducted by the Associated Press (AP) in the wake of the British Petroleum Deepwater Horizon disaster found that oil companies "routinely circumvented" regulations for temporarily abandoned wells. More than 1,000 temporarily abandoned wells in Gulf of Mexico "lingered in an unfinished condition for more than a decade."[75] In that same AP investigation, whilst an oil company representative insisted that it was in everyone's interest to seal wells and to do so properly, state officials estimated that "tens of thousands [were] badly sealed, either because they predate[d] strict regulation or because the operating companies violated the rules.[76]

Aside from compromising climate mitigation efforts, depending on volume and concentration, CO_2 leakage also has the potential to contaminate ground and surface waters, impact soil ecology and the marine environment, and harm human health. A natural example of the danger of CO_2 leakage occurred in a volcanically active area at Lake Nyos in Cameroon in 1986. Large quantities of CO_2 that had accumulated at the bottom of the lake were suddenly released, killing 1,700 people and thousands of cattle over a range of 25 kilometres.[77]

B. Liability for CO_2 Storage

Another barrier to CCS deployment is the question of who is liable for CO_2 once it is stored underground. The answer to this question determines who is likely responsible for monitoring a CO_2 storage site, remediating CO_2 leaks to the extent possible, providing financial security, and paying for any "harm" to the climate, private property, environment, human health, etc. in the event something goes wrong. It is for these reasons that public opposition to onshore CO_2 storage further limits opportunities to deploy CCS. Due to concerns regarding leakage and seismic events,[78]communities have mobilised to stop CO_2 storage projects from going forward. Public acceptance for onshore CO_2 storage, in particular, is limited in Europe, with storage projects

---

[73] IPCC (2005). IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H. C. de Coninck, M. Loos, and L. A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp.

[74] Anderson, S.T. (2017). Risk, Liability, and Economic Issues with Long-Term CO2 Storage—A Review. Natural Resources Research 26, pp.89–112 (2017). https://doi.org/10.1007/s11053-016-9303-6.

[75] Donn, J. and Weiss, M. (2010). Gulf awash in 27,000 abandoned wells. Associated Press. 7 July 2010. Available at: https://www.cbsnews.com/news/27000-abandoned-gulf-oil-wells-may-be-leaking/.

[76] *Ibid.* The article also mentions a 2006 report from the US Environmental Protection Agency regarding wells on land. The report notes that, "[h]istorically, well abandonment and plugging have generally not been properly planned, designed and executed."

[77] Diesendorf, M. (2006). Can geosequestration save the coal industry?, in J Byrne, L Glvoer & N Toly (eds), Transforming power: Energy as a social project, Energy and Environmental Policy Series vol. 9, 2006, pp. 223-248.

[78] Under pressure, CO_2 is an extremely efficient lubricant and may create earthquakes. According to the US National Academy of Sciences, "[l]arge-scale CCS may have the potential for causing significant induced seismicity." National Research Council (2013). Induced Seismicity Potential in Energy Technologies at 12. Washington, DC: The National Academies Press. https://doi.org/10.17226/13355.

scrapped in the Netherlands and Denmark as companies have failed to persuade residents that the benefits outweigh the risks.[79]

Industry actors are often unwilling to invest in CCS unless they are protected from the risks associated with long-term CO_2 storage. Concerns over liability are so great that utilities are often unwilling to make CO_2 available for storage unless they are relieved of ownership upon transfer of CO_2 from the power station. Others have urged that their legal liability for stored CO_2 be limited to defined periods of time, e.g. 10 years. In some countries, efforts to limit the liability of those engaged in CCS have included liability caps, federal indemnity programs, and a complete transfer of liability from the private to public sector.[80]

Long-term CO_2 storage over hundreds or even thousands of years hands over our climate responsibility to a plethora of future generations - it also raises questions about whether regulatory frameworks can appropriately manage and allocate risk throughout every phase of a CO_2 storage project. These questions remain unanswered as the world has limited experience with CO_2 storage (particularly sub-seabed) and CCS regulatory frameworks that exist are largely untested. In 2009, the European Union (EU) established "a legal framework for the environmentally safe geological storage" of CO_2.[81]

This framework creates a risk-based approach for CO_2 storage to prevent and eliminate environmental and public health risks as much as possible. This is a laudable goal but will be difficult to achieve in practice. To-date, the permitting framework for CO_2 storage has been infrequently used with a handful of permit applications submitted for review and only two storage permits issued.[82] The effectiveness of the framework's financial security mechanism, which includes provisions to ensure storage operations provide funding to maintain storage sites through their operation and post-closure phases, remains to be seen. How much funding will be needed, for example, to support long-term monitoring and mitigation is unknown. The risk of inadequate funding is significant with industry lobbying for lower funding requirements.

C. CO_2 Storage Capacity

Many CCS reports and studies assume abundant global or regional capacity to store captured CO_2. In Europe, for example, some have previously claimed the North Sea can store 1,000 years of CO_2 emissions.[83] Taking such claims at face value, is risky, as these types of top-down estimates of

---

[79] The Barendrecht onshore CO_2 storage project was cancelled by the Dutch government in 2010 due, in large part, to local opposition to the project. Carbon Capture & Sequestration Technologies @MIT (2016). Barendrecht Fact Sheet: Carbon Dioxide Capture and Storage Project. Available at: https://sequestration.mit.edu/tools/projects/barendrecht.html (accessed 1 February 2020); *see also* Acid News (2016), CCS sidelined by public oppositions, No.1, April 2016. Available at: https://www.airclim.org/acidnews/ccs-sidelined-public-opposition.

[80] Havercroft, I. and Macrory, R. (2014). Legal Liability and Carbon Capture and Storage: A Comparative Perspective. October 2014. Available at: https://sequestration.mit.edu/pdf/GHGT8_deFigueiredo.pdf.

[81] Directive 2009/31/EC.

[82] European Commission (n.d.). Implementation of the CCS Directive. European Commission. Available at: https://ec.europa.eu/clima/policies/innovation-fund/ccs/implementation_en (accessed 5 September 2019).

[83] Equinor (2019). Here's how your CO_2 emissions can be stored under the ocean, available at: https://www.equinor.com/en/magazine/carbon-capture-and-storage.html (accessed 1 February 2020).

CO_2 storage capacity (e.g. the 2,000 Gt CO_2 in IPCC SR CCS, 2005) are largely estimates of theoretical rather than effective or practical capacity.[84]

Theoretical storage capacity estimates are of limited use as they do not account for a variety of site-specific factors, including pore space availability and injectivity, which are a critical in evaluating the suitability of a geological formation for CO_2 storage. Injectivity refers to the rate at CO_2 can be injected through a well into a formation and is based on how much pressure can be increased within a formation without compromising site (e.g., caprock) integrity. Injectivity is poorly understood in most geological formations and has significant cost implications for CO_2 storage.[85] Such estimates also fail to account for the fact that potential CO_2 storage locations are not evenly distributed. Co-location of captured CO_2 and potential storage locations has economic implications for the cost of CO_2 transport and storage.

When such factors are evaluated, top-down capacity estimates are frequently revised drastically downwards. For example, the Utsira formation where the Sleipner CO_2 storage project operates had "practically unlimited" storage potential and could handle CO_2 emissions from "all power stations in Europe for the next 600 years."[86] However, after an in-depth study, the Norwegian Petroleum Directorate downgraded the storage capacity estimate for the Utsira formation from "able to store all European emissions for hundreds of years" to "not very suitable."[87]

---

[84] Bjureby, E., Rochon, E., Gulowsen, T. (2009). Reality Check on Carbon Storage. Greenpeace International. May 2019. Available at: http://www.globalislands.net/greenislands/docs/norway_reality-check-on-carbon-storage.pdf.

[85] Whiriskey, K. (2014). Scaling the CO_2 storage industry: A study and a tool. Bellona Europa. November 2014. https://bellona.org/assets/sites/4/Scaling-the-CO2-storage-industry_Bellona-Europa.pdf.

[86] Bjureby, E., Rochon, E., Gulowsen, T. (2009). Reality Check on Carbon Storage. Greenpeace International. May 2019. Available at: http://www.globalislands.net/greenislands/docs/norway_reality-check-on-carbon-storage.pdf.

[87] *Ibid.*

Appendix 2- Brief History of CCS (2001-2017): Expectations and Results

High hopes were pinned on CCS in the first decade of the 2000s after, among other things, promising results from the Sleipner storage site in Norway where roughly 1 $MtCO_2$ have been injected per year since 1996.[88] CCS garnered strong support from the US under the Bush administration, the EU, and governments in the UK, Canada, Australia, and Germany. The UN General Secretary (and Angela Merkel) appointed the Vattenfall CEO Lars G. Josefsson, a leading coal apologist and CCS champion, as climate advisor. The EU enacted legislation aimed at supporting 10-12 operating CCS demonstration projects (mostly power plants, but also for industrial process emissions) by 2015 and Norway's Prime Minister Stoltenberg claimed 2007 that CCS was that country's "moon landing" project.

Support for CCS only grew following the release of the IPCC Special Report on Carbon Dioxide Capture and Storage (IPCC Report) in 2005.[89] The IPCC Report claimed that "in /most scenarios/ in a least-cost portfolio of mitigation options, the economic potential of CCS would amount to 220–2,200 Gt CO_2 … cumulatively, which would mean that CCS could contribute 15–55% to the cumulative mitigation effort worldwide until 2100".[90] The IPCC Report also stated that it was "likely" that at least about 2,000 Gt CO_2 geological storage capacity existed. Almost every major power company believed coal was an inevitable part of the future, and the only way to make the continued use of coal consistent with efforts to lower global greenhouse gas emissions was through CCS.

The European Commission summed up the global mood on CCS in May 2008: "[i]ntroducing CCS may delay the need to reduce levels of fossil fuel use by at least half a century."[91] At the time, the conventional wisdom was that:

- Renewables were too expensive and CCS would be a bridge technology whilst alternatives to fossil fuels are further developed and deployed."
- There was a strong link between economic growth and energy growth, especially electricity consumption, so energy efficiency was a limited option.
- There was no realistic option and no major political power to stop coal growth, so the fuel shift option (from coal to gas) was limited.
- 550 ppm CO_2 and higher was considered as mitigation. The ultimate objective of UNFCCC in Art. 2 was only operationalised and adopted at COP 16 in 2010 ("2-degree limit"). At the G8-Summit in Heiligendamm (2007) there were intense discussions on the 2-degree limit but no consensus could be found as US-President Bush objected to that.

Since the early 2000s, however, a lot has changed in the energy landscape. World CO_2 emissions have decelerated to <0.5% growth per year between 2013 and 2017, compared to 2.5% the previous 10 years. Electricity consumption has more or less stabilized in major economies such as the US, EU, and Japan. Coal use in the power sector declined in the OECD from >4000 TWh to <3000 TWh between 2007 and 2017.

---

[88] The Sleipner project in Norway strips CO_2 that is co-produced with a natural gas stream from a field in the North Sea. The CO_2 is then re-injected below the seafloor in a saline aquifer in order to avoid payment of a CO_2 tax.

[89] IPCC (2005). IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H. C. de Coninck, M. Loos, and L. A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp.

[90] *Ibid.*

[91] *See, e.g.,* European Commission DG ENV (2008). News alert, Issue 105, May 2008. Available at: https://ec.europa.eu/environment/integration/research/newsalert/pdf/105na3_en.pdf.

New coal power has become a no-go in an increasing number of countries whilst a great deal of existing coal capacity has been phased out. CCS was presented as a "bridge technology" but as renewables have surged ahead, CCS has barely advanced. Renewable energy deployment is now booming across the globe thanks to significant cost declines. Wind power production, for example, has grown by a factor of more than 10 since the IPCC report was released in 2005- from 104 TWh 2005 to about 1,400 TWh in 2019. Solar power production has increased by more than a factor of 100- from 4 TWh in 2005 to more than 600 TWh in 2019[92]. Yet, wind and solar energy combined are presently responsible for only nearly 9% of global electricity and about 1.5% of global final energy demand, still far too low and much too slow than what could bring the world to an alternative path.

Meanwhile, CCS has failed to advance despite billions in public support. In the US, for example, nearly half of the US$2.6 billion spent by the US Department of Energy since 2010 to advance fossil fuel technologies was spent on CCS;[93] Australia has spent AUS$1.3 billion on CCS since 2003;[94] the provincial government in Alberta is in the process of spending CA$1.24 billion on two projects; [95] the UK spent £168 million on two failed CCS competitions and continues to allocate millions in public funds to CCS on an annual basis; [96] and despite passing the CCS Directive (2009/31/EC) and spending €424 million over 10 years, Europe has zero CCS demonstration plants to date.[97]

Notable project failures and technical flaws include:

- In Salah—Poor management at the CO_2 storage site in Algeria resulted in the cessation of injection activities in 2011 after over-pressurisation of the formation fractured the caprock;[98]
- FutureGen and Kemper—These high-profile US projects were cancelled after major cost overruns, delays, and technical issues;[99] and
- Mongstad—Norway's "moon landing" CCS project was scrapped after cost overruns and delays.[100]
- Sleipner—Discovery of fractures near the CO_2 storage site, discovered in 2012, have led to concerns that CO_2 could eventually leak;[101]

---

[92] World Energy Outlook, IEA 2020

[93] Patel, S. (2018). DOE Sank Billions of Fossil Energy R&D Dollars in CCS Projects. Most Failed. Power. 9 October 2019. Available at: https://www.powermag.com/doe-sank-billions-of-fossil-energy-rd-dollars-in-ccs-projects-most-failed/.

[94] Brown, B., Swann, T. (2017). Money for Nothing. The Australia Institute. 30 May 2017. Available at: https://www.tai.org.au/content/money-nothing.

[95] Alberta (2020). Carbon capture and storage, available at: https://www.alberta.ca/carbon-capture-and-storage.aspx.

[96] Rathi, A. (2017). The UK could have changed the way the world fights global warming. Instead it blew $200 million. Quartz. 2 May 2017. Available at: https://qz.com/972939/the-uk-could-have-changed-the-way-the-world-fights-global-warming-instead-it-blew-200-million/.

[97] Rathi, A. (2018). The EU has spent nearly $500 million on technology to fight climate change—with little to show for it. Quartz. 23 October 2018. Available at: https://qz.com/1431655/the-eu-spent-e424-million-on-carbon-capture-with-little-to-show-for-it/.

[98] Spotts, P. (2014). Can we hide carbon dioxide underground? Algeria site offers note of caution. Christian Science Monitor. 27 May 2014. Available at: https://www.csmonitor.com/Environment/2014/0527/Can-we-hide-carbon-dioxide-underground-Algeria-site-offers-note-of-caution.

[99] Mississippi ratepayers are responsible for US$1 billion of the cost of the failed Kemper project. Wilson, S. (2019). Two Years Since Kemper Clean Coal Project Ended. Mississippi Center For Public Policy. 17 July 2019. Available at: https://www.mspolicy.org/two-years-since-kemper-clean-coal-project-ended/.

[100] Holter, M. (2013). Norway Drops 'Moon Landing' as Mongstad Carbon Capture Scrapped. Bloomberg. 20 September 2013. Available at: https://www.bloomberg.com/news/articles/2013-09-20/norway-drops-moon-landing-as-mongstad-carbon-capture-scrapped.

[101] Acid News (2018). Myths about carbon storage—the Sleipner case, No.2, June 2018. Available at: https://airclim.org/acidnews/myths-about-carbon-storage-%E2%80%93-sleipner-case. However, leaks have not yet been detected. Cavanagh, A. (2015). Statoil CO_2 storage experience: 20 years and 20 million tonnes; http://conference.co2geonet.com/. Presentation in Session 5 from the second day (12 May 2015).

CALIFORNIA
AIR RESOURCES BOARD

Carbon Capture and Sequestration Protocol under the Low Carbon Fuel Standard

August 13, 2018

This Page Left Intentionally Blank

TABLE OF CONTENTS

FIGURES

TABLES

CARBON CAPTURE AND SEQUESTRATION PROTOCOL UNDER THE LOW CARBON FUEL STANDARD

A. DEFINITIONS AND APPLICABILITY

1. Applicability

The Carbon Capture and Sequestration (CCS) Protocol applies to CCS projects that capture carbon dioxide (CO_2) and sequester it onshore, in either saline or depleted oil and gas reservoirs, or oil and gas reservoirs used for CO_2-enhanced oil recovery (CO_2-EOR). The CCS Protocol applies to both new and existing CCS projects, provided the projects meet the requirements for permanence pursuant to section C of this protocol.

2. Definitions and Acronyms

(a) Definitions: For purposes of this document, the definitions in title 13, California Code of Regulations, section 95481 apply, except as otherwise specified in the document. The following definitions also apply to this document:

(1) "Active life" or "operational life" means the operational phase of a CCS project in which injection and, if applicable, production occurs. The term omits the monitoring and site care phase of the CCS project following injection completion.

(2) "Aqueous diffusion coefficient" is the magnitude of the molar flux through a surface per unit concentration gradient. Typical diffusion coefficients for organic compounds in aqueous solution range between 10^{-10} to 10^{-9} m^2/s.

(3) "Artificial penetration" means any man-made structures, such as wells or mines, which provide a flow path out of the sequestration zone or storage complex.

(4) "Assets" means all existing and all probable future economic benefits obtained or controlled by a particular entity.

(5) "Biogenic CO_2" refers to CO_2 produced from biomass.

(6) "Borehole" means a cylindrical hole cut into rock or soil by drilling. Also refers to the inside diameter of the wellbore wall (i.e., the rock face that bounds the drilled hole).

(7) "Bottom-hole pressure" means the pressure at the bottom of the wellbore within the sequestration zone. It may be measured directly with a downhole pressure transducer, or in some cases estimated from the surface pressure and the height and density of the fluid column.

(8) “Brine” is water containing dissolved minerals and inorganic salts in solution, including sodium, calcium, or bromides. Water containing dissolved solids in excess of 100 g/L is classified as brine. Large quantities of brine are often produced along with oil and gas.

(9) “Brittleness” is a property of a rock in which failure under a load occurs by fracturing, rather than by plastic deformation.

(10) “Capillary pressure” means the pressure difference across the interface of two immiscible fluids (e.g., CO_2 and water).

(11) “Capillary entry-pressure” means the pressure that a non-wetting fluid (e.g. CO_2) must overcome to displace water held tightly by capillary forces in the pores of a rock or sediment.

(12) “Capture Facility Operator” means the operator responsible for the CCS capture facility.

(13) “Carbon capture and sequestration (CCS)” means the process of concentrating CO_2 present in flue and/or exhaust gases, or air, via chemical and/or physical separation methods, transporting the CO_2 to an injection site, and injecting and permanently sequestering the captured CO_2.

(14) “Carbon dioxide equivalent” or “CO_2 equivalent” or “CO_2e” means the number of metric tons of CO_2 emissions with the same global warming potential as one metric ton of another greenhouse gas. For the purposes of the LCFS CCS Protocol, global warming potential values listed in the CA-GREET model are used to determine the CO_2 equivalent of GHG emissions.

(15) “Carbon intensity” has the same meaning as in 13, CCR, section 95481.

(16) “Casing” or “casing string” means a pipe or tubing of appropriate material (typically made of steel as used in oil and gas wells), of varying diameter and weight, lowered into a borehole during or after drilling in order to support the sides of the hole and thus prevent the walls from caving, to prevent the loss of drilling mud into porous ground, to prevent water, gas, or other fluid from entering or leaving the hole, or to allow conveyance of fluids to/from the surface from/to a specific location in the subsurface. “Long string casing” refers to the last, or longest, casing set in a well, set through the sequestration or production reservoir. “Surface casing” refers to the first string of casing that is set in a well, and varies in length from a few hundred to a few thousand feet.

(17) “Casing inspection logs (CIL)” are used to determine the presence or absence of corrosion in the long-string casing.

(18) “Casing shoe” means the bottom of the casing string or the equipment run at the bottom of the casing string.

(19) “CCS capture facility” means any plant, building, structure, or stationary equipment that captures CO_2 generated from industrial processes, or the atmosphere.

(20) “CCS project” means the overall CCS project operations, including those of the CCS capture facility and geologic sequestration site and activities.

(21) “CCS Project Operator” means the operator responsible for the CCS project.

(22) “CO_2-enhanced oil recovery (CO_2-EOR)” means the injection into and storage of CO_2 in oil reservoirs contributing to the extraction of crude oil.

(23) “CO_2 injection” means the process of injecting CO_2 into geologic reservoirs.

(24) “CO_2 leakage” means any movement of stored CO_2 out of the intended sequestration zone and out of the storage complex. “Atmospheric leakage” means the intended or unintended release of stored CO_2 outside the storage complex to the surface and atmosphere. “Subsurface leakage” means the vertical movement of stored CO_2 out of the storage complex that does not reach the atmosphere.

(25) “CO_2 plume” means the physical extent underground, in three dimensions, of the free-phase and dissolved CO_2 stream.

(26) “CO_2 stream” means CO_2 that has been captured from an emission source (e.g., a power plant), plus incidental associated substances derived from the source materials and the capture process, and any substances added to the stream to enable or improve the injection process.

(27) “CO_2 separation” means the process that separates CO_2 from produced oil, water, and natural gases for re-injection in the subsurface or transfer off site.

(28) “Completion interval” means the section of wellbore that has been prepared for production by creating channels between the reservoir formation and the wellbore.

(29) “Computational model” means a mathematical representation of the injection project and relevant features, including injection wells, site geology, and fluids present. For a CCS project, site-specific geological information is used as an input to a computational code, creating a computational model that provides predictions of subsurface conditions, fluid flow, and CO_2 plume and elevated

pressure migration at that site. The computational model includes all model input and predictions (i.e., outputs).

(30) "Confining pressure" means the combined hydrostatic and lithostatic stresses, or the total weight of the interstitial pore water and rock above a specified depth.

(31) "Confining system" means a multi-layered laterally extensive geologic formation, group of formations, or part of a formation, stratigraphically overlying the sequestration zone that exhibits low permeability and/or high capillary entry-pressure (e.g. a clay-rich shale or mudstone) such that it impedes the upward migration of fluid(s). The "primary confining layer" refers to the confining layer directly above the sequestration zone. "Secondary confining layer" refers to any confining layer directly above a dissipation zone and above the storage complex.

(32) "Constitutive relationships" represent empirically based approximations used to simplify the real-world system and estimate unknowns. Examples include saturation-relative permeability relationships, interphase mass transfer relations, and solution reaction relations.

(33) "Corporate parent" means a corporation that directly owns at least 50 percent of the voting stock of the corporation that is the CCS Project Operator; the latter corporation is deemed a subsidiary of the parent corporation.

(34) "Corrective action" means the use of California Air Resources Board-approved well remediation methods to ensure that any artificial penetrations within a storage complex do not serve as conduits for the movement of fluids out of the intended storage complex.

(35) "Corrosion" means the loss of metal due to chemical or electrochemical reactions that may cause loss of mass or thickness, cracking, or pitting of well components (casing, tubing, or packer).

(36) "Corrosion coupons" are small, pre-weighed, and measured pieces of metal made of the construction materials that are exposed to well fluids for a defined period, then removed, cleaned, and weighed to determine the corrosion rate. The coupon is made from the same material as the well's casing or tubing. The average corrosion rate in the well is calculated from the weight loss of the coupon.

(37) "Corrosion loops" are sections of tubing that are valved so that some of the injection stream is passed through a small pipe running parallel to the injection pipe at the surface of the well. These loops allow for monitoring and analysis of corrosion.

(38) “Current assets” means cash or other assets or resources commonly identified as those that are reasonably expected to be realized in cash, sold, or consumed during the normal operating cycle of the business.

(39) “Current liabilities” means the obligations whose liquidation is reasonably expected to require the use of existing resources properly classifiable as current assets or the creation of other current liabilities.

(40) “Darcy’s law” is an equation that defines the ability of a fluid to flow through a porous medium such as rock. It relies on the fact that the amount of flow between two points is directly related to the difference in pressure between the points, the distance between the points, and the interconnectivity of flow pathways in the rock between the points.

(41) “Depleted oil and gas reservoirs” means reservoirs that do not currently produce oil or gas, and are considered to have no economically recoverable oil or gas with current technology.

(42) “Depositional environment” is a specific type of place on the surface of the earth in which certain chemical, biological, and physical characteristics affect the deposition of sediments. The three overarching types of depositional environment include continental, marginal marine, and deep marine.

(43) “Deviated well” means a well that is not drilled vertically for its whole length, or a well with an inclination designed to be other than zero degrees from vertical.

(44) “Dissipation interval” is a stratigraphic interval with hydrogeologic properties sufficient to attenuate pressure created by CO_2 or formation fluid migration along an unidentified leakage pathway through the confining system.

(45) “Downhole measurements” are measurements collected from within the wellbore or borehole, either while drilling or during well maintenance or operation. Downhole measurements are used to determine physical, chemical, and structural properties of formations penetrated by a drill hole.

(46) “Ductility” means the property of a rock by which the rock plastically deforms under a load, rather than breaking by fracturing.

(47) “Elevated pressure” means the fluid response to CO_2 injection such that the pressure rise creates a risk of CO_2 or brine leakage.

(A) In a normally pressured system, elevated pressure is defined as the pressure increase such that brine from the sequestration zone would be lifted above the storage complex if a conduit opened.

(B) If the sequestration zone is naturally overpressured, such that brine would be lifted above the storage complex prior to injection if a conduit opened, elevated pressure is defined as a 20-psi increase, unless otherwise adjusted based on site and risk characteristics.

(48) "Embodied GHG" means lifecycle greenhouse gas emissions associated with production and transport of process fuels and chemicals to the point of use (e.g., GHG from the production and transport of natural gas as process fuel to a refinery).

(49) "Entrained CO_2" means CO_2 that remains in water, oil, or natural gas after the (oil, water, and natural gas) separation has taken place.

(50) "Equation of state" refers to an equation that expresses the equilibrium phase relationship between pressure, volume, and temperature for a particular chemical species.

(51) "Fluid" means liquid or gas.

(52) "Fluid pressure" means the measure of the potential energy per volume of fluid, based on force acting per unit area (psi or kPa).

(53) "Formation compressibility" is the relative volume change of a formation per unit pressure change.

(54) "Fracture pressure" or "parting pressure" is the pressure in the wellbore above which the injection of fluids will cause the rock formation to fracture hydraulically.

(55) "Fracture gradient" is the factor used to determine formation-fracturing pressure as a function of well depth in units of psi/ft.

(56) "Free-phase CO_2 plume" means the portion of CO_2 in supercritical, gaseous, or liquid phase, rather than as a dissolved component in native fluid (e.g., dissolved in brine), that occupies pore space within the sequestration zone.

(57) "Freshwater aquifer" means an aquifer that contains fewer than 10,000 mg/L total dissolved solids per the U.S. EPA Safe Drinking Water Act[1].

(58) "Fugitive emissions" means unintentional leakage of greenhouse gases from such as connectors, block valves, control valves, pressure relief valves, orifice meters, and regulators.

(59) "Geographic location" means the location of a well or monitoring site as referenced to a geographic coordinate system (e.g. latitude and longitude).

[1] U.S. EPA Underground Injection Control Program, 40 C.F.R. §144 (2014).

(60) "Geologic carbon sequestration (GCS)" means the permanent (≥ 100 years) containment of CO_2 within deep subsurface rock formations. This term does not include the capture or transport of CO_2.

(61) "Geologic formation" means a body of rock characterized by a degree of lithologic homogeneity that is prevailingly, but not necessarily, tabular and is mappable on the earth's surface or traceable in the subsurface.

(62) "Geomechanical analysis" means to study rock mechanical characteristics and properties, such as fault and reservoir rock stability and confining system integrity.

(63) "GHG emissions reductions" means the amount of greenhouse gas emissions (MT CO_2) avoided by limiting the carbon intensity of fuels under LCFS.

(64) "Governing equation" means the mathematical formulae that form the basis of a computational code. For computational modeling, they govern the predicted behavior of fluids in the subsurface provided by the code. Governing equations are mathematical approximations for describing flow and transport of fluids and their components in the environment.

(65) "Hydraulic conductivity" is a measure of a material's capacity to transmit a fluid. It is defined as a constant of proportionality relating the specific medium under a unit hydraulic gradient.

(66) "Hydraulic head" is the force per unit area exerted by a column of liquid at a height above a depth and pressure of interest. If connected by permeable flow paths, fluids flow down a hydraulic gradient, from points of higher hydraulic head to points of lower hydraulic head.

(67) "Injectivity" means the pressure differential over existing reservoir pressure required to inject a unit volume of fluid in a given unit of time. It is typically expressed as psi/bbl/day (psi per barrel per day), but can be expressed in any combination of pressure, volume, and time units.

(68) "Isopach map" means a contour map showing equal values of true stratigraphic thickness of a formation.

(69) "Leak-off test" is a test to determine the strength or fracture pressure of the formation, usually conducted immediately after drilling below a new casing shoe.

(70) "Liner" means a casing string that does not extend to the top of the wellbore (i.e., the ground surface), but instead is anchored or suspended from inside the bottom of the previous casing string.

(71) “Lithofacies” means a mappable subdivision of a rock unit with distinctive and characteristic lithologic features.

(72) “Lithology” means the general description and classification of a rock or rock sequence in terms of their color, texture, and composition.

(73) “Lithostatic stress” means component of confining pressure derived from the weight of the column of rock and fluid above a specified level.

(74) “Mechanical integrity” means that all well barrier envelopes, including but not limited to, the tubing, packer, wellhead, and casing, reliably perform their primary functions of containing pressure and are free from leakage.

(75) “Mechanical integrity test” means a test that consists of two parts conducted on a well to ensure that there are no leaks and that the mechanical components of the well function in a way that is protective of public health and the environment. The injection well has two parts: internal and external. The internal part has mechanical integrity if no leakage is noted in the packer, casing, or tubing. The external part has mechanical integrity if no movement of fluid is noted through the vertical channels that are adjacent to the well.

(76) “Microannuli” means small gaps that may form between the casing or liner and the surrounding cement sheath within a well.

(77) “Model domain” means the lateral extent of the model in all directions.

(78) “Model parameter” means a variable in the governing equations of a computational model that may vary throughout the domain, or may vary in space and time. Various system aspects are sometimes lumped together in simulation models and described by effective parameters that are estimated or averaged. Parameters describe properties of the fluids present, porous media, and fluid sources and sinks (e.g., injection well). Examples of model parameters include intrinsic permeability, fluid viscosity, and fluid injection rate.

(79) “Multiphase flow” means the flow of two immiscible phases. For the purposes of the CCS Protocol, the pertinent phases are CO_2 (as a gas, liquid, or supercritical fluid), and brine or oil.

(80) “Net worth” means total assets minus total liabilities and is equivalent to owner’s equity.

(81) “Net working capital” means current assets minus current liabilities.

(82) “Permanent sequestration” or “permanence” means sequestered CO_2 will remain within the storage complex for at least 100 years.

(83) “Permeability” means the measure of a rock’s ability to transmit fluids.

(84) “Petrophysical analysis” means the study of the fundamental chemical and physical properties of reservoir rocks and their contained fluids. The term, “petrophysics,” encompasses multiple types of rock studies, including core analysis, sample descriptions, petrography, scanning electron microscopy, well log analysis, and other forms of detailed laboratory data.

(85) “Plume stabilization” means that CO_2 plume migration and pressure changes are small and predictable, such that the measured rate of plume migration has a high certainty of no CO_2 leakage over a 100-year period.

(86) “Pore pressure” means the pressure of a fluid held within spaces between particles (i.e. pore space) in a rock.

(87) “Pore space” means the voids in a rock or soil that can be filled by a fluid, such as water, air, or CO_2.

(88) “Porosity” means the volume percentage of pore space.

(89) “Post-injection site care” means appropriate monitoring and other actions (including corrective action) needed following the completion of injection to ensure permanence of sequestered CO_2.

(90) “Post-injection site care and monitoring period” means the time between the date of injection completion and 100 years after injection completion.

(91) “Precipitation kinetics” means the rates of mineral precipitation from a solution. Mineralization reactions are very sensitive to kinetic rate parameters.

(92) “Pressure fall-off test” means a field test conducted by ceasing injection for a period (i.e., shutting-in the well) and monitoring pressure decay at the well. The pressure change is analyzed using pressure transient analysis, a technique based on the mathematical relationships between flow rate, pressure, and time. The information from these analyses helps determine injection potential. It can also derive permeability, reservoir boundary shape, and reservoir pressures.

(93) “Project GHG emissions” means the GHG emissions from various activities associated with a CCS project.

(94) “Pump test” means a field experiment in which a well is pumped at a controlled rate and water-level response (drawdown) is measured in one or more surrounding observation wells and optionally in the pumped well itself. Response data from pumping tests are used to estimate the hydraulic properties of aquifers, evaluate well performance, and identify aquifer boundaries.

(95) “Reactive transport model” means a model of the chemical reactions between constituents (e.g., injected CO_2, formation fluids, and the reservoir rock). These models incorporate rate-limited intra-aqueous reactions, mineral dissolution and precipitation, changes in porosity and permeability due to these reactions, and multi-component gas mixtures to model and predict the impact of CO_2 and its co-injectates (e.g., hydrogen sulfide, sulfur dioxide) on aquifer acidification, the concomitant mobilization of metals, and any mineral trapping of CO_2. These models can also be used to assess corrosion of well construction materials.

(96) “Recycled CO_2” means CO_2 that is separated from oil, water, and natural gases, and reinjected back into the reservoir.

(97) “Relative permeability” means the ratio of the effective permeability of a particular fluid at a particular saturation to the absolute permeability of that fluid at total saturation (dimensionless). If a single fluid is present in a rock, its relative permeability is 1.0.

(98) “Rock compressibility” means the relative volume change of matter per unit pressure change under conditions of constant temperature. Rock compressibilities are typically displayed in psi^{-1}.

(99) “Sequestration and storage site” means the surface site and corresponding infrastructure where CO_2 injection occurs, and includes the storage complex at depth, where CO_2 is stored.

(100) “Site closure” means the point or date, after at least 100 years and as determined by the Executive Officer following the requirements under subsection C.5.2, at which point the CCS Project Operator is released from post-injection site care responsibilities.

(101) “Sequestration zone” means the reservoir into which CO_2 is injected for geologic sequestration.

(102) “Skin factor” means a dimensionless pressure drop caused by a flow restriction in the near-wellbore region, typically associated with damage during drilling and well operations.

(103) "Specific storage" means the volume of water released from storage from a unit volume of aquifer per unit decline in hydraulic head (displayed in L^{-1}).

(104) "Step rate test" means test in which a fluid is injected for a defined period in a series of increasing pump rates. The resulting data are used to determine the maximum safe injection rate possible without fracturing the reservoir rock.

(105) "Stratigraphic test well" means a hole drilled for the sole purpose of gaining structural or stratigraphic information to aid in subsurface exploration.

(106) "Storage coefficient" means the volume of water released from storage by a confined aquifer per unit surface area of aquifer per unit decline in hydraulic head normal to the surface and equal to the product of specific storage and the saturated thickness (dimensionless).

(107) "Storage complex" means the three-dimensional subsurface volume that is characterized, modified by corrective actions, and monitored so that the CCS Project is able to meet the requirements for carbon sequestration under the Permanence Requirements (section C).

(A) For saline and depleted oil and gas reservoirs, the storage complex includes the injection zone (in which the CO_2 is emplaced), a sequestration volume, which is expected to contain the CO_2, and overlying and possibly underlying geologic formations that are required to provide assurance of storage. The storage complex must include a multilayered confining system that retards vertical migration of CO_2. The storage complex must extend laterally over (1) the volume from which CO_2 (as a free or dissolved phase) could escape from storage in the subsurface if a permeable pathway exists, and (2) the area over which the plume may migrate.

(B) For CCS projects utilizing CO_2 injection for EOR purposes, the storage complex is the three-dimensional extent of the reservoir used for oil production and CO_2 storage. The storage complex for a CO_2-EOR CCS project is delineated by the geologic extent of the reservoir as defined by impervious rock, structural closure, decrease or loss of porosity and permeability, or natural hydrodynamic forces in a three dimensional volume.

(108) "Stratigraphy" means the classification of sedimentary rocks based on their lithologic properties and geometric relations, such as spatial distribution, depositional environment, composition, and age.

(109) "Supercritical CO_2" means the physical state where CO_2 exhibits properties of both a gas and a liquid when its temperature and pressure exceeds the critical temperature (87.98 °F) and pressure (1,071 psi).

(110) "System boundary" means a delineation of activities/processes that are considered part of the project when analyzing emissions from CCS projects.

(111) "Tangible net worth" means the tangible assets that remain after deducting liabilities; such assets would not include intangibles such as goodwill and rights to patents or royalties.

(112) "Total dissolved solids (TDS)" means milligrams per liter of total dissolved solids content. Solids content includes inorganic salts (principally calcium, magnesium, potassium, sodium, bicarbonates, chlorides, and sulfates) and some small amounts of organic matter that are dissolved in water.

(113) "Transmissibility" means a measure of the conductivity of the formation corrected for the viscosity of the flowing fluid. It is a coefficient associated with Darcy's law, which characterizes flow through porous media. It is equal to the coefficient of permeability (hydraulic conductivity) multiplied by the thickness of the formation.

(114) "Transmissive fault or fracture" means a fault or fracture that has sufficient permeability and vertical extent to allow fluids to move laterally or vertically along the fault or fracture, or within an associated damaged zone.

(115) "True stratigraphic thickness" means the thickness of rock layer after correcting for the dip (inclination) of the layer and the deviation of the well that penetrates it. Values of true stratigraphic thickness in an area can be plotted to create an isopach map.

(116) "True vertical depth" means the vertical distance from a point in the well (usually the current or final depth) to a point at the surface. If the well is deviated, the measurement may be different from the "measured depth."

(117) "True vertical thickness" means the thickness of a layer of rock measured vertically from a reference point at the surface. Values of true vertical thickness in an area can be plotted to create an isopach map.

(118) "Tubing" or "production tubing" means any tubing used to inject or produce fluids, respectively.

(119) "Unconfined compressive stress" is a measure of a material's strength. The unconfined compressive strength (UCS) is the maximum axial compressive stress that a right-cylindrical sample of material can withstand under unconfined conditions. It is also known as the "uniaxial compressive strength" of a material because the application of compressive stress is only along one axis-the longitudinal axis-of the sample.

(120) "Vadose zone" means the unsaturated zone of the subsurface above the groundwater table. The soil and rock within this zone typically contains air and water within its pore space.

(121) "Validation" means, for purposes of this protocol, an initial review by a third party that is approved by the Executive Officer of modeling, plans, and data submitted as part of the application for permanence, against the requirements in this protocol. Any validation services conducted under the protocol are separate from verification services.

(122) "Vented emissions" means intentional or designed releases of CH_4 or CO_2 including process designed flow to the atmosphere through seals or vent pipes, equipment blowdown for maintenance, and direct venting of gas used to power equipment (such as pneumatic devices).

(123) "Verification" means a systematic, independent, and documented process for the evaluation of reported data against the requirements specified in this protocol. Verification occurs after a CCS Project Operator submits quarterly or annual reports of GHG emissions reductions.

(124) "Vertical stress" means the force per unit area imposed on a layer of rock. Vertical stress is the combined stress due to the total weight of rock and interstitial fluids above a specified depth.

(125) "Viscosity" means the measure of a liquid's resistance to flow.

(126) "Well" or "wellbore" means a hole that is drilled into the Earth's subsurface. A wellbore can be encased by materials such as steel and cement, or it may be uncased.

(127) "Wireline" means a wire or cable that is used to deploy tools and instruments downhole and transmits data to the surface.

(128) "Workover" means the process of performing major maintenance or remedial treatments on an injection or production well. In many cases, workover implies the removal and replacement of the production tubing string after the well has been killed and a workover rig has been placed on location.

(b) Acronyms:

"API" means American Petroleum Institute.
"APCD" means Air Pollution Control District.
"AQMD" means Air Quality Management District.
"ASTM" means ASTM International, formerly known as the American Society for Testing and Materials.
"CARB" means California Air Resources Board.

"CA-GREET" means the Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model, as referred to in the LCFS regulation.
"CERCLA" means Comprehensive Environmental Response, Compensation, and Liability Act.
"CAA" means Clean Air Act.
"CWA" means Clean Water Act
"CCS" means Carbon Capture and Sequestration.
"CH_4" means methane.
"CIL" means casing inspection log.
"CO" means carbon monoxide.
"CO_2" means carbon dioxide.
"CO_2e" means CO_2 equivalent.
"$CO_{2(aq)}$" means carbon dioxide dissolved in an aqueous solution.
"$CO_{2(g)}$" means carbon dioxide as a free gas phase.
"CO_2-EOR" means CO_2-enhanced oil recovery.
"GCS" means geologic carbon sequestration.
"DOGGR" means the California Division of Oil, Gas, and Geothermal Resources.
"GHG" means greenhouse gas.
"GPS" means global positioning system.
"LCFS" means the Low Carbon Fuel Standard (title 17, California Code of Regulations, section 95480 et seq.)
"MRR" means the Regulation for the Mandatory Reporting of Greenhouse Gas Emissions (title 17, California Code of Regulations, sections 95100 et seq.)
"MT" means metric ton.
"N_2O" means nitrous oxide.
"NESHAPS" means the National Emission Standards for Hazardous Pollutants preconstruction approval under the Clean Air Act.
"NPDES" means the National Pollution Discharge Elimination System under the Clean Water Act.
"PSD" means the Prevention of Significant Deterioration program under the Clean Air Act.
"PSI" means pounds per square inch.
"RCRA" means the Resource Conservation and Recovery Act.
"SDWA" means Safe Drinking Water Act.
"SIC" means Standard Industrial Classification codes for classifying industries by a four-digit code.
"SSR" means sources, sinks, and reservoirs.
"TDS" means total dissolved solids.
"TOC" means total organic carbon.
"US EPA UIC" or "UIC" means the United States Environmental Protection Agency Underground Injection Control program.[2]
"VOC" means volatile organic compound.

[2] EPA Underground Injection Control Program, 40 C.F.R. §144, §145, and §146 (2014).

B. ACCOUNTING REQUIREMENTS FOR CCS PROJECTS UNDER THE LCFS

1. System Boundary

The Accounting Requirements for CCS delineate a system boundary that covers all CO_2 sources, sinks, and reservoirs (SSRs) from a CCS project. All SSRs within the system boundary must be accounted for when quantifying emissions reductions from CO_2 sequestration.

The specific types of equipment and sources covered by the system boundary can vary by CCS project types. Figure 1 shows the system boundary for capturing CO_2 and sequestering it in oil and gas reservoirs used for CO_2-EOR indicating which SSRs are included. Figure 2 shows the system boundary for capturing CO_2 and sequestering it in depleted oil and gas reservoirs and saline formations.

In either case, the system boundary begins with carbon capture and ends with injection operations including CO_2 leakage. Any emissions downstream of the sequestration site (except entrained CO_2 in the case of CO_2-EOR) are excluded since they are associated with the downstream products rather than the CCS project.

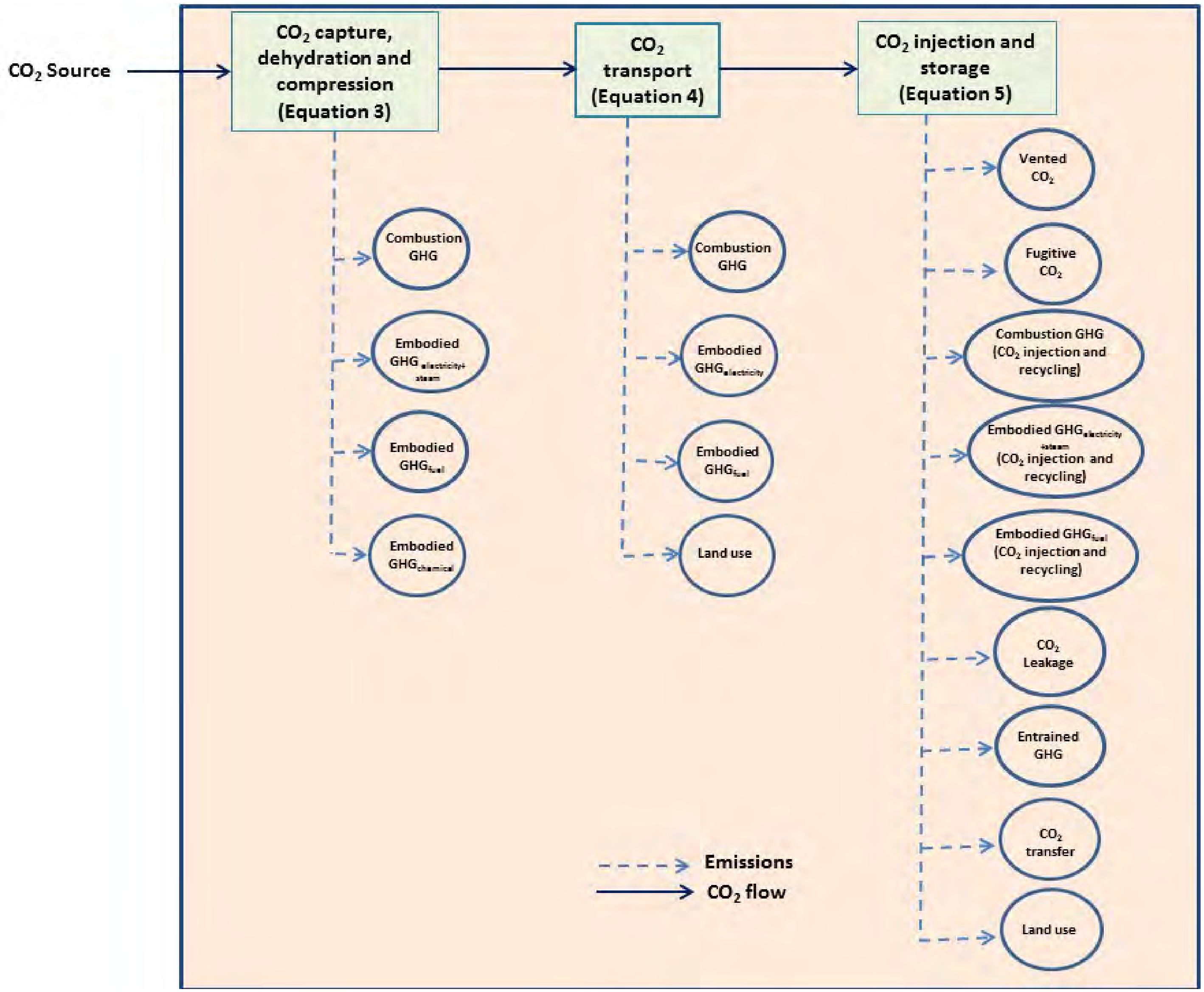


Figure 1. System boundary for CO_2 capture and sequestration in oil and gas reservoirs used for CO_2-EOR.

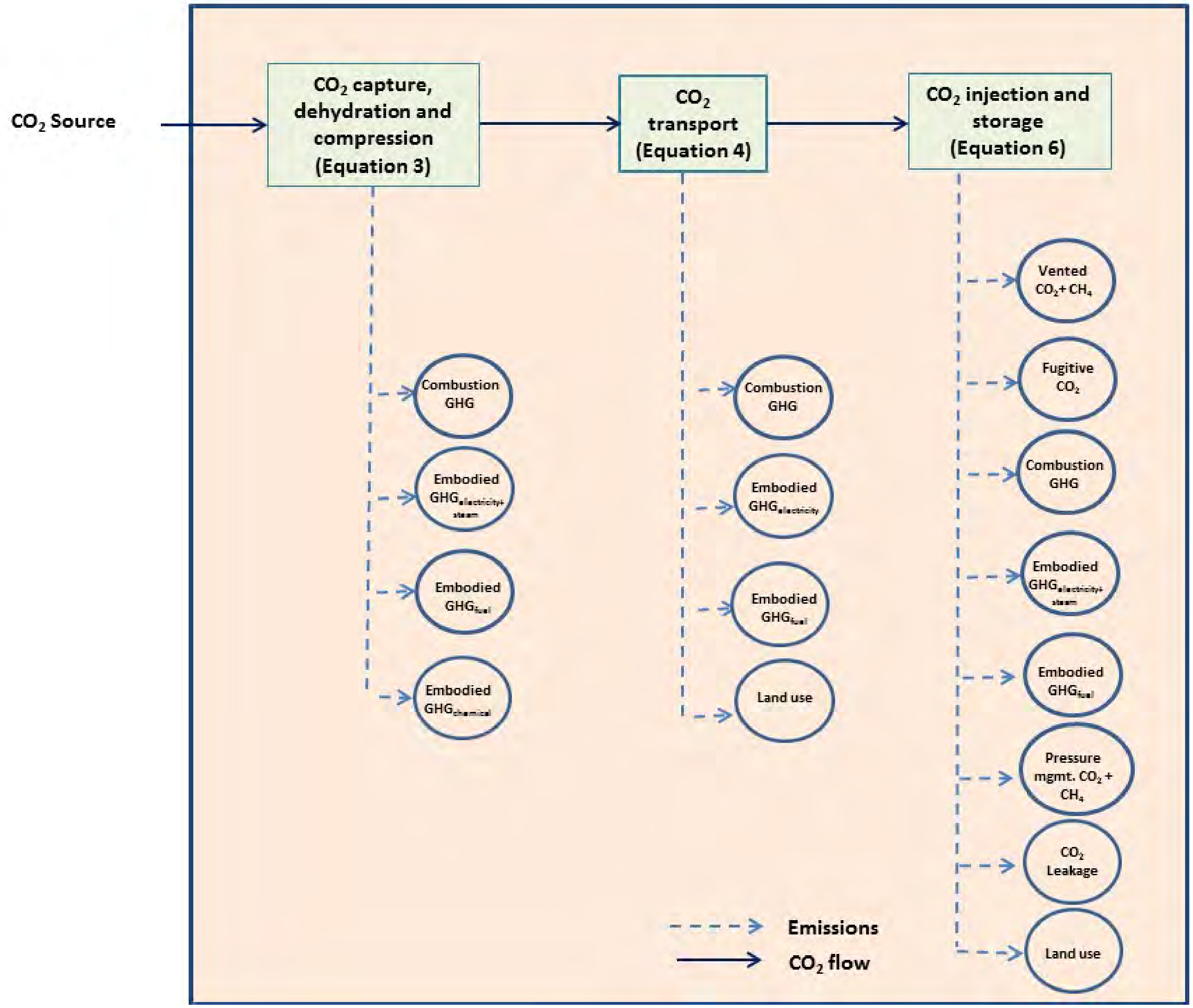


Figure 2. System boundary for CO_2 capture and sequestration in depleted oil and gas reservoirs and saline formations.

2. Quantification of Geologic Sequestration CO_2 Emission Reductions

This section describes the methodology for estimating GHG emissions reductions by sequestering CO_2 in oil and gas or saline reservoirs.

2.1. Covered Greenhouse Gas Emissions for the LCFS

In addition to CO_2, CH_4, and N_2O, CA-GREET, the model used in LCFS accounting, treats volatile organic compounds (VOC) and carbon monoxide (CO) as GHGs because they are eventually oxidized to CO_2. In the context of CCS projects, emissions covered in this document under the LCFS are CO_2, N_2O, CH_4, CO and VOC. The global warming potential values listed in the CA-GREET model are used to determine the CO_2 equivalent of emissions. If N_2O, CH_4, CO and VOC present in the CO_2 stream are sequestered during CO_2 injection, they are not included in the quantification and will not be credited under LCFS.

2.2. Greenhouse Emissions Reductions Calculation

(a) Net annual GHG emissions reductions from CCS projects must be quantified using Equation 1.

$$GHG_{reduction} = CO_{2_{injected}} - GHG_{project} \tag{1}$$

Where:

$GHG_{reduction}$ = Net GHG reductions (MT CO_2e/year).

$CO_{2_{injected}}$ = Amount of injected CO_2 (MT CO_2/year). Excludes recycled CO_2 in the case of CO_2-EOR (equal to purchased CO_2 per year measured before the point of injection and after transportation[3]).

$GHG_{project}$ = CCS project GHG emissions (MT CO_2e/year).

If the injected CO_2 consists of CO_2 derived from various sources/facilities, a mass-balance approach must be used to assign the injected amount to the various sources of carbon capture based on metered data and contractual agreements between the CO_2 supplier and CCS project operator. CO_2 from natural underground CO_2 reservoirs must be omitted from $CO_{2injected}$ in Equation 1.

(b) Annual CCS project GHG emissions must be calculated using Equation 2. Each variable in Equation 2 must include both direct emissions as well as upstream (indirect) emissions associated with the corresponding specific activity, and must be determined pursuant to subsections B.2.2(c) through B.2.2(e) below.

[3] See subsection C.4.1(a)(14)(F)3 for requirements related to the measurement and quantification of flow meter data.

$$GHG_{project} = GHG_{capture} + GHG_{transport} + GHG_{injection} + GHG_{dLUC} \quad (2)$$

Where:

$GHG_{project}$ = CCS project GHG emissions (MT CO_2e/year).

$GHG_{capture}$ = GHG emissions associated with carbon capture, dehydration, and compression (MT CO_2e/year).

$GHG_{transport}$ = GHG from CO_2 transport (MT CO_2e/year). Transport can be by pipeline, ships, rail, or trucks.

$GHG_{injection}$ = GHG emissions from injection operations (MT CO_2e/year).

GHG_{dLUC} = GHG emissions from direct land use change (MT CO_2e/year).

(c) Annual GHG emissions from carbon capture, dehydration, and compression must be calculated according to Equation 3. GHG emissions from fuel combustion and electricity use must be determined using emission factors available in CA-GREET. If an emission factor for a particular fuel is not available in CA-GREET, applicants must refer to Tables E1-E3 in Appendix E.[4]

$$GHG_{capture} = GHG_{combustion} + EmbodiedGHG_{electricity+steam} + EmbodiedGHG_{fuel} + EmbodiedGHG_{chemical} \quad (3)$$

Where:

$GHG_{capture}$ = GHG emissions from capture, dehydration, and compression (MT CO_2e /year).

$GHG_{combustion}$= GHG emissions from fuel combustion in stationary equipment including emissions from parasitic load (MT CO_2e/year).

$EmbodiedGHG_{electricity+steam}$
= Embodied (upstream) GHG emissions from purchased electricity and steam use (MT/CO_2e year).

$EmbodiedGHG_{fuel}$
= Embodied (upstream) GHG emissions of fuel used in stationary equipment including embodied emissions associated with parasitic load (MT/CO_2e year).

$EmbodiedGHG_{chemical}$
= Embodied (upstream) GHG emissions from chemicals used in carbon capture, including replacements from loss/deterioration (MT CO_2e/year). Depending on the technology used, carbon capture may involve the use of chemicals such as monoethanolamine (MEA), NaOH, and activated carbon.

---

[4] Combustion emission factors provided in the CA-GREET and Table A1 may differ from the emission factors mentioned in the Regulation for the Mandatory Reporting of Greenhouse Gas Emissions (CARB).

GHG emissions from fuel combustion ($GHG_{combustion}$) must be calculated using the amounts of fuels used, and their corresponding emission factors provided in the CA-GREET model. If specific emission factors are not available in CA-GREET, refer to emission factors provided in Tables E1-E3.

Embodied GHG emissions of electricity must be calculated using electricity emission factors in the CA-GREET model. Embodied GHG emissions of steam can be calculated based on the enthalpy of steam as well as the fuel source and efficiency of the boiler.

Embodied GHG emissions of chemicals ($EmbodiedGHG_{chemical}$) must be calculated using the CA-GREET model or an equivalent method if the chemical in question is not modelled in CA-GREET.

Embodied (upstream) GHG emissions of fuel ($EmbodiedGHG_{fuel}$) must be calculated using the CA-GREET model or an equivalent method if the fuel in question is not modelled in CA-GREET.

(d) Annual GHG emissions from CO_2 transport must be calculated using Equation 4.

$$GHG_{transport} = GHG_{combustion} + EmbodiedGHG_{electricity} + EmbodiedGHG_{fuel} \quad (4)$$

Where:

$GHG_{transport}$ = GHG emissions from CO_2 transport (MT CO_2e/year).

$GHG_{combustion}$ = GHG emissions from fuel combustion at stationary equipment (MT CO_2e/year) used in CO_2 transport.

$EmbodiedGHG_{electricity}$ = Embodied (upstream) GHG emissions from electricity use (MT CO_2e/year) in CO_2 transport.

$EmbodiedGHG_{fuel}$ = Embodied (upstream) GHG emissions of fuels used in CO_2 transport (MT CO_2e/year).

If a pipeline carries CO_2 to multiple geological sites or serves multiple uses, CO_2 transport emissions must be prorated using the mass-based allocation method and assigned to the CCS project under consideration.

If the injected CO_2 comes via two or more different transport modes, $GHG_{transport}$ in Equation 4 must be calculated and summed together for each transport mode.

(e) Annual GHG emissions from CO_2 injection operations must be calculated using Equation 5 for CO_2-EOR and Equation 6 for depleted oil and gas reservoirs and saline formations.

Entrained CO_2 emissions in Equation 5 are calculated using the formula provided in Equation F.1 in Appendix F.

GHG Emissions from fuel combustion, electricity use and embodied (upstream) emissions of fuels must be restricted to CO_2 injection and recycling operations only. GHG emissions associated with fuel combustion, electricity use and embodied (upstream) emissions of fuels used for other activities at the CO_2-EOR site are excluded from the credit calculation because they are assigned to the crude oil production pathway.

$$GHG_{injection} = GHG_{combustion} + EmbodiedGHG_{electricity+steam} + EmbodiedGHG_{fuel} + CO_{2_{vent}} + CO_{2_{fugitive}} + CO_{2_{entrained}} + CO_{2_{leakage}} + CO_{2_{transfer}} \quad (5)$$

Where:

$GHG_{injection}$ = GHG emissions in CO_2e associated with injection operations in CO_2-EOR (MT CO_2e/year).

$GHG_{combustion}$ = GHG emissions from fuel combustion at stationary equipment used in CO_2 injection and recycling (MT CO_2e/year).

$EmbodiedGHG_{electricity+steam}$ = Embodied (upstream) GHG emissions from electricity and steam use in CO_2 injection and recycling (MT CO_2e/year).

$EmbodiedGHG_{fuel}$ = Embodied (upstream) GHG emissions of fuels used (excluding electricity) in CO_2 injection and recycling (MT CO_2e/year).

$CO_{2_{vent}}$ = CO_2 emissions from venting (MT CO_2/year) including biogenic CO_2 and CO_2 from direct air capture.

$CO_{2_{fugitive}}$ = Fugitive CO_2 emissions from surface equipment (MT CO_2/year) including biogenic CO_2 and CO_2 from direct air capture.

$CO_{2_{entrained}}$ = Entrained CO_2 in produced water, natural gas, and crude oil downstream of separator units (MT CO_2/year). Excludes entrained CO_2 if it is reinjected into reservoirs.

$CO_{2_{leakage}}$ = Atmospheric CO_2 leakage from the storage complex (MT CO_2/year). Includes subsurface and atmospheric leakage.

$CO_{2_{transfer}}$ = Intentional transfer of stored CO_2 outside of the CCS project boundary (MT CO_2/year).

And:

$$GHG_{injection} = GHG_{combustion} + EmbodiedGHG_{electricity+steam} + EmbodiedGHG_{fuel} + GHG_{vent} + CO_{2_{fugitive}} + CO_{2_{leakage}} \quad (6)$$

Where:

$GHG_{injection}$ = GHG emissions associated with CO_2 injection operations (MT CO_2e/year).

$GHG_{combustion}$ = GHG emissions from stationary combustion equipment (MT CO_2e/year).

$EmbodiedGHG_{electricity+steam}$ = Embodied (upstream) GHG emissions from electricity and steam use (MT CO_2e/year).

$EmbodiedGHG_{fuel}$ = Embodied (upstream) GHG emissions of fuels excluding electricity (MT CO_2e/year).

GHG_{vent} = CO_2 and CH_4 vented from equipment located between the injection flow meter and the injection wellhead (MT CO_2e/year).

$GHG_{pressure}$ = CO_2 and CH_4 emissions from pressure management activities including brine production (MT CO_2e/year).

$CO_{2_{fugitive}}$ = Fugitive CO_2 emissions from surface equipment per year (MT CO_2/year).

$CO_{2_{leakage}}$ = Atmospheric CO_2 leakage from the storage complex (MT CO_2e/year). Includes subsurface and atmospheric leakage.

There are planned and unplanned venting events in CO_2 injection operations. For CO_2-EOR, these must include any CO_2 taken out of the ground but not reinjected into wells towards the end of EOR project completion, and any CO_2 blowdown.

Vented CO_2 emissions from CO_2-EOR must be determined for each applicable venting source using the methods described in Appendix B. In the case of CO_2 injection operations in depleted oil and gas or saline reservoirs**,** vented CO_2 emissions from surface facilities must be calculated using the event-based approach described in Appendix A(b) and Equation A.2. This must include CO_2/CH_4 releases from pressure management including brine production.

In the case of CO_2-EOR operations, fugitive CO_2 emissions must be calculated using either leak detection and leaker emission factors, or using population count and emission factors as described in Appendix B. Fugitive CO_2 emissions occur from fittings, flanges, valves, connectors, meters, and headers associated with CO_2-EOR operations. In the case of CO_2 injection operations in depleted oil and gas reservoirs/saline formations, fugitive CO_2 and CH_4 emissions from equipment must be calculated using the equipment count method described in Appendix A(a) and Equation A.1.

In the case of CO_2-EOR operations, CO_2 can remain in water, natural gas and crude oil after they are separated from produced CO_2 in separators for either sales or disposal/injection of water. CO_2 from these product streams will eventually be released and must be calculated using Equation F.1 in Appendix F.

To be conservative, $CO_{2leakage}$ must be considered to be equal to half the detection limit of the method used to detect leaks deployed in the CCS project's monitoring and testing plan, or the volume of leakage detected, whichever is larger. The CCS Project Operator must provide a description and justification for the method used to calculate the detection limit.

In cases where atmospheric or subsurface leakage has occurred, $CO_{2leakage}$ must be calculated using a method identified in the CCS project's Testing and Monitoring Plan.

In the event the stored CO_2 is intentionally released via decompression and transferred to other EOR locations it must be counted as emissions and included in $CO_{2transfer}$. The new location can apply under this Protocol.

(f) Installation of new pipelines and construction of new CO_2 injection sites can cause changes in above and belowground carbon stock depending on the type of land use where these facilities are going to be located. In such a case, direct land use change GHG emissions must be calculated using land use change emission factors utilized in the Global Trade Assessment Project model or using similar CARB-approved land use change emission factors. Direct land use change emissions must be amortized over a period of 30 years. If CCS projects utilize existing pipeline and CO_2 injection infrastructure where land use change have already occurred, direct land use change emissions are considered part of the baseline and are not considered. Indirect land use change GHG emissions are omitted from the Accounting Requirements since they are considered negligible.

(g) For the purpose of estimating CCS credits, data measurement/generation and reporting requirements for energy and chemical inputs are described in Appendix D.

3. Invalidation and Buffer Account

(a) LCFS credits issued for verified GHG emission reductions associated with CCS projects will be invalidated if the sequestered CO_2 associated with them migrates outside the storage complex or is released to the atmosphere.

(b) The amount of verified GHG emission reduction to be invalidated for CCS projects is equal to the CO_2 leakage from the storage complex ($CO_{2leakage}$), which must be determined in accordance with subsection C.4.3.2 of the CCS Protocol.

(c) The following will apply to all CCS projects seeking credit issuance under the LCFS.

(1) All CCS projects must contribute a percentage of LCFS credits to the Buffer Account at the time of LCFS credit issuance by CARB;

(2) Sequestered CO_2 must remain within the storage complex for at least 100 years in order to be considered permanently sequestered and subsequently credited; and

(3) Buffer Account contributions: The CCS project's contribution to the Buffer Account is determined by a project-specific risk rating method, outlined in Appendix G.

C. PERMANENCE REQUIREMENTS FOR GEOLOGIC SEQUESTRATION

1. Permanence Certification of Geologic Carbon Sequestration Projects

1.1. Application and Certification

(a) A CCS Project Operator must apply for Sequestration Site Certification pursuant to subsection C.1.1.2(b) and CCS Project Certification following subsection C.1.1.2(d), which are collectively called Permanence Certification. The application must include the third-party review, data, and plans specified in subsections C.1.1.1 and C.1.1.2. A flow diagram depicting the application process for a typical CCS project is shown in Figure 3, below.

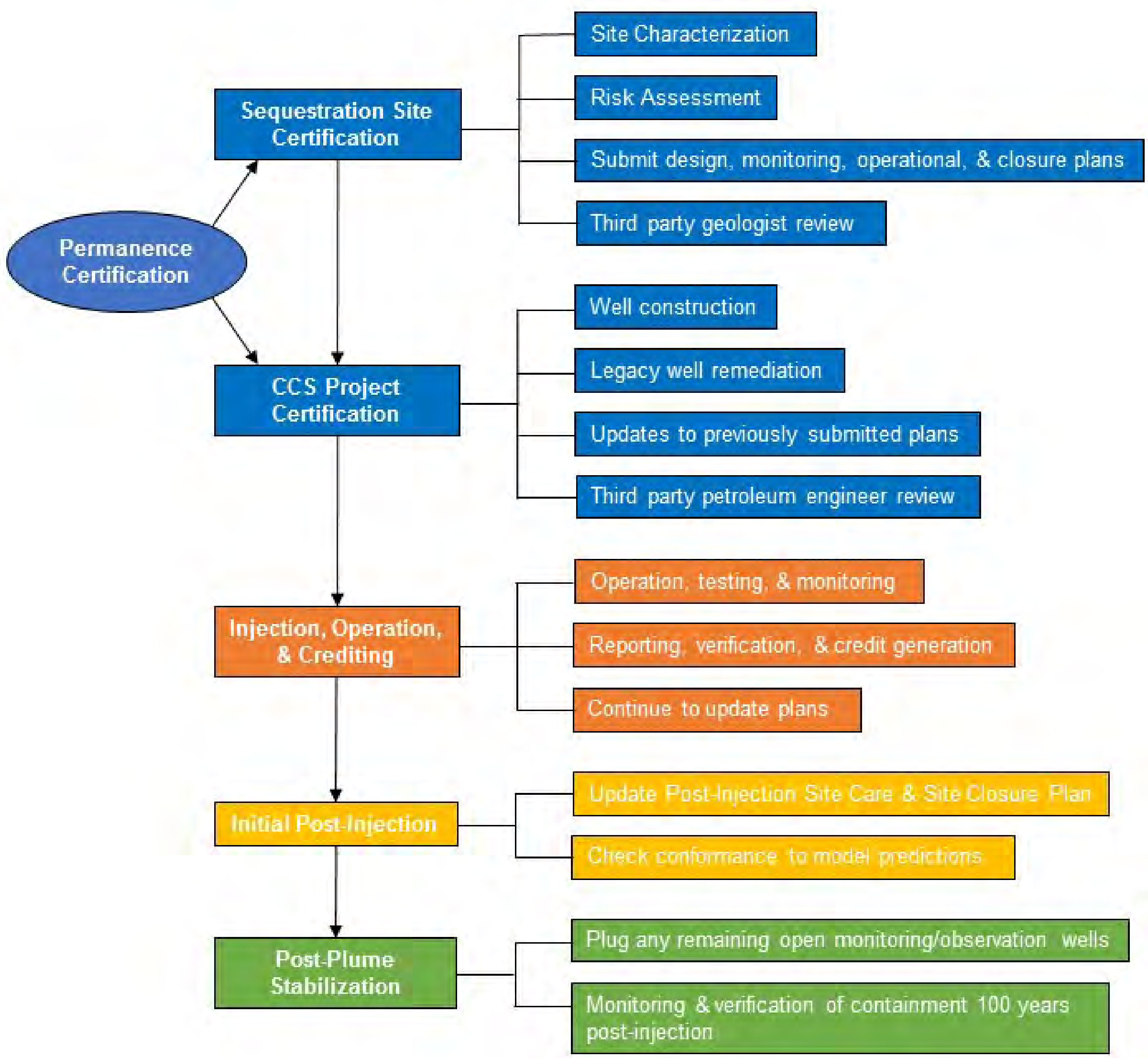


Figure 3. CCS Protocol certification, operation, and closure process.

(b) If after reviewing the submitted material, the Executive Officer determines that the CCS project meets the specifications for sequestering carbon pursuant to the Permanence Requirements, the Executive Officer will post an initial determination along with the application package for public comment for 15 days, address those comments if considered valid, and then issue a Permanence Certification for the project by executive order.

1.1.1. Third Party Review

(a) Prior to submittal of an application to the Executive Officer for Permanence Certification, the CCS Project Operator must have their application reviewed by a third party or parties that are approved by the Executive Officer. For purposes of evaluating potential for conflict of interest, third parties must disclose to the Executive Officer all services provided to the applicant during the prior 5 years and any services provided within one year following certification. Individuals and firms are prohibited from providing third party review of a Permanence Certification application if they have provided or intend to provide other professional services associated with the CCS project. The applicant is responsible for all costs of the application review.

(b) The third-party reviewer must certify that the data submitted as part of the application in subsection C.1.1.2(b) are true, accurate, and complete.

(c) The third-party reviewer must certify that the plans submitted as part of the application in subsection C.1.1.2(d) are sufficiently robust that, in their professional judgment, the CCS project is able to meet the permanence requirements for carbon sequestration.

(d) The third-party reviewer must certify that the Site-Based Risk Assessment submitted as part of the application in subsection C.1.1.2 is accurate and complete, and that the risks identified are either sufficiently monitored or sufficiently remediated in the Emergency and Remedial Response Plan submitted in the application.

(e) Third-party evaluation completed under the provisions of subsection C.1.1.1(b) must be completed by a professional geologist licensed under Chapter 12.5 of Division 3 of the California Business and Professions Code §§ 7800 – 7887, or equivalent professional geologist from another jurisdiction that is approved by the Executive Officer.

(f) Third-party evaluation completed under the provisions of subsection C.1.1.1(c) must be completed by a professional engineer licensed under Chapter 7 of Division 3 of the California Business and Professions Code §§ 6700 – 6799, or equivalent professional engineer from another jurisdiction that is approved by the Executive Officer.

1.1.2. Certification Application Materials

All applications for Permanence Certification, pursuant to the Permanence Requirements, must include the following information:

(a) General Information Requirements:

(1) Statement of the primary purpose of the project;

(2) A brief description of the nature of the business;

(3) The name, mailing address, and latitude and longitude of the CCS project or well for which the Permanence Certification is submitted;

(4) The operator's name, address, telephone number, ownership status, and status as a federal, state, private, public, or other entity;

(5) The activities conducted by the operator which would require it to obtain permits under RCRA, the U.S. EPA UIC program, the NPDES program under CWA, or the PSD program under CAA; and

(6) The activities conducted by the operator that would require it to obtain any drilling permits, valid access agreements, or any encroachment permits under county or city guidelines, or any federal, state, or local air, water, or restricted land use operating permits.

(7) A listing of all permits or construction approvals received or applied for and their status under any of the following programs:

(A) Hazardous Waste Management program under RCRA;

(B) U.S. EPA UIC program under SDWA;

(C) NPDES program under CWA;

(D) PSD program under CAA;

(E) Nonattainment program under CAA;

(F) NESHAPS preconstruction approval under CAA;

(G) Dredge and fill permits under section 404 of Clean Water Act; and

(H) Other relevant environmental permits such as federal, state, county, or city permits.

(b) Application for Sequestration Site Certification:

(1) Site-Based Risk Assessment pursuant to subsection C.2.2, including a Risk Management Plan following subsection C.2.2(c);

(2) The following plans:

(A) A Geologic Evaluation report pursuant to subsection C.2.3, including a Formation Testing and Well Logging Plan following subsections C.2.3.1 and C.2.3.1(a);

(B) A Storage Complex Delineation and Corrective Action Plan pursuant to subsection C.2.4, including a description of the computational model used following subsection C.2.4.1 and the report on the results of the plume extent modeling following subsection C.2.4.2;

(C) Baseline Testing and Monitoring Plan pursuant to subsection C.2.5(a);

(D) Well Construction Plan pursuant to subsection C.3.1(b), Pre-Injection Testing Plan (subsection C.3.2(b)), and a plan describing the proposed operating requirements and restrictions (subsection C.3.3(a));

(E) A Testing and Monitoring Plan pursuant to subsection C.4.1, including plans for mechanical integrity testing (subsection C.4.2), emissions monitoring (subsection C.4.3.1), and monitoring, measurement, and verification of containment (subsection C.4.3.2);

(F) A Well Plugging and Abandonment Plan pursuant to subsection C.5.1;

(G) A Post-Injection Site Care and Site Closure Plan pursuant to subsection C.5.2; and

(H) An Emergency and Remedial Response Plan pursuant to subsection C.6;

(3) The following demonstrations:

(A) A Financial responsibility demonstration pursuant to subsection C.7;

(B) A Legal understanding demonstration pursuant to subsection C.9; and

(C) Any other plans or information required by the Executive Officer in order to evaluate the application for Sequestration Site Certification.

(c) Sequestration Site Certification will be implemented by an executive order from CARB.

(d) Application for CCS Project Certification:

(1) Any updates to information or plans from subsection C.1.1.2(b);

(2) Formation testing and well logging report pursuant to subsection C.2.3.1(k);

(3) Updated storage complex delineation and computational modeling results pursuant to subsection C.2.4.2;

(4) Corrective action report pursuant to subsection C.2.4.3(c);

(5) Baseline testing and monitoring report pursuant to subsection C.2.5(d);

(6) Well construction and pre-injection testing report pursuant to subsections C.3.1(b) and C.3.2(c); and

(7) Any other information required by the Executive Officer that is necessary to evaluate the application for CCS Project Certification.

(e) CCS Project Certification will be implemented by an executive order from CARB.

1.1.3. Reporting

1.1.3.1. Electronic Reporting

(a) The CCS Project Operator must submit to the Executive Officer any reports, submittals, notifications, and records made and maintained by the operator under this Permanence Certification in an electronic format. The accuracy of all electronic submissions must be attested to at the time of submission.

(b) The CCS Project Operator is solely responsible for ensuring that the Executive Officer receives its reports, submittals, notifications, and records as required in this section. For the Executive Officer to be able to deem an electronically submitted report to be valid, the report must be accompanied by a digital signature that meets the requirements of California Code of Regulations, title 2, sections 22000 *et seq*.

1.1.3.2. Quarterly or Annual Reporting

(a) For crediting purposes, CCS Project Operators are required to submit quarterly or annual (depending on how often the project elects to undergo verification) reports of GHG emissions reductions and ongoing monitoring results. Reports must include the quantification and documentation of CO_2 sequestered pursuant to the Accounting Requirements in section B. Data quality management must be sufficient to support quantification and verification of CO_2 sequestered. Reports must comply with the formatting and timing required in the LCFS regulation.

Verification may only be conducted after the CCS Project Operator submits the report and attests that the reported information is true, accurate, and complete.

(b) CCS Project Operators must submit quarterly or annual reports that include:

(1) All metered measurements of inputs to GHG emissions reductions as calculated in subsection B.2.2;

(2) Analysis of the CO_2 stream following subsection C.*4.3.1.1*(b); and

(3) Injection rate and volume pursuant to subsection C.*4.3.1.2*(e).

1.1.3.3. Annual Reporting

(a) For crediting purposes, CCS Project Operators are required to submit annual reports of GHG emissions reductions, project operations, and ongoing monitoring results. Reports must include measurements of relevant parameters sufficient to ensure that the quantification and documentation of CO_2 sequestered is replicable and verifiable pursuant to the Accounting Requirements in section B and the Permanence Requirements in section C. Data quality management must be sufficient to support quantification and verification of CO_2 sequestered. If there are no changes to the plans, pursuant to subsection C.1.1.3, and if acceptable to the Executive Officer, the CCS Project Operator may submit a report demonstrating how they are following the plans.

(1) CCS Project Operators must submit annual reports that include:

(A) Metered measurements of all annual GHG emissions reductions as calculated in subsection B.2.2;

(B) The results of operational parameters and emissions and containment monitoring pursuant to subsections C.3.4, C.4.3.1, and C.4.3.2;

(C) A summary of any incidents or changes in operational parameters that triggered a storage complex reevaluation following subsections C.2.4.4, C.*2.4.4.1*, and C.3.4;

(D) A summary of any incidents that required implementation of emergency and remedial response pursuant to subsection C.6;

(E) Mechanical integrity testing results of project wells pursuant to subsection C.4.2.1, as well as reports documenting any incidents where the loss of mechanical integrity occurred and a demonstration of the actions taken by the CCS Project Operator to mitigate or repair the well;

(F) Results of pressure fall-off testing of injection wells at least once every five years pursuant to subsection C.*4.3.1.5(*a). Pressure fall-off testing results must be submitted to the Executive Officer in writing within 30 days following the test, and the results of these tests must be amended to the annual report pursuant to subsection C.*4.3.1.5*(e);

(G) A report of any corrective action taken by the CCS Project Operator and a justification for why and how the corrective action was implemented, pursuant to subsection C.2.4.3;

(H) The results of each storage complex reevaluation and a report of the actions taken by the CCS Project Operator as a result of the reevaluation, to be performed no less than once every five years, pursuant to subsection C.2.4.4; and

(I) Any other information required by the Executive Officer.

(b) Reports must comply with the formatting and timing required in the LCFS regulation, and must include an attestation that the information submitted is true, accurate, and complete.

1.1.3.4. Advanced Notice Reporting

(a) Well tests: The CCS Project Operator must give at least 30 days advance written notice to the Executive Officer of any planned mechanical integrity test or workover.

(b) Planned Changes: The CCS Project Operator must give written notice to the Executive Officer, as soon as possible, of any planned physical alterations or additions to the injection project other than minor repair/replacement or maintenance activities. An analysis of any changes to the composition of the injection fluid must be submitted to the Executive Officer for review and written approval at least 30 days prior to injection; this approval may result in a CCS project certification modification.

1.1.3.5. Noncompliance and Event Reporting

(a) In the event of an emergency that falls into the “major” or “serious” emergency category pursuant to subsection C.6.1(b) and requires implementation of response actions pursuant to the Emergency and Remedial Response Plan, subsection C.6, the CCS Project Operator must report to the Executive Officer and any relevant local or state agency (including DOGGR and the California Governor’s Office of Emergency Management, if the CCS project is in California), or equivalent. Any information must be provided orally and in an electronic format within 24 hours from the time the CCS Project Operator becomes aware of the circumstances. Such reports must include, but not be limited to the following information:

(1) Any evidence of whether the injected CO_2 stream or associated elevated pressure may endanger public health, or any monitoring or other information which indicates that any contaminant may endanger public health;

(2) Any evidence of noncompliance with a Permanence Certification condition, or malfunction of the injection system, which may cause an uncontrolled release of fluid or gas out of the storage complex;

(3) Any triggering of the shut-off system required in subsection C.3.3(g) (e.g., downhole or at the surface) or incident specified in subsection C.3.4;

(4) Any failure to maintain mechanical integrity;

(5) Pursuant to compliance with the testing and monitoring requirements in subsection C.4.3.2, any uncontrolled release of CO_2 outside of the storage complex that may result in atmospheric leakage; and

(6) Actions taken to implement appropriate protocols outlined in the Emergency Remedial Response Plan (subsection C.6).

(b) A written submission must be provided to the Executive Officer within five business days of the time the CCS Project Operator becomes aware of the circumstances described in subsection C.*1.1.3.5*(a). The submission must contain a description of any noncompliance and its cause, the period of noncompliance, including exact dates and times, and, if the noncompliance has not been corrected, the anticipated time it is expected to continue as well as actions taken to implement appropriate protocols outlined in the Emergency and Remedial Response Plan, and steps taken or planned to reduce, eliminate, and prevent recurrence of the noncompliance.

1.1.3.6. Additional Reporting

(a) Noncompliance: The CCS Project Operator must report all instances of noncompliance not otherwise reported in subsection C.*1.1.3.5* with the next quarterly monitoring report. The reports must contain the information listed in subsection C.*1.1.3.5*(b).

(b) Well plugging and abandonment: CCS Project Operators must submit, in writing, a Notice of Intent to Plug 30 days before plugging any well that is part of the CCS project pursuant to subsection C.5.1(h). If amendments to the Well Plugging and Abandonment Plan are necessary, a revised plan must be submitted with the notice of intent, following subsection C.5.1(i). Within 60 days of plugging, the

CCS Project Operator must submit a plugging report pursuant to subsection C.5.1(k).

(c) Other information: When the CCS Project Operator becomes aware of failure to submit any relevant facts in the Permanence Certification or that incorrect information was submitted in a Permanence Certification or in any report to the Executive Officer, the CCS Project Operator must submit such facts or corrected information within 10 days.

(d) Reports must comply with the formatting and timing required in the LCFS regulation, and must include an attestation that the information submitted is true, accurate, and complete.

1.1.4. Recordkeeping

(a) The CCS Project Operator must retain records and all monitoring information, including all calibration and maintenance records and all original chart recordings for continuous monitoring instrumentation and copies of all reports required by the Permanence Certification (including records from pre-injection, active injection, and post-injection phases) for a period of 10 years after site closure.

(b) The CCS Project Operator must maintain records of all data required to complete the Permanence Certification and any supplemental information (e.g. modeling inputs for storage complex delineations and plume extent reevaluations, plan modifications, etc.) submitted under subsection C.1.1.2 and reports submitted under subsection C.1.1.3, for a period of at least 10 years after site closure.

(c) The CCS Project Operator must retain records concerning the nature and composition of all injected fluids until 10 years after site closure.

(d) The CCS Project Operator must retain records and all monitoring information for the post-injection site care and monitoring period for at least 10 years after site closure (see subsection C.5.2).

(e) The retention periods specified in subsections C.1.1.4(a) and C.1.1.4(b) may be extended by request of the Executive Officer at any time. The CCS Project Operator must continue to retain records after the retention period specified in subsections 1.1.4(a) and 1.1.4(b) or any requested extension thereof expires unless the operator delivers the records to, or obtains written approval from, the Executive Officer to discard the records.

1.2. Terms and Conditions

(a) Any changes to the operational parameters of a Permanence Certification are subject to approval by the Executive Officer and must be noted in either an addendum to the Permanence Certification or a revised Permanence Certification.

(b) The Permanence Certification is non-transferable.

(c) Permanence Certification must expire, and be deemed null and void, upon the first day following 24 consecutive months of no injection at the GSC project, and a new approval process and re-certification would be required prior to restarting injection.

2. Site Characterization

2.1. Minimum Site Selection Criteria

(a) As part of the application for Sequestration Site Certification, the CCS Project Operator must demonstrate that the geologic system comprises:

(1) A sequestration zone of sufficient volume, porosity, permeability, and injectivity to receive the total anticipated volume of the CO_2 stream;

(2) A minimum injection depth of 800 m (2,600 ft), or the depth corresponding to pressure and temperature conditions where CO_2 exists in a supercritical state (>31°C and >7 MPa);[5]

(3) A confining system free of transmissive faults or fractures and of sufficient areal extent, integrity, thickness, and ductility to contain the injected CO_2 stream and displaced formation fluids and allow injection at proposed maximum pressures and volumes without initiating or propagating fractures in the primary confining layer; and

(4) A confining system composed of a layered interval of low and moderate permeability rocks that will (1) dissipate any excess pressure caused by CO_2 injection, (2) impede vertical migration of CO_2 and/or brine above the storage complex, potentially to the surface and atmosphere via possible leakage paths, and (3) provide opportunities for monitoring, measurement, and verification of containment.

(5) Depending on the distance between the sequestration zone and basement rock, the Executive Officer may require the CCS Project Operator to identify and characterize additional dissipation interval(s) below the storage complex to limit the extent of downward overpressure propagation and lower the potential for induced seismicity within formations beneath the injection zone.

[5] Lin, H., Takashi, F., Reisuke, T., Takahashi, T., and Hashida, T., Experimental evaluation of interactions in supercritical CO_2/water/rock minerals system under geologic CO_2 sequestration conditions (2008) Journal of Materials Science, v. 43, n. 7, p. 2307–2315.

2.2. Risk Assessment

(a) As part of the application for Sequestration Site Certification, the CCS Project Operator must complete a Site-Based Risk Assessment that quantifies the risk of CO_2 leakage over 100 years post-injection, and describes the potential pathways for leaks or migration of CO_2 out of the storage complex and the potential scenarios that could occur as a result. The results of the risk assessment must be used to inform and design the Testing and Monitoring Plan (subsection C.4.1).

(b) At a minimum, the risk assessment must examine 1) leakage risk, and 2) the scenarios in the Emergency and Remedial Response Plan under subsection C.6.1. Any other risks that could be reasonably anticipated must be included.

(c) The CCS Project Operator must develop and submit a Risk Management Plan (RMP) with the Site-Based Risk Assessment that documents the results of the risk analysis. The RMP must summarize the activities evaluated for risk, what those risks are, how they are ranked, and the steps the CCS Project Operator will take to manage, monitor, avoid, or minimize those risks. Any risk scenarios identified as important but not included in the Emergency and Remedial Response Plan must be included in the RMP.

(d) The operator must use appropriate tools to characterize potential risks of adverse impacts on the environment, health, or safety, by combining the assessment of the probability of occurrence and the magnitude of the adverse impacts of identified project risk scenarios. Risk scenarios identified as part of this assessment must be classified high risk, medium risk, or low risk, according to the combination of probability of occurrence during a 100-year period and the severity of potential consequences (see Table 1, below). The severity of potential consequences identified as part of this assessment must be classified as having a consequence that is insubstantial, substantial, or catastrophic. Any classification of probability of occurrence or severity of potential consequences must be accompanied by a sufficient explanation.

Table 1. Risk scenario classification

	Insubstantial[2]	**Substantial**[2]	**Catastrophic**[2]
> 5%[1]	Medium risk	High risk	High risk
1-5%[1]	Low risk	Medium risk	High risk
< 1%[1]	Low risk	Medium risk	Medium risk

[1] Probability of occurrence over 100 years
[2] Severity of potential consequences

(e) Any risk scenarios that are classified as high risk under subsection C.2.2(d) must be mitigated such that they can be re-classified as medium or low risk. Any CCS project with risk scenarios that are classified as high risk that cannot be mitigated to medium or low risk will not be granted Permanence Certification. Risk scenarios classified as high or medium risk must be included in a CCS project's Emergency and Remedial Response Plan.

(f) Risks of CO_2 leakage must be evaluated using the same techniques required in subsection C.2.4.1. Only sites in which the fraction of CO_2 retained in the storage complex is very likely (greater than 90% probability of occurrence) to exceed 99% over 100 years post-injection will be eligible to receive Permanence Certification. Uncertainties identified during site characterization and well installation must be inventoried, and the impact of the uncertainties on storage permanence must be evaluated. Uncertainties that have a material impact on storage permanence must be inventoried and incorporated into the risk assessment, and be used to design monitoring that will reduce leakage risk. Examples of possible material uncertainties include, but are not limited to:

(1) High permeability zones that may lead to horizontal CO_2 leakage;

(2) Natural or well-related flaws in the confining system that may allow vertical CO_2 leakage;

(3) Compartmentalization of the sequestration zone that may lead to elevated pressure; and

(4) Geomechanically sensitive features that may be activated by pressure changes and increase risk of unacceptable seismicity.

2.3. Geologic and Hydrologic Evaluation Requirements

(a) CCS Project Operators are required to submit, with the application for Sequestration Site Certification, an evaluation of the geological and hydrological characteristics of the sequestration zone and confining system derived from academic journals, historical records, laboratory and field data such as geologic core samples, outcrop data, well logs, two- and three-dimensional seismic surveys, and names and lithologic descriptions. The CCS Project Operator must submit the following information:

(1) Regional geologic information:

(A) A brief synopsis of the geologic history of the CCS project site;

(B) Porosity, permeability, lithofacies, depositional environment, and the geologic names and ages of formations;

(C) Regional hydrogeology of the sequestration zone, including all available data pertaining to groundwater flow direction, flux, and flow patterns; and

(D) Structural geology of the regional area, including faults and fault orientations, the presence and trends of folds, and whether these structures penetrate into the storage complex.

(2) Site-specific geologic and hydrogeologic information:

(A) Depth interval of confining system and sequestration zone below ground surface and depth interval of planned completion interval;

(B) Lithologic description from core or hand samples, including petrology, mineralogy, grain size, sorting or grading, cementation and dissolution features, and lithofacies or geologic rock name for both the confining system and sequestration zone;

(C) Structural geology of the local area including faults and fault orientations, the presence and trends of folds, and whether these structures penetrate into the storage complex;

(D) Confining system and sequestration zone thickness, as well as total thicknesses of the confining layer(s) and the sequestration reservoir, thicknesses of any high permeability or porosity intervals in the sequestration zone (if applicable), and thicknesses of planned perforated interval(s); and

(E) Porosity, permeability, and capillary pressure of the sequestration zone, confining layer(s), and location of the completion interval. These data must be used in the calculation of the following properties of the sequestration zone and confining layer:

1. Hydraulic conductivity;

2. Specific storage; and

3. Storage coefficient.

(3) Site-specific geomechanical and petrophysical information:

(A) Fracture/parting pressure of the sequestration zone and primary confining layer, and the corresponding fracture gradients determined via step rate or leak-off tests performed in the wellbore. For new CCS projects, these testing and logging activities may be undertaken during the drilling of a stratigraphic test well, or during the drilling and construction of any new injection, production, observation, or monitoring well;

(B) Rock compressibility, or a similar estimation of the measure of rock strength, for the confining layer(s) and sequestration zone;

(C) Rock strength and the ductility of the confining layer(s). Rock strength is usually determined by performing a triaxial load test of the uniaxial compressive strength (*UCS*) on a core sample. Ductility and rock strength must be assessed via the following equations:

1. Ductility of the confining layer(s) must be calculated using the following brittleness index (*BRI*):

$$BRI = \frac{UCS}{UCS_{NC}} \tag{7}$$

Where *UCS* is the unconfined compressive strength of the confining layer as measured from intact samples, and the UCS_{NC} is the confining layer's compressive strength if it was normally consolidated, as measured from remolded samples that are normally reconsolidated;

2. *UCS* can also be estimated from the pressure wave velocity (V_p) through intact samples or measured *in situ* within the wellbore via the equation:

$$\log(UCS) = -6.36 + \log\left(0.86V_p - 1172\right) \tag{8}$$

3. The UCS_{NC} can also be estimated from the effective vertical stress (σ'), where:

$$UCS_{NC} = 0.5\sigma' \tag{9}$$

If *BRI* < 2, the confining layer is sufficiently ductile to anneal any discontinuities. If *BRI* > 2, discontinuities may be open.

(D) Pore pressure, or the measure of *in situ* fluid pressure, formation temperature; and

(E) Estimation of the injection volume and the maximum allowable injection rate and pressure, such that neither the primary confining layer nor the sequestration zone hydraulically fracture during injection, must be based on step rate test results as in subsection C.2.3.1(g).

(4) Injectivity or pump tests of the sequestration zone based on CO_2 reservoir flow modeling using information determined from subsection C.2.3.1(h).

(5) Geologic characteristics of any secondary confining layers above the primary confining layer and below the sequestration zone, as well as characteristics of any dissipation intervals above and below the target sequestration zone and confining layer.

(6) A full description of significant geologic structures, including faults and fractures, which intersect the storage complex and all data relevant to assessing the transmissivity of these features. The CCS Project Operator must include a determination that these features will not interfere with containment, supported by information including, but not limited to:

(A) The location, depth, displacement, and geometry of the fault or fracture;

(B) Data on aperture, cement, and fault gouge;

(C) The orientation of the local state of stress and a full geometric description in support of modeling the response to changes in the state of stress during injection; and

(D) Any additional methods and results of fault stability analyses and comparison to anticipated or modeled pressures during injection.

(7) An evaluation of the seismic history of the proposed sequestration site, including the date, magnitude, depth, and location of the epicenter of seismic sources and a determination that the seismicity would not cause a catastrophic loss of containment, either by breaching the integrity of the well or the sequestration formation, following a risk assessment pursuant to subsection C.2.2(e);

(8) A tabulation of readily available information on freshwater aquifers and springs in the surface projection of the storage complex. This information should include:

(A) The numbers, thicknesses, and lithologies of freshwater aquifers, including interbedded and low permeability zones;

(B) Water quality such as TDS, alkalinity, pH, dissolved trace metals, and TOC;

(C) The deepest depth of freshwater aquifers;

(D) Whether any freshwater aquifers in the surface projection of the storage complex are currently accessed for human use; and

(E) The location and distance to nearest water supply well and nearest downgradient water supply well, as well as any water wells and springs in the surface projection of the storage complex.

(9) A tabulation of readily available geochemical data on subsurface formations and formation fluids in and around the storage complex, including:

(A) Reservoir fluid data for the sequestration zone, such as TDS, dynamic viscosity, density, temperature, pH, and information on the potentiometric surface, if available;

(B) Characteristics of any aquifers directly above or below the sequestration zone, if applicable, including TDS, temperature, and information on the potentiometric surface, if available; and

(C) For CO_2-EOR and depleted oil and gas reservoir sites, data such as oil gravity and viscosity, presence, concentrations, and specific gravity of non-hydrocarbon components in the associated gas (e.g. hydrogen sulfide), and any other compositional data as needed for modeling fluid interactions.

(10) The location and description of known mineral deposits or other natural resources above, beneath, or near the storage complex, including but not limited to stone, sand, clay, gravel, coal, oil, and natural gas.

(b) Characterization of other injection or production fluids in or near the storage complex:

(1) CCS Project Operator must describe and quantify any fluids injected or produced related to the CCS project, in addition to the injection fluid.

(2) The CCS Project Operator must provide a management strategy for all of the following:

(A) The potential unintentional release of production fluid must be mitigated pursuant to the Emergency and Remedial Response Plan from subsection C.6.1;

(B) Other injection, such as waste water disposal, must be considered in regards to pressure changes and the geomechanical response to such injection; and

(C) Distant parameters, such as production or disposal, should be considered in the boundary conditions of the computational model parameters pursuant to subsection C.2.4.1.

(c) Site-specific maps and cross-sections, including:

(1) Geologic and topographic maps and cross-sections illustrating regional geology, hydrogeology, and geologic structure of the local area;

(2) Maps and stratigraphic cross-sections indicating the general vertical and lateral limits of all freshwater aquifers, water wells, and springs within the surface projection of the storage complex, their positions relative to the storage complex, and the direction of shallow groundwater movement, where known;

(3) Structural contour and isopach maps of the storage complex including all faults and fractures, as well as any lateral containment features;

(4) Stratigraphic columns or cross-sections of the regional basin showing lateral continuity of storage complex, as well as the lack of any significant compartmentalization or heterogeneity in the sequestration zone that could inhibit proposed injection volumes;

(5) Representative electric log to a depth below the sequestration zone and lower confining layer or dissipation interval(s) identifying all geologic units, formations, freshwater aquifers, and oil or gas zones. If CO_2 injection is for CO_2-EOR, the electric log must extend to a depth below the deepest producing zone;

(6) At least one cross-section of the storage complex to surface through the injection well(s);

(7) Maps showing the locations of any seismic lines and cross-sections; and

(8) Maps showing any known mineral deposits or natural resources within the surface projection of the storage complex.

(d) Description of any accumulation of gas above, below, or within the storage complex, including but not limited to, the type of gas, location, depth, and areal extent on the surface.

(e) Any additional information requested by the Executive Officer that is necessary to complete the geological and hydrogeological site evaluation.

2.3.1. Formation Testing and Well Logging Program

(a) As part of the application for Sequestration Site Certification, the CCS Project Operator must submit a Formation Testing and Well Logging Plan. The plan must demonstrate to the Executive Officer how the CCS Project Operator will collect the geologic and hydrogeologic data required to show that the selected storage complex is suitable for receiving and containing injected CO_2.

(b) For new CCS projects, the testing and logging activities described in subsections C.2.3.1(d) through C.2.3.1(i) may be undertaken during and after drilling of a stratigraphic test well, or during and after the drilling and construction of any new injection, production, observation, or monitoring well.

(c) For a CO_2 injection well to be transitioned from a pre-existing injection, monitoring, stratigraphic test, or production well, the testing and logging information required by subsections C.2.3.1(d) through C.2.3.1(i) can be provided from previous and ongoing testing and monitoring of the formation and from well tests and logs conducted during the previous use of the well.

(d) For existing CCS projects, historical data that provides a demonstration of the suitability of the selected storage complex for sequestering CO_2 may be submitted in lieu of the data required by subsections C.2.3.1(b) and (c), provided the data is determined by the Executive Officer to be equivalent or better than that required by those same subsections.

(e) Well logging requirements:

(1) During the drilling and construction of a CCS project injection well, the CCS Project Operator must run appropriate logs, conduct surveys, and perform tests to determine or confirm the depth, thickness, porosity, permeability, lithology, and salinity of all relevant geologic formations.

(2) Well logging activities must be used to supplement data on the geologic and hydrogeologic properties of relevant subsurface formations collected during initial site characterization and to support building a conceptual understanding of the site, conducting the storage complex determination, and designing the CCS project.

(3) Well logging results must also be used to establish baseline data against which to compare to future measurements under subsection C.2.5, and to ensure conformance with the injection well construction requirements under subsection C.3.1.

(4) CCS Project Operators must use well logging results to create a temperature vs. depth and hydrostatic pressure profile, which should be used to inform the risk evaluation (subsection C.2.2) and monitoring (subsection C.4.3).

(f) Core analyses:

(1) The CCS Project Operator must take whole cores or sidewall cores of the sequestration zone and primary confining layer, and formation fluid samples from the sequestration zone, during drilling and prior to well construction. The cores of the sequestration zone and primary confining layer must be collected during the initial stages of project development, from a stratigraphic well or from the injection well itself, pursuant to the needs of the operator. The CCS Project Operator must submit to the Executive Officer a detailed report prepared by an experienced log analyst that includes: well log data and analyses (including the logs themselves), core analyses, and formation fluid sample information.

(2) Information from cores must be used to refine site characterization data submitted pursuant to subsection C.1.1.2.

(3) The Executive Officer may accept information on cores from nearby wells that were previously collected if the CCS Project Operator can demonstrate that core retrieval is not possible and that such cores are representative of conditions at the well site.

(4) Core logs must include descriptions or indications of the following characteristics: lithology, thickness, grain size, sedimentary structures, diagenetic features, geologic contacts, textural maturity, oil staining, fracturing, and porosity.

(5) Laboratory analysis of cores must include petrology and mineralogy, petrophysical properties, and geomechanical properties, including but not limited to, relative permeability, capillary pressure, fluid compatibility, wettability, and pore volume compressibility.

(6) The Executive Officer may require the CCS Project Operator to take core samples of other formations in the wellbore, such as dissipation intervals or secondary confining layers in the stratigraphic column, in order to characterize the mitigation potential of over- and underlying geologic formations.

(g) Characterization of the chemical and physical properties and downhole conditions of fluids in the sequestration zone:

(1) Upon completion of the injection well and prior to operation, the CCS Project Operator must collect data on downhole conditions needed to support monitoring and computational modeling design. The CCS Project Operator must justify the sufficiency of the data collected, and that the method by which it was collected and analyzed is suitable for the purposes to which it is applied. Data required include fluid temperature, pH, conductivity, reservoir pressure, and fluid density.

(2) If geochemical data are to be used for monitoring, a site-specific procedure to separate leakage signal from background must be developed. For example, dissolved gases must be assessed with correction for pressure and temperature effects; and

(3) The CCS Project Operator must submit the results of all downhole analyses and any laboratory results on samples, including quality assurance samples (e.g., blanks, duplicates, matrix spikes).

(h) Fracture/parting pressure of the sequestration zone and primary confining layer:

(1) The CCS Project Operator must perform step rate tests for each CO_2 injection well that is part of the CCS project, and use the results of each test to determine the fracture pressure of the sequestration zone and primary confining layer.

(A) The CCS Project Operator must report the results of all step rate tests for each CO_2 injection well. Such data must be used to determine the maximum allowable injection pressure for the CCS project such that injection will not initiate or propagate faults of fractures in the sequestration zone or primary confining layer; and

(B) Step rate tests must meet the following requirements:

1. Real-time downhole pressure recording must be employed;

2. Bottom-hole pressure must be recorded at a zero injection rate for at least one full time step before the first step of the step rate test, and before one full time step after the last step of the step rate test; and

3. Step rate test data reported under subsection C.1.1.2 must be raw and unaltered, and include the injection rate, bottom-hole pressure, surface pressure, pump rate volume, and time recorded continuously at a rate of every one second during the step rate test.

(2) The CCS Project Operator must also discuss how the calculated fracture pressure compares with data from core tests or other wells in the area, if available.

(i) Hydrogeologic testing:

(1) Upon completion of the injection well, prior to operation, the CCS Project Operator must conduct at least one of the following transient analysis tests to determine hydrogeologic characteristics of the sequestration zone:

(A) A pressure fall-off test;

(B) A pump test; or

(C) Injectivity tests.

(2) These tests must be designed to determine the injectivity of the sequestration zone to set operating limits for CO_2 injection rates and volumes; and

(3) Pressure fall-off tests must be conducted to determine hydrogeologic parameters, including but not limited to, the transmissibility of the sequestration zone, the static sequestration zone pressure, the skin factor, and to identify faults or fractures adjacent to the wellbore.

(j) The CCS Project Operator must determine or calculate any additional physical and chemical characteristics of the sequestration zone and confining system needed to augment other information gathered during the site characterization process, support the development of the storage complex delineation and plume extent model, or support setting of permit conditions (e.g., operational limits).

(k) The CCS Project Operator must provide the Executive Officer, or delegate, with the opportunity to witness all logging and testing in this subsection. A state licensed engineer, or equivalent, may be allowed to witness logging and testing, if approved by the Executive Officer.

(l) The CCS Project Operator must submit a descriptive report that includes an interpretation of the results of the formation testing and well logging program with the application for CCS Project Certification. At a minimum, the report must include:

(1) The results of each test, log, and any supplemental data;

(2) An interpretation of the tests and logs, including any assumptions, and the determination of the sequestration zone and confining system characteristics, including porosity, permeability, lithology, thickness, depth, and formation fluid salinity of relevant geologic formations;

(3) Any changes in interpretation of site stratigraphy based on formation testing and well logs; and

(4) A description of any alternative methods used that provide equivalent or better information, and that are required and approved by the Executive Officer.

(5) The CCS Project Operator must demonstrate that the information collected is consistent with other available site characterization data submitted with the

Permanence Certification and that the data support other assessments of stratigraphy and formation properties. The Executive Officer may compare

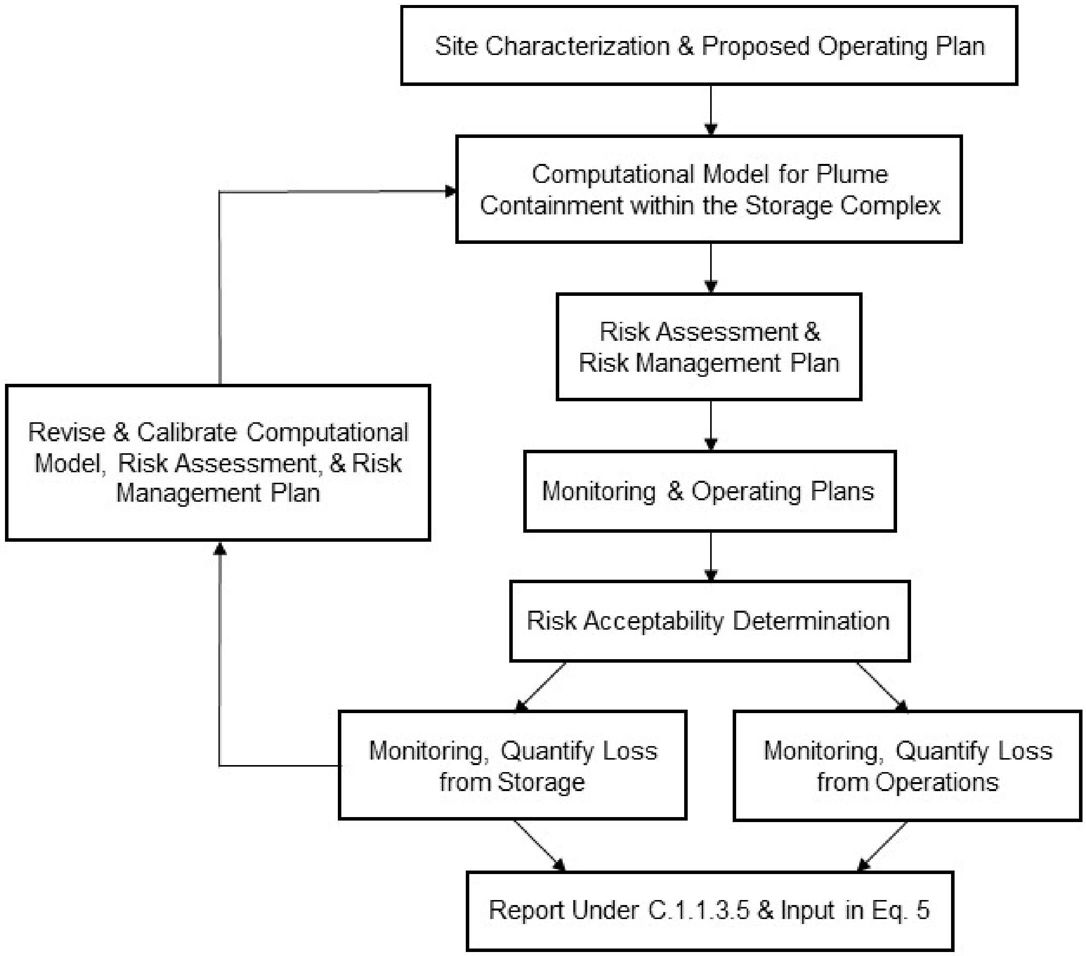


Figure 4. Flow chart showing the process for CCS project design.

the results of formation testing logs from different wells in the vicinity to interpret local stratigraphy, and confirm the depths and properties of the proposed sequestration zone and confining system.

2.4. Storage Complex Delineation and Corrective Action

(a) The storage complex delineation and corrective action requirements are to ensure that the surface areas and subsurface volumes potentially impacted by a proposed GSC project are delineated, all wells that need corrective action receive it, and that this process is updated throughout the active life of the CCS project. The general relationship between site characterization, risk assessment, modeling, monitoring, risk management, quantification, and reporting activities at a CCS project is shown on Figure 4.

(b) The basic requirements of the storage complex delineation effort and corrective action requirements are as follows:

(1) The CCS Project Operator must prepare, maintain, and comply with a plan to delineate the storage complex for a proposed CCS project, periodically reevaluate the delineation, and perform corrective action that meets the requirements of this section and is acceptable to the Executive Officer, which includes the following:

(A) Delineate the storage complex using computational modeling as discussed in subsection C.2.4.1, based on available site characterization, monitoring, and operational data;

(B) Identify all wells that penetrate the storage complex and that require corrective action pursuant to subsections C.2.4 and C.*2.4.3.1*;

(C) Perform corrective action on all wells that may be potential vectors for CO_2 leakage, including wells that either (1) penetrate the storage complex, or (2) are within the surface projection of the storage complex, pursuant to subsections C.2.4(b)(2) and C.2.4.3, and the risk assessment in subsection C.2.2.;

(D) Reevaluate the retention and containment of the CO_2 plume within the storage complex throughout the life of the CCS project following subsection C.2.4.4;

(E) Ensure that the Emergency and Remedial Response Plan and financial responsibility demonstration account for the approved storage complex delineation; and

(F) Retain all modeling inputs and data used to support initial storage complex delineations and plume extent reevaluations of the retention and containment of the CO_2 plume within the storage complex for the life of the CCS project and 10 years following site closure.

(2) Storage Complex and Corrective Action Plan:

(A) As a part of the application for Sequestration Site Certification, the CCS Project Operator must submit an Storage Complex Delineation and Corrective Action Plan that includes the following information:

(B) The method for delineating the storage complex that meets the requirements of subsection C.2.4, including a detailed report on the computational model used, assumptions made, and site characterization data on which the computational model will be based; and

(C) A description of:

1. The minimum fixed frequency, not to exceed five years, at which the CCS Project Operator will reevaluate the extent of the plume and a justification for the proposed reevaluation frequency;

2. How monitoring and operational data (e.g., injection rate and pressure) will be used to inform a plume extent reevaluation; and

3. How corrective action will be conducted to meet the requirements of subsection C.2.4, including what corrective action will be performed prior to injection, how corrective action will be adjusted if there are any changes in the storage complex delineation or injection operation, and how site access will be guaranteed for future corrective action.

2.4.1. Computational Modeling Requirements

(a) The CCS Project Operator must delineate the storage complex and perform a risk assessment that shows that the storage complex will contain the CO_2 plume over the life of the project and for a minimum of 100 years post injection (see subsection C.2.2). Any time the CCS Project Operator performs computational modeling under this subsection, the modeling must encompass the timeframe from the beginning of the project through 100 years post-injection. The risk assessment must be based on a computational model that accounts for the physical properties and site characteristics of the sequestration zone and injected CO_2 stream over the proposed life of the CCS project and prepare a report on the outcomes via the following actions:

(1) The computational model of the storage complex must incorporate various parameters including site characterization, monitoring, operational data, and:

(A) Predict the lateral and vertical migration of the free-phase CO_2 plume and elevated pressure, as well as the dissolved CO_2 plume in the subsurface, from the commencement of injection activities until plume stabilization;

(B) Be designed to simulate multiphase flow of several fluids (groundwater, CO_2, and hydrocarbons, if present), phase changes of CO_2, significant pressure changes, and any other pertinent processes in geologic media based on scientific principles and accepted mathematical and governing equations;

(C) Be based on detailed geologic, hydrogeologic, and geomechanical data collected for the characterization of the sequestration zone and confining layer(s). The CCS Project Operator must consider and report on the justification for the following list of inputs when designing the computational model and must conduct and report on sensitivity analyses and provide justification for all simplifications selected, based on site-specific conditions:

1. Regional and site-specific geology, such as stratigraphy, formation lithology, elevation, thickness, and structural geology (including faults, folding, fractures). This data must be used to justify all boundary conditions selected for the computational model that are relevant to pressure management during injection;

2. Reservoir conditions including (1) hydrogeologic conditions such as intrinsic and relative permeabilities, porosity, capillary pressure, formation compressibility, water saturation, CO_2 saturation, and storativity, and (2) reservoir fluid properties such as brine or hydrocarbon viscosity, density, composition or salinity, and compressibility;

3. Geomechanical information on fracture pressure and gradient in the sequestration zone and confining layer(s), as well as any geomechanical processes or models that are incorporated into the storage complex delineation effort based on initial site characterization efforts;

4. Existing and proposed operational and monitoring data, including the location of injection and/or extraction wells, fluid injection and withdrawal rates, bottom-hole pressure measurements, fluid characterization, inputs from monitoring systems (as recorded in, e.g., verification wells), CO_2 saturations and injected volumes, the location and number of injection, production, and monitoring wells, and well construction details (e.g., perforated intervals, etc.);

5. Computational model parameters such as: (1) initial conditions (e.g., fluid composition and distribution, etc.) within the domain at the beginning of the model run, (2) time steps and a justification for the selection, (3) vertical and horizontal gridding design and a justification that they are fit-to-purpose, and (4) other model design parameters; and

6. Any other models, model parameters, and/or general assumptions that are incorporated or considered for the CCS project and storage complex delineation based on site-specific conditions. For example, mineral precipitation kinematic parameters may be introduced into a reactive transport model of the reservoir if the planned injectate and composition of water at depth are predicted, based on sampling and monitoring data, to react such that mineral precipitation may modify the permeability of the reservoir. For injection into depleted reservoirs or CO_2-EOR operations, the measurements and computational

assumptions (e.g., “black oil” or compositional model) made about the CO_2-fluid interactions must be specified, sensitivity analysis conducted, and the selected approaches justified;

(D) Parameter values must be based on site data to the best extent possible. In cases where certain detailed site geologic characterization data are unavailable, parameter values may be estimated from standard values or relationships in the scientific literature. CCS Project Operators must indicate the range of values possible for their site and conditions, and must provide a justification for using each particular parameter value not directly measured in the field or the laboratory. Probability and statistical methods of distributing attributes should be documented and sensitivity analyses performed;

(E) All data collected to comply with site characterization requirements must be considered in the storage complex delineation. Any additional data available in the vicinity of the site that may affect the storage complex delineation, e.g., from the U.S. Geological Survey or other wells drilled within the vicinity of the storage complex must also be considered in model development. Simplifications must be documented and justified;

(F) Utilize and document appropriate equations of state and constitutive relationships derived from equilibrium phase relationships and empirically based approximations, respectively;

(G) Explicitly state model orientation and gridding parameters, including the spatial temporal domains, grid spacing and gridding routine, coordinate system, horizontal datum, and the physical properties and assumptions used to define the domain boundaries;

(H) Describe and justify the method and assumptions used to history match the pressure distribution;

(I) Take into account any geologic heterogeneities, other discontinuities, data quality, and their possible impact on model predictions;

(J) Modeling must consider potential migration through faults, fractures, and artificial penetrations, and determine the detectable response to such leakage. The outcomes of these models must be included in the risk assessment, monitoring and testing plans, and proposed operations; and

(K) Perform sensitivity analysis on model input parameters and qualify the model by assessing the implications of uncertainties in input data to the model predictions. Any material uncertainties that could result in the loss of permanent storage must be considered, and models showing the impact of uncertainties must be incorporated into the risk assessment to determine how the uncertainties can be detected by monitoring.

(2) The computer code(s) requirements:

(A) Computer code(s) utilized in the storage complex delineation and plume extent modeling must be:

1. Validated for use in peer-reviewed literature;

2. Available to CARB and CCS Project Operators during CARB's review of any permanence certification application, and preferably open source; and

3. Validated by a third party approved by the Executive Officer and applicant. Third-party validation must occur any time the CCS Project Operator submits an application for certification or recertification by CARB, including: Sequestration Site Certification, CCS Project Certification, Plume extent reevaluations pursuant to subsection C.2.4.4(b), and approval of plume-stability pursuant to subsection C.5.2(b).

(B) The code(s) used for modeling the storage complex must demonstrate the capability to:

1. Predict the evolution of the three-dimensional geometry of the CO_2 plume under reservoir conditions at the site during injection and post-injection;

2. Support the risk assessment by allowing the evaluation of the response of key geological formations, both within and above the storage complex, to CO_2 leakage response;

3. Support assessment of geomechanical response to pressure and fluid change during injection, especially with regard to risk of induced seismicity;

4. Provide a reliable timeline showing plume extent modeling and pressure equilibration; and

5. Support comparison of the modeled response to the reservoir response during monitoring.

(C) Techniques to demonstrate that the code(s) is appropriate include:

1. Successful application in a similar setting leading to successful history matching;

2. Comparison of a new code against a proven code to show reasonable match; or

3. Sensitivity studies showing that the code reproduces the relevant physics properly.

(D) Codes must properly manage key properties of the reservoir fluid system, including three-dimensionally heterogeneous formations, and characteristic-curve hysteresis and residual phase trapping. If important, mineral precipitation/dissolution reactions and subsequent mineral phase trapping or leaching of heavy metals may be considered. The system response to leakage through faults, fractures, and wellbores must be modeled, and results used for the risk assessment and testing and monitoring design; and

(E) If using a non-peer-reviewed independently developed or untested code, the developer must validate the model's appropriateness by modeling validated test cases of problems with similar physics found in the literature before submitting the application for Sequestration Site Certification.

2.4.2. Storage Complex Delineation using Computational Modeling Results

(a) The initial storage complex delineation and plume extent model must be submitted with the proposed Storage Complex and Corrective Action Plan in the application for Sequestration Site Certification pursuant to subsection C.1.1.2(b). The model must be updated using all additional characterization and pre-injection testing data, and finalized prior to obtaining CCS Project Certification following subsection C.1.1.2(d). Versions of the model must be given unique identifiers.

(b) The storage complex boundaries must be based on simulated predictions of the lateral extent of the separate-free-phase CO_2 plume and elevated pressure until it stabilizes after the end of injection for the cumulative CCS project model, and must account for the anticipated injection rates from all planned injection and production (if applicable) wells.

(c) A single modeling exercise must be conducted for all wells within a single CCS project.

(d) The application for Sequestration Site Certification submittal must include the following in support of the storage complex delineation:

(1) Attributes of the code(s) used to create the computational model(s), including the code name, version, name of the developing organization, and full

accounting of or reference to the model governing equations, scientific basis, and simplifying assumptions;

(2) A description of the model domain, such as the model's lateral and vertical extents, geologic layer thickness, and grid cell sizes, as presented on maps and cross-sections;

(3) An accounting of all equations of state used for all modeled fluids (groundwater, CO_2);

(4) Any constitutive relationships, such as relative-permeability saturation relationships, and how they were determined; and

(5) Model results, including predictions of the free-phase CO_2 plume extent and elevated pressure over the lifetime of the CCS project. Model results must be presented in contour maps, cross sections, and/or graphs showing the CO_2 plume extent and elevated pressure as a function of time, and the application for Sequestration Site Certification submittal must include the outcome of parameter sensitivity analysis and model calibration.

2.4.3. Corrective Action Requirements

(a) Corrective Action Plan:

(1) The CCS Project Operator is required to submit a Corrective Action Plan with the initial application for Sequestration Site Certification pursuant to subsections C.1.1.2 and C.2.4.3(a). The Corrective Action Plan must describe:

(A) Methods for the identification of all artificial penetrations that either penetrate the storage complex or are within the surface projection of the storage complex;

(B) Proposed corrective action for unplugged or improperly or insufficiently plugged wells that either penetrate the storage complex or are within the surface projection of the storage complex; and

(C) The schedule of corrective action activities that minimizes risk to public health and the environment.

(b) Following Executive Officer approval and pursuant to the Corrective Action Plan, CCS Project Operators of CO_2 injection wells must perform the following actions:

(1) Use best available methods and technologies to identify all artificial penetrations, including all wells that either penetrate the storage complex or are within the surface projection of the storage complex, and provide a

tabulation of each well's type, construction, date drilled, location, depth, record of plugging and/or completion, casing diagrams for those wells pursuant to subsection C.*2.4.3.1*, and any additional information the Executive Officer may require; and

(2) Use a variety of methods to identify all wells that either penetrate the storage complex or are within the surface projection of the storage complex that require corrective action, such as those that are improperly plugged or abandoned such that they may leak gas or fluid, or those that are currently leaking gas or fluids, including, but not limited to:

(A) Historical research of state and local databases, county records, and private data;

(B) Site reconnaissance, including interviewing local residents and property owners, as well as conducting a physical search for features indicative of abandoned wells;

(C) Aerial photography and satellite imagery review;

(D) Geophysical methods including magnetic, ground penetrating radar, and electromagnetic surveys;

(E) Abandoned well plugging records; and

(F) Well field testing, such as the analysis of each well using CH_4 detection equipment.

(c) CCS Project Operators must perform corrective action on all wells that either penetrate the storage complex or are within the surface projection of the storage complex that are determined to need corrective action, including all wells that penetrate the storage complex and are determined to have been plugged and abandoned in a manner such that they could serve as a conduit for fluid movement into the shallower subsurface, prior to the commencement of injection. Figure 5 presents a flow chart that illustrates how the various evaluation tools must be used together to evaluate abandoned wells. CCS Project Operators must submit a descriptive report with the application for CCS Project Certification that demonstrates how corrective action was applied to deficient wells. Any historical records search must include a description of the completeness of state or federal databases.

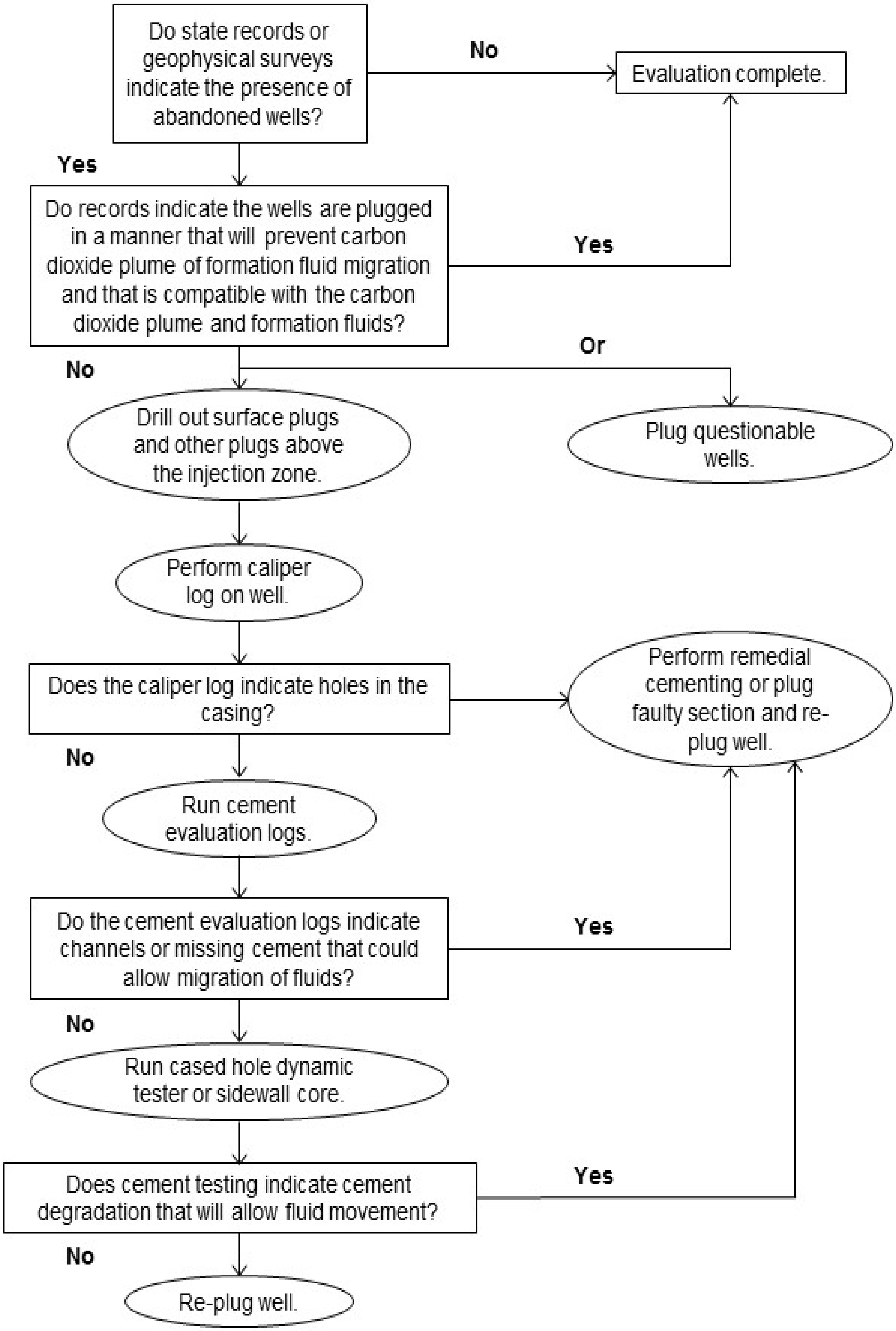


Figure 5. Well evaluation flow chart.

(d) Prior to CCS Project Certification, CCS Project Operators must perform corrective action on all wells that either penetrate the storage complex or are within the surface projection of the storage complex that require corrective action. In performing corrective action, CCS Project Operators must use methods designed to prevent the movement of fluid out of the storage complex into a shallower zone, including use of materials compatible with the CO_2 stream, where appropriate.

(1) A well requires plugging if:

(A) Records indicate that a well plug sufficient to prevent upward movement of fluids does not exist at a depth corresponding to the primary confining layer, or there are no well plugs below permeable formations that may exhibit cross flow of mobilized fluids along the wellbore or casing; or

(B) Field evaluations reveal cracks, channels, or annuli in the plug that would allow fluid migration or suggest the plug material may corrode in response to reactions with CO_2; or

(C) Field tests indicate the well is leaking gas or fluids.

(2) A well requires remedial cementing if records or field evaluations indicate that the cement surrounding the wellbore has failed or has cracks, channels, or annuli that could allow migration of CO_2, or if the well has not been cemented.

(3) Materials used for cementing of abandoned wells must be supplemented with or replaced by materials such as polymer gels and acrylic grouts, if required by the Executive Officer.

(e) If corrective action is warranted during the injection or post-injection period based on a storage complex reevaluation pursuant to subsection C.2.4.4, the CCS Project Operator is required to take the following actions:

(1) Identify all wells or features that either penetrate the storage complex or are within the surface projection of the storage complex that require corrective action;

(2) Identify the appropriate corrective action the well or feature requires pursuant to subsection C.2.4.3;

(3) Prioritize corrective actions to be performed; and

(4) Conduct corrective actions under a schedule that minimizes risk to public health and the environment.

2.4.3.1. Casing Diagrams of Wells Penetrating the Confining System

(a) Casing diagrams submitted under subsection C.*2.4.3.1* must demonstrate that the wells will not be potential conduits for CO_2 or fluid leakage or otherwise have any adverse effects on the CCS project or cause damage to public health or the environment, and must meet the following requirements:

(1) Casing diagrams must include the following data to the extent known:

(A) Operator name, lease name, well number and API number of the well;

(B) Ground elevation from sea level;

(C) Reference elevation (i.e. rig floor or Kelly bushing);

(D) Base of freshwater;

(E) Sizes, grades, connection type, and weights of casing and tubing;

(F) Depths of casing shoes, stubs, and liner tops;

(G) Depths of perforation or other completion intervals, water shutoff holes, cement port, cavity shots, cuts, casing damage, and type and extent of any debris left in well, and any other feature that influences flow in the well or may compromise the mechanical integrity of the well;

(H) Information regarding associated equipment such as subsurface safety valves, packers, and gas lift mandrels;

(I) Diameter and measured and true vertical depth of wellbore;

(J) Wellbore path that includes inclination and azimuth measurements;

(K) Cement plugs inside casings, including top and bottom of cement plug, with measuring method indicated;

(L) Cement fill behind casings, including top and bottom of cement fill, with measuring method indicated;

(M) Type and density of fluid between cement plugs;

(N) Depths and names of the formations, zones, and sand markers penetrated by the well, including the top and bottom of the zone where injection will occur;

(O) All steps of cement yield and cement calculations performed;

(P) All information used to calculate the cement slurry (volume, density, yield), including but not limited to, cement type and additives, for each cement job completed in each well; and

(Q) When multiple boreholes are drilled, all of the information listed in this section for the original hole and for any subsequent redrilled or sidetracked wellbores.

(2) Casing diagrams must be submitted as both a graphical diagram and as a flat file data set.

(3) Any additional information that the Executive Officer may require.

2.4.4. Plume Extent Reevaluation

(a) Every five years, or when monitoring and operational conditions warrant pursuant to subsection C.*2.4.4.1*, CCS Project Operators must update and validate the computational model, reevaluate the size and shape of the CO_2 plume in the manner specified in subsections C.2.4, C.2.4.1, and C.2.4.2, and determine if the plume is within the storage complex;

(b) To reevaluate the computational model, CCS Project Operators must take the following steps:

(1) Review monitoring data and compare it to model predictions to assess whether the predicted CO_2 plume geometry and elevated pressure is consistent with actual data;

(2) Review operating data to validate that it is consistent with the inputs used in the reevaluation of the modeling effort;

(3) Review any new geologic data acquired since the last modeling effort and identify if any new data materially differ from that input into the model;

(4) Modify model input parameters and recalibrate the model using the results of subsections C.2.4.4(b)(1) through C.2.4.4(b)(3);

(5) Rerun the model to determine if the CO_2 plume is predicted to stay within the storage complex until the end of the post-injection site care and monitoring period;

(6) Have a third-party validate the reevaluated model pursuant to subsection C.2.4.1(a)(2); and

(7) If necessary, reevaluate the injection plan, the project accounting, or the storage complex delineation, risk assessment, and monitoring plan.

(c) If the information reviewed is consistent with, or unchanged from, the most recent modeling assumptions, or confirms modeled predictions about the maximum extent of CO_2 plume and elevated pressure, the CCS Project Operator must prepare a report demonstrating that no corrective action is needed. The report must include the data and results demonstrating that no changes are necessary;

(d) If the CO_2 plume is determined to have migrated outside the storage complex, the CCS Project Operator must take the following actions:

(1) Quantify and verify the amount of CO_2 leakage that occurred, and modify the injection operation to avoid further leakage; and

(2) If the injection operation cannot be modified to avoid further leakage, the CCS Project Operator must cease injection pursuant to subsection C.3.4. The CCS Project Operator may restart injection after re-applying for, and receiving, CCS Project Certification pursuant to subsection C.1.1.2(d), with a newly delineated storage complex for which the operator can avoid further leakage.

(e) If the updated model of the plume extent predicts that CO_2 leakage will occur prior to the end of the post-injection site care and monitoring period, the CCS Project Operator must modify the operation and injection plan such that the modeled plume remains inside the storage complex until stabilization. If the operation cannot be modified such that the modeled plume remains inside the storage complex, the CCS Project Operator must re-apply for, and receive, CCS Project Certification pursuant to subsection C.1.1.2(d), with a newly delineated storage complex for which the operator can avoid the predicted leakage prior to the date by which leakage is predicted to occur.

(f) The Storage Complex and Corrective Action Plan, Emergency and Remedial Response Plan, Testing and Monitoring Plan, Post-Injection Site Care and Closure Plan, and the demonstration of financial responsibility in subsection C.7 must account for the storage complex delineated as specified in subsection C.2.4.2, or most recently evaluated storage complex delineated under subsection C.2.4.4.

2.4.4.1. Triggers for Plume Extent Reevaluations Prior to the Next Scheduled Reevaluation

(a) Unscheduled reevaluations of the CO_2 plume extent must be based on observational or quantitative changes of the monitoring parameters of the CCS project.

(b) Triggers for CO_2 plume extent reevaluations must be developed and quantified as part of the CO_2 plume extent evaluation pursuant to subsection C.2.4.2, based on site-specific risks identified in the Risk Assessment pursuant to subsection C.2.2.

(c) Observations that will trigger an CO_2 plume extent reevaluation include:

(1) Observed migration of the CO_2 plume beyond the acceptable range predicted by the computational model;

(2) Observed shape of the CO_2 plume is not consistent with model predictions, suggesting potential movement of CO_2 outside of the intended formation;

(3) A trend in pressure increase at the injection well(s) or other monitoring points that deviates systematically from the predicted trend; and/or

(4) CO_2 leakage charging a zone above the storage complex;

(d) An unscheduled CO_2 plume extent reevaluation may also be needed if it is likely that the actual free-phase CO_2 plume or elevated pressure extend beyond that modeled because any of the following has occurred:

(1) An earthquake of magnitude 2.7[6] or greater within a one mile radius of the CCS project; or

(2) New site characterization data change the computational model to such an extent that the predicted free-phase CO_2 plume or elevated pressure extends vertically or horizontally beyond that predicted.

(e) Any site-specific criteria that will trigger a CO_2 plume extent reevaluation for a particular CCS project must be included in the Storage Complex Delineation and Corrective Action Plan.

2.5. Baseline Testing and Monitoring

(a) As part of the testing required to meet certification pursuant to subsection C.4, CCS Project Operators must monitor the surface, near-surface, and deep subsurface for CO_2 leakage that (1) may endanger public health or the environment or (2) require reversals of the storage credits due to a failure to achieve and maintain permanence. In order to meet the requirements of subsection C.4, CCS Project Operators must design a baseline testing strategy that supports and informs a testing and monitoring program that is capable of detecting leaks of CO_2 outside of the sequestration zone and storage complex.

[6] Cal. Code Regs., tit. 14, § 1724.14, "Pre-Rulemaking Discussion Draft 04-26-17 Updated Underground Injection Control Regulations," (2017).

(b) Baseline testing and monitoring plan requirements:

(1) The CCS Project Operator must submit a Baseline Testing Plan with the application for Sequestration Site Certification; and

(2) The baseline testing strategy must be sufficient to detect, validate, and quantify potential CO_2 leakage. The baseline testing strategy must also be sufficient to support conclusions about, and validation of, mitigation of CO_2 leakage. The baseline testing strategy must be determined on a site-specific basis consistent with (1) the risk assessment pursuant to subsection C.2.2, (2) the results of computational modeling pursuant to subsection C.2.4.1.

(c) Baseline testing and monitoring data collection and analysis:

(1) The frequency and spatial distribution of baseline data collection must be designed according to a timeline and schedule set forth in the application for Sequestration Site Certification, utilizing no less than one year prior to the initiation of injection;

(2) Baseline data on the physical and chemical conditions of the sequestration zone, confining system, and surface must be collected prior to operation, and must be (1) sufficient to track the three-dimensional evolution of the CO_2 plume, and (2) is capable of being used for history matching the computational model, and for comparison to levels during and after the operational phase of the CCS project;

(3) Any property of the storage complex, groundwater, overburden, or surface projection of the storage complex that is shown by the risk assessment (pursuant to subsection C.2.2) to potentially be impacted by injection operations must be evaluated, including but not limited to: downhole pressure, sequestration zone fluid chemistry, soil-gas composition, vegetation type and density, and fresh and overburden water chemistry and pressure;

(4) Natural background variability at daily, seasonal, or long duration trends (e.g., climate change, sea level rise, urbanization, or other landscape evolution) must be considered, and may require advanced approaches to separate CO_2 leakage signals from natural changes;

(5) Potential tools CCS Operators may choose to use for baseline testing pursuant to this subsection and testing and monitoring pursuant to subsection C.4.1 include, but are not limited to:

(A) Time-lapse geophysical tools such as seismic, electrical, gravity, and pulse neutron methods;

(B) Soil-gas and air monitoring tools; and

(C) Pressure and chemical tools.

(6) For each method chosen by the CCS Project Operator for baseline testing, the process by which the survey can be accurately repeated in terms of location and instrumentation must be provided.

(d) Baseline testing and monitoring report:

(1) The CCS Project Operator must submit a descriptive report of baseline monitoring data and interpretations with the application for CCS Project Certification. The report must include geophysical, pressure, and chemical data from the subsurface, near surface, and surface analyses, and CCS Project Operators must submit, at a minimum, the following:

(A) Site characteristics (e.g., downhole pressure, sequestration zone fluid chemistry, soil-gas composition, vegetation type and density, and fresh and overburden water chemistry and pressure);

(B) Sampling locations (in map form) and dates sampled;

(C) Atmospheric conditions, if applicable;

(D) Sampling and analytical methods, including detection limits;

(E) Results presented as concentrations and fluxes in tabular and graphic form, including quality assurance (QA) samples and analyses;

(F) Methods and results of any regression analyses; and

(G) Methods and results of any ecological modeling or sensitivity analysis performed, including input data and outputs.

(e) The CCS Project Operator must assess the impact of baseline site characteristics on operational and long term monitoring, and demonstrate that the locations sampled represent a reasonable grid size and determine if potential point sources are represented and if locations will serve as a good baseline to compare to future monitoring data. The CCS Project Operator must also demonstrate that seasonal and diurnal variations in CO_2 levels have been captured and describe the variability in the data for future reference and to compare to operational and post-operational monitoring.

3. Well Construction and Operating Requirements

3.1. Well Construction

(a) General Requirements:

(1) The CCS Project Operator must ensure that all injection, observation or monitoring, and production wells associated with the CCS project are constructed and completed to:

(A) Prevent the movement of fluids into or between any unauthorized zones;

(B) Permit the use of appropriate testing devices and workover tools; and

(C) Permit continuous monitoring of the pressure in the annulus space between the injection tubing and long string casing.

(b) The CCS Project Operator is required to submit a Well Construction Plan with the application for Sequestration Site Certification, pursuant to subsection C.1.1.2.

(c) Casing and cementing of CCS project wells:

(1) Casing and cement or other materials used in the construction of each well associated with a certified CCS project must have sufficient structural strength and be designed for the life of the CCS project. All well materials must be compatible with fluids with which the materials may be expected to come into contact (e.g., corrosion-resistant well casings) and must meet or exceed standards developed for such materials by API, ASTM International, or comparable standards acceptable to the Executive Officer. The casing and cementing program must be designed to prevent the movement of fluids out of the sequestration zone and above the storage complex. In determining and specifying the casing and cementing requirements, the CCS Project Operator must consider the following factors:

(A) Depth to the sequestration zone;

(B) Injection pressure, external pressure, internal pressure, and axial loading;

(C) Hole size;

(D) Size and grade of all casing strings (wall thickness, external diameter, nominal weight, length, joint specification, and construction material);

(E) Corrosiveness of the CO_2 stream and formation fluids;

(F) Downhole temperatures;

(G) Lithology of sequestration and confining layer(s);

(H) Type or grade of cement and cement additives; and

(I) Quantity, chemical composition, and temperature of the CO_2 stream.

(2) Surface casing must extend through the base of the lowermost freshwater aquifer and be cemented to the surface through the use of a single or multiple strings of casing and cement.

(3) At least one long string casing, using a sufficient number of centralizers, must extend to the sequestration zone and must be cemented by circulating cement to the surface in one or more stages. The CCS Project Operator may use an alternate method of cementing if cementing to surface will compromise the integrity of the well or confining layer(s), provided the operator:

(A) Submits a demonstration as part of the Well Construction Plan describing the proposed method of cementing and an explanation for why the particular method was chosen;

(B) Follows best practices that meet or exceed standards developed for such methods and materials by API, ASTM International, or comparable standards acceptable to the Executive Officer; and

(C) Receives Executive Officer approval prior to well construction.

(4) Cement and cement additives must be of sufficient quality and quantity to maintain integrity over the design-life of the CCS project. The integrity and location of the cement must be verified using technology capable of (1) evaluating cement quality radially and (2) identifying the location of channels to ensure against the likelihood of an unintended release of CO_2 from the sequestration zone above the storage complex.

(5) Cement and cement additives must be compatible with the CO_2 stream and formation fluids (e.g., corrosion-resistant) within the sequestration zone.

(6) Any changes to casing and/or cement materials or designs that deviate from the casing and cementing program in the initial Sequestration Site Certification application must be submitted and approved by the Executive Officer before CCS Project Certification is granted.

(d) Tubing and packer:

(1) Tubing and packer materials used in the construction of each well associated with the CCS project must be compatible with fluids with which the materials may be expected to come into contact and must meet or exceed standards

developed for such materials by API, ASTM International, or comparable standards acceptable to the Executive Officer.

(2) CCS Project Operators of must inject fluids through tubing with a packer set within the long string casing at a point within or below the primary confining layer, or at an interval at a location approved by the Executive Officer.

(3) In determining and specifying the tubing and packer requirements, the CCS Project Operator must consider the following factors:

(A) Depth of setting;

(B) Characteristics of the CO_2 stream (chemical content, corrosiveness, temperature, and density) and formation fluids;

(C) Maximum proposed injection pressure;

(D) Maximum proposed annular pressure;

(E) Proposed injection rate (intermittent or continuous) and volume and/or mass of the CO_2 stream;

(F) Size of tubing and casing; and

(G) Tubing tensile strength, burst, and collapse pressures.

(4) Any change to the tubing and packer used in the well that deviates from those proposed in initial CCS project application for CCS Project Certification must be submitted and approved by the Executive Officer before CCS Project Certification is granted.

(e) Wellheads and Valves:

(1) The CCS Project Operator must equip all wells associated with the CCS project with wellheads, valves, piping, and surface facilities that meet or exceed design standards developed for such materials by API, ASTM International, or comparable standards acceptable to the Executive Officer.

(2) All piping, valves, and facilities must meet or exceed design standards for the maximum anticipated allowable injection pressure, and must be maintained in a safe and leak-free condition.

(3) The CCS Project Operator must equip all ports on the wellhead assembly above the casing bowl of injection wells with valves, blind flanges, or similar equipment.

(4) The CCS Project Operator must equip wells with valves to provide isolation of the wells from the pipeline system and to allow for entry into the wells.

(f) Routine well maintenance:

(1) Routine well maintenance must be conducted at a minimum of every six months. Routine maintenance consists of wellhead valve maintenance and measurement of casing annular pressures. If a significant deviation such that the mechanical integrity of the well is compromised or may become compromised, the appropriate remediation plan must be triggered.

3.2. Pre-Injection Testing

(a) When drilling and constructing wells for a CCS project, the CCS Project Operator must run appropriate logs, surveys, and tests to: (1) determine or confirm the depth, thickness, porosity, permeability, and lithology of the sequestration zone, (2) measure the salinity and TDS of any formation fluids in all relevant geologic formations, (3) ensure conformance with the well construction requirements under subsection C.3.1, and (4) establish accurate baseline data against which future measurements will be compared.

(b) The CCS Project Operator is required to submit a Pre-Injection Testing Plan with the application for Sequestration Site Certification, pursuant to subsection C.1.1.2.

(c) The CCS Project Operator must submit, with the application for CCS Project Certification, a descriptive report that includes an interpretation of the results of such logs and tests. At a minimum, such logs and tests must include:

(1) If pilot holes are drilled as part of the CCS project, the CCS Project Operator must log deviation checks during drilling of all holes constructed by drilling a pilot hole that is enlarged by reaming or another method. Such checks must be at sufficiently frequent intervals to determine the location of the borehole and to ensure that vertical avenues for fluid movement in the form of diverging holes are not created during drilling; and

(2) A series of tests before and upon installation of the surface casing, and before and upon installation of the long string casing:

(A) A series of tests to evaluate the geological and hydrological characteristics of the wellbore following procedures outlined in subsection C.2.3.1; and

(B) Casing inspection logs to evaluate the integrity of the cement bond, such as variable density, temperature, and acoustic logs, or an alternative method approved by the Executive Officer, after the casing is set and cemented.

(3) A series of tests designed to demonstrate the internal and external mechanical integrity of injection wells, which must include:

(A) An annulus pressure test or a radioactive tracer survey, pursuant to subsection C.4.2(b)(1) and C.4.2(b)(3);

(B) A temperature, noise, or oxygen activation log, or a radioactive tracer survey; and

(C) A casing inspection log pursuant to subsection C.*4.3.1.4*.

(4) Any alternative methods that provide equivalent or better information and that are required or approved by the Executive Officer.

(d) The CCS Project Operator must record the fluid temperature, pH, conductivity, and reservoir pressure of the sequestration zone.

(e) At a minimum, the CCS Project Operator must determine or calculate the following information concerning the sequestration zone and confining layer(s) pursuant to subsection C.2.3(a):

(1) Fracture pressure;

(2) Other physical and chemical characteristics of the sequestration zone and confining layer; and

(3) Physical and chemical characteristics of the formation fluids in the sequestration zone.

(f) Upon completion, but prior to operation, the CCS Project Operator must conduct tests to determine hydrogeologic characteristics of the sequestration zone pursuant to subsection C.2.3(a), including a pressure fall-off test and a pump test or injectivity tests.

(g) The CCS Project Operator must provide the Executive Officer with the opportunity to witness all logging and testing conducted in accordance with this section. A state licensed engineer, or equivalent, may be allowed to witness logging and testing, if approved by the Executive Officer.

3.3. Injection Well Operating Requirements

(a) The CCS Project Operator is required to submit a Well Operating Plan with the application for Sequestration Site Certification, pursuant to subsection C.1.1.2. This operating plan must include:

(1) A map showing the injection facilities;

(2) Maximum anticipated surface injection pressure (pump pressure) and daily rate of injection, by well;

(3) Monitoring schedule and system or method to be utilized to ensure that no damage is occurring to the well or associated surface facilities and that all injection fluid is confined to the sequestration zone;

(4) Method of injection; and

(5) Treatment of water injected during water alternating gas (WAG) methods are used for CO_2-EOR purposes;

(b) The CCS Project Operator must ensure that injection pressure does not exceed 80 percent of the fracture/parting pressure of the sequestration zone so as to ensure that injection does not initiate or propagate existing fractures in the sequestration zone. In no case may injection pressure initiate fractures in the confining system, cause movement of the injection or formation fluids out of the storage complex, or unacceptably increase risk of significant induced seismicity. The CCS Project Operator may propose an alternative injection pressure, provided the operator:

(1) Submits a demonstration as part of the Well Operating Plan that provides an explanation for why injecting below 80 percent of the fracture/parting pressure is not feasible, and why an alternative pressure must be used;

(2) Follows best practices that meet or exceed standards developed for such methods and materials by API, ASTM International, or comparable standards acceptable to the Executive Officer; and

(3) Receives Executive Officer approval of the alternative injection pressure prior to injection.

(c) Injection between the outermost casing and the wellbore is prohibited. The space between the casing and the formation is to be cemented following subsection C.3.1(c)(3).

(d) The CCS Project Operator must fill the annulus between the tubing and the long string casing with a non-corrosive fluid (e.g., a brine containing a corrosion inhibitor).

(e) Other than during periods of well workover approved by the Executive Officer in which the annulus between the tubing and long string casing is disassembled for maintenance or corrective procedures, the CCS Project Operator must monitor and maintain mechanical integrity in all wells associated with the CCS project at all times.

(f) If an un-remedied shutdown (either downhole or at the surface) is triggered or a loss of mechanical integrity is discovered, the CCS Project Operator must immediately investigate and identify as expeditiously as possible the cause of the shutdown. If, upon such investigation, the well appears to be lacking mechanical integrity, or if monitoring required under subsection C.3.3(e) of this section otherwise indicates that the well may be lacking mechanical integrity, the CCS Project Operator must:

(1) Immediately cease injection in the affected well(s) and in any other wells that may exacerbate the leakage risk of the affected well(s), otherwise, all credits generated are subject to invalidation;

(2) Take all steps reasonably necessary to determine whether there may have been a release of the injected CO_2 stream or formation fluids into any unauthorized zone;

(3) Notify the Executive Officer in writing within 24 hours;

(4) Restore and demonstrate mechanical integrity prior to resuming injection; and

(5) Notify the Executive Officer when injection can be expected to resume.

3.4. Operating Restrictions and Incident Response

(a) In order to receive credit, the CCS Project Operator must cease injection into the affected injection well and must not resume injection into the well without subsequent approval from the Executive Officer if any of the following occurs:

(1) The CCS Project Operator has not performed mechanical integrity testing on the well as required by subsection C.4.2 or the notification and results required under subsection C.4.2.1 have not been provided to the Executive Officer;

(2) The well failed a mechanical integrity test required by subsection C.4.2, or there is any other indication that the well lacks mechanical integrity or is otherwise incapable of performing as approved by the Executive Officer;

(3) An un-remedied automatic alarm or automatic shut-off system is triggered;

(4) The well experiences a significant, unexpected change in pressure in the annulus between the tubing and the long string casing, or injection pressure;

(5) There is any indication of a failure, breach, or hole in the well tubing, packer or well casing, including failures above or below a packer;

(6) There is any indication that fluids being injected into the well are not confined to the intended zone of sequestration;

(7) There is any indication that damage to public health, the environment, natural resources, or loss of hydrocarbons is occurring by reason of the injection; or

(8) Any non-compliance with any certification condition or local regulatory requirement is discovered and the Executive Officer determines that the injection must cease.

(b) The CCS Project Operator must immediately notify the Executive Officer upon ceasing injection operations by reason of subsection C.3.4(a), indicating the affected well and the specific reason for ceasing injection.

(c) The CCS Project Operator must comply with all operational and remedial directives of the Executive Officer related to the reason for ceasing injection.

4. Injection Monitoring Requirements

4.1. Testing and Monitoring

(a) Testing and Monitoring Plan. The CCS Project Operator must prepare, maintain, and comply with a plan for testing and monitoring to ensure that the CCS project is operating as certified and that the CO_2 injected is permanently sequestered. The Testing and Monitoring Plan must be submitted with the application for Sequestration Site Certification, and must include a description of how the CCS Project Operator will meet the testing and monitoring requirements, including accessing sites for all necessary monitoring and testing during the active life of the CCS project and the post-injection site care period. Testing and monitoring associated with CCS projects during the active life of the CCS project must include:

(1) Analysis of the CO_2 stream with sufficient frequency to yield data representative of its chemical and physical characteristics pursuant to subsection C.*4.3.1.1*;

(2) Installation and use, except during well workovers, of continuous recording devices to monitor: (1) injection rate and volume pursuant to subsection C.*4.3.1.2*, (2) injection pressure and the pressure on the annulus between the tubing and the long string casing pursuant to subsection C.*4.3.1.3*, and (3) the annulus fluid volume added;

(3) Corrosion monitoring of well materials, upon well completion and a minimum of once per every five years thereafter, for loss of mass, thickness, cracking, pitting, and other signs of corrosion, to ensure that well components meet the minimum standards for material strength and performance set by API, ASTM International, or equivalent, by:

(A) Analyzing corrosion coupons of the well construction materials placed in contact with the CO_2 stream; or

(B) Routing the CO_2 stream through a loop constructed with the material used in the well and inspecting materials in the loop;

(C) Performing casing inspection logs; or

(D) Using an alternative method approved by the Executive Officer.

(4) Periodic monitoring of pressure and/or composition above the storage complex. In sites where it is feasible and useful, groundwater quality and geochemistry must be considered. The rationale and leakage detection threshold of the selected monitoring method must be demonstrated;

(5) The location and number of monitoring wells based on specific information about the CCS project, including injection rate and volume, geology, the presence of artificial penetrations and other factors;

(6) The monitoring frequency and spatial distribution of monitoring wells based on any modeling results required by subsection C.2.4.1;

(7) A demonstration of external mechanical integrity pursuant to subsection C.4.2 at least once per year, or on a schedule approved by the Executive Officer, but not to exceed once every five years, until the injection well is plugged, and, if required by the Executive Officer, a casing inspection log pursuant to requirements at subsection C.4.2(c) at a frequency established in the Testing and Monitoring Plan;

(8) A pressure fall-off test pursuant to subsection C.*4.3.1.5*;

(9) A demonstration of the suitability of the testing and monitoring plan to provide data sufficient to validate the computational model, as required by subsection C.2.4, and to ensure that the CO_2 plume will remain inside the storage complex at least until the end of the post-injection site care and monitoring period. The demonstration must include plans for testing and monitoring to:

(A) Track the extent of the CO_2 plume, and the presence or absence of elevated pressure. Monitoring data must be used to:

1. Assess the three-dimensional extent of the CO_2 plume, and to determine if it is contained within the sequestration zone and storage complex;

2. Update and test the computational model; and

3. Determine if the modeled CO_2 plume migration will remain within the storage complex until at least the end of the post-injection site care and monitoring period, pursuant to subsections C.2.4.2 and C.2.4.4.

(B) The demonstration must include an inventory of the testing and monitoring methods, and a description of the suitability of the methods to provide site-specific, risk-based data.

(10) A demonstration of how the monitoring plan and methods will be designed to detect and quantify any CO_2 leakage. The demonstration must include plans for testing and monitoring that:

(A) Specifies the process and detection threshold at which leakage from any potential pathway, from reservoir to surface, will be detected and quantified;

(B) Uses maps and computational modeling to show how measurements and computational models will be used to trigger a finding of leakage; and

(C) Describes how monitoring data will be used to (1) determine and quantify any CO_2 leakage, and (2) show that mitigation attempts have been effective.

(11) Surface monitoring to detect potential shallow subsurface or atmospheric CO_2 leakage;

(12) A description of the methods, and estimate of precision and accuracy of the methods used to measure and quantify CO_2 leakage from the storage complex (MT CO_2/year), as required by subsection B.2.2(e) Equation 6.

(13) At a minimum, the Testing and Monitoring Plan must stipulate and include:

(A) The frequency of data acquisition;

(B) A record keeping plan;

(C) The frequency of instrument calibration activities;

(D) The QA/QC provisions on data acquisition, management, and record keeping that ensures it is carried out consistently and with precision;

(E) The role of individuals performing each specific monitoring activity; and

(F) Methods to measure and quantify the following data:

1. Quantity of CO_2 emitted from the capture site;

2. Quantity of CO_2 sold to third parties (e.g., for enhanced oil recovery) including sufficient measurements to support data required; and

3. Quantity of CO_2 injected into each well in the CCS project metered at a location approved by the Executive Officer, that accounts for complicating factors, such as the individual flows that may occur at wellheads or pressure and temperature variations, and that provides sufficiently accurate data.

(14) Any additional monitoring, as required by the Executive Officer, necessary to support, upgrade, and improve computational modeling of the CO_2 plume extent required under subsection C.2.4.1;

(15) The CCS Project Operator must periodically review the Testing and Monitoring Plan to incorporate monitoring data collected under this subsection, operational data collected under subsection C.3, and the most recent CO_2 plume extent reevaluation performed under subsection C.2.4.4; and

(16) The CCS Project Operator must review the Testing and Monitoring Plan no less than once every five years. Based on this review, the CCS Project Operator must submit an amended Testing and Monitoring Plan or demonstrate to the Executive Officer that no amendment to the Testing and Monitoring Plan is needed. Any amendments to the Testing and Monitoring Plan must be approved by the Executive Officer. Amended plans or demonstrations must be submitted to the Executive Officer as follows:

(A) Within one year of a CO_2 plume extent reevaluation; or

(B) When required by the Executive Officer.

4.2. Mechanical Integrity Testing

(a) Any well that is part of a CCS project must have and maintain mechanical integrity at all times during operation, other than during periods of well workover for maintenance or corrective action. A well has mechanical integrity if:

(1) There is no internal leak in the casing, tubing, or packer;

(2) There is no significant external fluid movement out of the sequestration zone through channels adjacent to the wellbore; and

(3) Corrosion monitoring, pursuant to subsection C.*4.3.1.4*, reveals no loss of mass or thickness that may indicate the deterioration of well components (casing, tubing, or packer).

(b) The CCS Project Operator must conduct mechanical integrity testing as follows:

(1) Internal mechanical integrity must be demonstrated prior to commencing injection operations. Thereafter, the internal mechanical integrity of each well must be tested at least once every five years, after every workover (see subsection C.4.2(c)(6), below), or at the request of the Executive Officer. CCS Project Operator must submit a descriptive report of the internal mechanical integrity test results with the application for CCS Project Certification.

(2) External mechanical integrity must be demonstrated within three months after injection has commenced. Thereafter, wells must be tested at least once each year, or on a testing schedule approved by the Executive Officer.

(3) The CCS Project Operator must demonstrate internal mechanical integrity and test for possible leaks in the casing, tubing, or packer, under subsection C.4.2(b)(1), via:

(A) An annulus pressure test;

(B) A radioactive tracer survey; or

(C) An alternative test approved by the Executive Officer.

(4) The CCS Project Operator must demonstrate external mechanical integrity and test for possible leaks from channels adjacent to the wellbore under subsection C.4.2(b)(2), via:

(A) A temperature log;

(B) A noise log;

(C) An oxygen activation log;

(D) A radioactive tracer survey; or

(E) An alternative test approved by the Executive Officer.

(5) The well must pass a suitable annulus pressure test to demonstrate mechanical integrity after any workover that has the potential to compromise the internal mechanical integrity of the well, including but not limited to the downhole replacement of tubing, safety valves, and/or electrical submersible pumps.

(6) The CCS Project Operator must demonstrate external mechanical integrity prior to plugging the well following the requirements of this subsection and subsection C.5.1.

(c) Following the initial annulus pressure test, the CCS Project Operator must continuously monitor pressure on the annulus between the tubing and long string casing, except during well workovers. Continuous monitoring of the pressure on the annulus must be used to confirm internal mechanical integrity during the injection phase of the project, and must be performed in concert with continuous monitoring of injection pressure, rate, and annulus fluid volume pursuant to subsections C.4.3.1.1, C.4.3.1.2, and C.4.3.1.3.

(d) In conducting and evaluating the tests listed in this section or others to be allowed by the Executive Officer, the CCS Project Operator must apply methods and standards generally accepted in the industry. When the CCS Project Operator reports the results of mechanical integrity tests to the Executive Officer, he/she must include a description of the tests and a justification for the methods used.

(e) Prior notice and reporting.

(1) The CCS Project Operator must notify the Executive Officer of his or her intent to demonstrate mechanical integrity at least 30 days prior to such demonstration. At the discretion of the Executive Officer, a shorter time period may be allowed.

(2) Reports of mechanical integrity demonstrations that include logs must include an interpretation of results by an experienced log analyst. The CCS Project Operator must report the results of a mechanical integrity demonstration within the time period specified in subsection C.1.1.3.

(f) Gauge and meter calibration: The CCS Project Operator must calibrate all gauges used in mechanical integrity demonstrations and other required monitoring to an accuracy of not less than five percent of full scale, within one year prior to each required test.[7] The date of the most recent calibration must be noted on or near the gauge or meter. A copy of the calibration certificate must be submitted to the Executive Officer with the report of the test. Pressure gauge resolution must be no greater than five psi. Certain mechanical integrity and

[7] With the exception of any permanent downhole gauges that cannot be calibrated at the surface.

other testing may require greater accuracy and must be identified in the procedure submitted to the Executive Officer prior to the test.

4.2.1. Reporting of Mechanical Integrity Tests

(a) The CCS Project Operator must submit a descriptive report prepared by an experienced log analyst that includes the results of any mechanical integrity test with the application for CCS Project Certification, and annually, thereafter through the active life of the CCS Project. At a minimum, the report must include:

(1) Chart and tabular results of each log or test;

(2) The interpretation of log results provided by the log analyst;

(3) A description of all tests and methods used;

(4) The records and schematics of all instrumentation used for the tests and the most recent calibration of any instrumentation;

(5) The identification of any loss of mechanical integrity, evidence of fluid leakage, and remedial action taken;

(6) The date and time of each test;

(7) The name of the logging company and log analyst;

(8) For any tests conducted during injection, operating conditions during measurement, including injection rate, pressure, and temperature (for tests run during well shut-in, this information must be provided relevant to the period prior to shut-in); and

(9) For any tests conducted during shut-in, the date and time of the completion of injection and records of well pressure re-equilibration.

4.2.2. Loss of Mechanical Integrity

(a) If the CCS Project Operator or the Executive Officer finds that a well (1) fails to demonstrate mechanical integrity during a test, (2) fails to maintain mechanical integrity during operation, or (3) that a loss of mechanical integrity is suspected during operation, the CCS Project Operator must:

(1) Take all steps reasonably necessary to determine whether there may have been a release of the injected CO_2 stream or formation fluids into any unauthorized zone. If there is evidence of substantial endangerment to public health or the environment from any fluid movement out of the intended

storage complex, implement the Emergency and Remedial Response Plan, as described in subsection C.6;

(2) Follow the reporting requirements as directed in subsection C.1.1.3; and

(3) Restore and demonstrate mechanical integrity prior to resuming injection or plugging the well.

(b) If the well loses mechanical integrity prior to the next scheduled test date, then the well must be repaired and retested within 30 days of losing mechanical integrity.

(c) If the well lost mechanical integrity prior to the next scheduled test date, and it was repaired, the CCS Project Operator must submit a descriptive report documenting the type of failure, the cause, the required repairs, and a new test of mechanical integrity following the requirements of subsection C.4.2 in the next quarterly report.

4.3. CCS Project Monitoring

(a) Monitoring requirements for CCS projects are addressed in two separate categories: CCS project emissions monitoring, and the monitoring, measurement, and verification of containment. The first includes quantification and measurement activities required to quantify the net GHG reductions from the CCS project. The second category is for monitoring, measurement, and verification activities that are required to ensure that the CO_2 injected is permanently contained with the storage complex.

(b) The CCS Project Operator must install and use:

(1) Continuous recording devices to monitor: the injection pressure, the rate, volume and/or mass, and temperature of the CO_2 stream, and the pressure on the annulus between the tubing and the long string casing and annulus fluid volume; and

(2) Alarms and automatic surface shut-off systems (e.g., automatic shut-off, check valves) for wells, or other mechanical devices that provide equivalent protection.

(c) The CCS Project Operator must retain all records and all monitoring information, including all calibration and maintenance records and all original chart recordings for continuous monitoring instrumentation and copies of all reports, for emissions and containment monitoring for a period of 10 years after site closure.

4.3.1. CCS Project Emissions Monitoring

(a) Emissions monitoring requirements include measurements of relevant parameters to account for all supplemental energy inputs (e.g., fossil fuels and electricity) required for the operation of the CCS project. Data capture must be sufficient to ensure that the quantification and documentation of CO_2 sequestered is replicable and verifiable pursuant to the Accounting Requirements in section B.

(b) CCS project monitoring techniques must use calibrated metering equipment such as fluid flow meters, utility meters (gas and electricity), and fluid chemistry analyzers. Meters must be maintained to operate consistent with design specifications and must be calibrated on a regular basis.

(c) Data quality management must include sufficient data capture to support quantification and verification of CO_2 sequestered. Any assumptions and contingency procedures must be documented. Any monitoring plan and implementation must take into account the location, type of equipment, and frequency by which each variable is measured.

4.3.1.1. Analysis of the CO_2 Stream

(a) The CCS Project Operator must sample and analyze the CO_2 stream at a frequency sufficient to yield data representative of the chemical and physical characteristics of the injectate (i.e., at least once every quarter), whenever the result may deviate from the original certified specifications, and as requested by the Executive Officer.

(b) Analysis of the CO_2 stream must be reported quarterly, pursuant to subsection C.1.1.3. The report must include characteristics such as fluid composition (i.e., fraction of CO_2 and other constituents measured on a volumetric or mass basis at a known temperature and pressure), temperature, pressure, and any other parameters needed to identify potential interactions between the injectate and the formation or well materials. The CCS Project Operator must justify that the samples are representative of the fluid streams and suitable for use in accounting and fluid-flow modeling. The CCS Project Operator must submit, at a minimum, the following:

  (1) A list of chemicals analyzed, including CO_2 and other constituents (e.g., sulfur dioxide, hydrogen sulfide, nitrogen oxides);

  (2) A description of the sampling methodology, noting any differences from those listed in the Testing and Monitoring Plan and an explanation of why a different method was used;

  (3) Any laboratory analytical methods used, the name of the laboratory performing the analysis, and official laboratory analytical reports including sample chain-of-custody forms;

(4) All sample dates and times;

(5) A tabulation of all available carbon dioxide stream analyses, including QA/QC samples;

(6) Interpretation of the results with respect to regulatory requirements and past results;

(7) Identification and explanation of data gaps, if any; and

(8) Any identified necessary changes to the CCS project Testing and Monitoring Plan.

(c) The report must include a determination that any potential chemical reactions between the injectate and the formation or well materials are minimal and will not significantly affect the integrity of the well or the injectivity of the formation.

(d) The report must include a determination that no component of the injectate meets the qualifications of hazardous waste under the RCRA, 42 U.S.C. 6901 *et seq.* (1976), and/or CERCLA, 42 U.S.C. 9601 *et seq.* (1980).

(e) Injectate fluid samples must be collected from a point such that the sample is representative of the composition of the injectate. CCS Project Operators must provide a demonstration of the suitability of the sample point, along with any calculations required for complex systems (e.g., CO_2-EOR operations with more than one source of CO_2).

4.3.1.2. Continuous Monitoring of Injection Rate and Volume

(a) The CCS Project Operator must continuously monitor the injection rate and volume for each CCS injection well.

(b) Flow rate data must be used (1) to determine the cumulative volume of CO_2 injected, and (2) to confirm compliance with the operational conditions of the Permanence Certification.

(c) Monitoring requirements must include measurements of relevant parameters to account for the flow rate of injected fluids, the concentration of the fluid stream, and the energy inputs required for operation.

(d) CCS Project Operators are required to perform the following measurements and monitoring for injected fluids:

(1) Flow rate of injection stream:

(A) Continuous measurement of the fluid flow rate, composition, and density, where continuous measurement is defined as a minimum of one measurement every 15 minutes;

(B) Meter readings need to be temperature and pressure compensated such that the meter output is set to standard reference temperatures and pressures;

(C) Flow meters must be located such that accurate measurements can be collected for accounting purposes. Where possible, flow meters should be placed immediately upstream of the gas injection process, such that they are downstream of all capture, compression, and transport to account for any fugitive losses or venting. CCS Project Operators must justify their meter placement in the Testing and Monitoring Plan pursuant to subsection C.4.1. Flow meters must be placed based on manufacturer recommendations;

(D) Flow meters must be calibrated according to manufacturer specifications. Meters must be checked/calibrated at regular intervals according to these specifications and industry standards; and

(E) Ownership transfer must be clearly documented for CO_2 transferred (third-party injection activity).

(2) Concentration of injection stream:

(A) Continuous measurement of the fluid composition and density where continuous measurement is defined as a minimum of one measurement every 15 minutes; and

(B) The fluid composition must be metered downstream of the capture and processing equipment, and volume measured upstream, prior to any mixing of new and recycled CO_2.

(e) Injection rate and volume data must be submitted in the quarterly reports pursuant to subsection C.1.1.3. The report must include, at a minimum:

(1) Tabular data of all flow rate measurements and a description of interpretation of the data aided with charts or graphs;

(2) A description of the measuring methodology and technology, noting any differences from those given in the Testing and Monitoring Plan and an explanation of why a different methodology was used;

(3) The monthly average flow rate;

(4) The monthly maximum and minimum values;

(5) The total volume (mass) injected each month;

(6) The cumulative volume (mass) calculated for the CCS project;

(7) If flow rate exceeded certified operational limits during the reporting period, an explanation of the event(s), including the cause of the excursion, the length of the excursion, and response to the excursion;

(8) Identification and explanation of data gaps, if any; and

(9) Any identified necessary changes to the CCS project Testing and Monitoring Plan and the justification for those changes.

4.3.1.3. Continuous Monitoring of Injection Pressure

(a) During operation, the CCS Project Operator must continuously monitor injection pressure, at the wellhead (i.e., wellhead pressure) and downhole (i.e., bottom-hole pressure).

(b) Injection pressure is monitored to ensure that the fracture pressure of the sequestration zone and the burst pressure of the well tubing are not exceeded and that the owner or CCS Project Operator is in compliance with certified operating conditions.

(c) The CCS Project Operator must ensure that the injection pressure remains at or below 80 percent of the fracture pressure of the sequestration zone, or below the Executive Officer-approved injection pressure pursuant to subsection C.3.3(b).

(d) During injection, pressure in the annular space directly above the packer must be maintained at a pressure higher[8] than the tubing pressure.

(e) Maximum allowable surface pressure must equal top perforation or completion depth, in true vertical depth, multiplied by the difference between the injection gradient and the injectate fluid gradient.

(f) Significant changes of the pressure in the annulus between the tubing and the long string casing during injection may indicate a loss of internal mechanical integrity. If pressure monitoring indicates that the well is experiencing a loss of mechanical integrity, the CCS Project Operator must follow the procedures outlined in subsection C.4.2.2.

---

[8] U.S. EPA Region 8, Groundwater Section Guidance Number 39, (1995; updated 2006), Denver, CO.

(g) Pressure data must be reported in the annual reports following subsection C.1.1.3. The CCS Project Operator must submit, at a minimum, the following:

(1) Tabular data of all pressure measurements, a description and interpretation of the data aided with charts or graphs, and gauge calibration records;

(2) A description of the measurement methodology, noting any differences from what was established in the Testing and Monitoring Plan, and a justification of why a different methodology was used;

(3) Corrections made due to the impacts of fluctuating injectate temperature;

(4) The monthly average value for injection pressure;

(5) The monthly maximum and minimum values for injection pressure;

(6) If pressure exceeded permit limits during the reporting period, an explanation of the event(s), including the cause of the exceedance, the length of the excursion, and response to the excursion;

(7) Identification and explanation of data gaps, if any; and

(8) Any identified necessary changes to the CCS project Testing and Monitoring Plan to ensure continued protection of public health and the environment, including any changes in the data measurement or averaging methods.

4.3.1.4. Corrosion Monitoring and Casing Inspection

(a) CCS Project Operators must monitor well materials for corrosion at a frequency specified in the Testing and Monitoring Plan following subsection C.4.1, not to exceed once every five years.

(b) Well components must be monitored for corrosion using at least one of the following methods:

a. Corrosion coupons or loops;

b. Casing inspection logs (CILs), such as caliper, electromagnetic phase-shift, electromagnetic flux test log, or ultrasonic test logs; or

c. An alternative method approved by the Executive Officer.

(c) Well corrosion monitoring data must be reported annually to CARB including, including at a minimum, the following:

(1) A description of the techniques used for corrosion monitoring;

(2) Measurement of (mass and thickness/weight) loss from any corrosion coupons or loops used;

(3) Assessment of additional corrosion, including pitting, in any corrosion coupons or loops;

(4) Measurement of thickness loss or corrosion detected in any CILs;

(5) All measured CILs and comparison to previous logs;

(6) Identification and explanation of data gaps, if any; and

(7) Any identified necessary changes to the CCS project Testing and Monitoring Plan.

4.3.1.5. Pressure Fall-Off Testing

(a) CCS Project Operators must perform a pressure fall-off test of each well at least once every five years pursuant to subsection C.4.1. The CCS Project Operator may propose an alternative test method and/or schedule, provided the operator:

(1) Submits a demonstration as part of the Testing and Monitoring Plan that:

i. Describes the proposed alternative method of testing; and

ii. Provides an explanation for why fall-off tests are inappropriate and how the proposed alternative method will provide data equivalent data fall-off tests.

(2) Follows best practices that meet or exceed standards developed for such methods and materials by API, ASTM International, or comparable standards acceptable to the Executive Officer; and

(3) Receives Executive Officer approval of the alternative test method and/or schedule prior to operation.

(b) Upon shutting-in the well, pressure measurements must be taken continuously for a period of time, and pressure decay at the well must be monitored;

(c) The CCS Project Operator must use temperature and bottom-hole pressure measurements, although surface pressure at the wellbore may suffice, if positive pressure is maintained throughout the test; and

(d) The results of pressure fall-off tests must be reported to the Executive Officer within 30 days following the test and summarized with the annual reporting requirements pursuant to subsection C.1.1.3. Reports must include, at a minimum:

(1) The location and name of the test well and the date/time of the shut-in period;

(2) Depths of recorded bottom-hole pressure and temperature;

(3) Records of gauges;

(4) Raw data collected during the fall-off test in a tabular format, if required by the Executive Officer;

(5) Measured injection rates and pressure from the test well and any off-set wells in the same zone, including data from before shut-in;

(6) Information on pressure gauges used (e.g., manufacturer, accuracy, depth deployed) and demonstration of gauge calibration according to manufacturer specifications;

(7) Diagnostic curves of test results, noting any flow regimes;

(8) Description of quantitative analysis of pressure-test results, including use of any commercial software, and any considerations of multi-phase effects;

(9) Calculated parameter values from analysis, including transmissivity, permeability, and skin factor;

(10) Analysis and comparison of calculated parameter values to previously measured values (using any previous methods) and to values used in computational modeling and storage complex delineation;

(11) Identification of data gaps, if any; and

(12) Any identified necessary changes to the CCS project Testing and Monitoring Plan.

4.3.1.6. Monitoring of Wellheads and Valves

(a) The CCS Project Operator must prepare, maintain, and comply with an Inspection and Leak Detection Plan for all surface equipment, including wellheads, valves, and pipelines. This Inspection and Leak Detection Plan must be approved by the Executive Officer;

(b) The Inspection and Leak Detection Plan must include, at a minimum, procedures that the CCS Project Operator will follow that include:

(1) Quarterly inspection of all wellheads, valves, and piping, employing effective gas leak detection technology;

(2) Bi-annual testing of all surface and subsurface safety valve systems to ensure ability to hold anticipated pressure; and

(3) Annual testing of the master valve and wellhead pipeline isolation valve for proper function and verification of the valve's ability to isolate the well.

(c) The plan must include inspection of the wellhead assembly and attached pipelines for each of the injection wells used in association with the CCS project, as well as the surrounding area within a 100-foot radius of the wellhead of each of the wells;

(d) The CCS Project Operator must select and use gas leak detection technology that takes into account detection limits, remote detection of difficult to access locations, response time, reproducibility, accuracy, data transfer capabilities, distance from source, background lighting conditions, local ecology, geography, and meteorology;

(e) Upon finding that a surface or subsurface safety valve is inoperable, the CCS Project Operator must immediately shut-in the well and repair the valve within 90 days. An appropriate alternative timeframe for testing a valve or addressing an inoperable surface or subsurface safety valve may be approved by the Executive Officer;

(f) Documentation of all inspections, tests, and results must be maintained by the CCS Project Operator and available for CARB review during the active life of the CCS project; and

(g) Testing of surface equipment operational integrity must be conducted in accordance with API Recommended Practice 14B[9], or equivalent.

4.3.2. Monitoring, Measurement, and Verification of Containment

(a) Every CCS project must undertake monitoring activities to ensure safe and permanent storage of CO_2 in accordance with the Permanence Certification.

(b) The Monitoring, Measurement, and Verification Plan must be linked to the risk assessment (pursuant to subsection C.2.2), and must be used as an effective part of the risk management strategy for the CCS project.

---

[9] API Recommended Practice 14B, "Design, Installation, Operation, Test, and Redress of Subsurface Safety Valve Systems," 6 (2005): 37 p.

(c) The Monitoring, Measurement, and Verification Plan must be specific to the CCS project's storage complex, including a demonstration that the methods selected are sensitive to the CO_2 plume within the geologic environment of the storage reservoir. At a minimum, the Monitoring, Measurement, and Verification Plan must meet the requirements of section 95491.1(c) of the LCFS Regulation and include GHG reductions as well as containment. The plan must be able to;

(1) Validate that the computational modeling shows the CO_2 plume will remain within the storage complex at least until the end of the post-injection site care and monitoring period; and

(2) Ensure that if any CO_2 leakage occurs, it is detected with a detection threshold equal to, or better than, 5% the total volume of leaked CO_2.

(d) The Monitoring, Measurement, and Verification Plan must be submitted as part of the Testing and Monitoring Plan with the application for Sequestration Site Certification. The plan must include the methods the CCS Project Operator will use to monitor the extent of the CO_2 plume and elevated pressure, any atmospheric CO_2 leakage, and natural and induced seismic activity.

(e) The Monitoring, Measurement, and Verification Plan must include methods and plans for the quantification of CO_2 leakage if it occurs, including an estimate of the accuracy and precision of those methods and plans, which will be used to inform GHG emission reduction credit invalidation.

(f) The Executive Officer may require the CCS Project Operator to perform additional monitoring, as necessary, to support, upgrade, and improve computational modeling of the storage complex and to determine compliance with Permanence Certification.

4.3.2.1. Plume and Elevated Pressure- Tracking

(a) CCS Project Operators must track the extent of the free-phase CO_2 plume, and the pressure development within the storage complex by using:

(1) Well-based methods within the storage complex; and

(2) Indirect methods such as seismic, gravity, or electromagnetic surveys and CO_2 detection tools.

(b) The Monitoring, Measurement, and Verification Plan and schedule must be designed to:

(1) Monitor the free-phase CO_2 plume location, thickness, and saturation;

(2) Track the pressure development within the storage complex over time;

(3) Validate computational modeling results; and

(4) Demonstrate that operations are not leading to elevated CO_2 or brine leakage or seismic risks.

(c) Monitoring free-phase CO_2 plume development: CCS Project Operators must monitor the free-phase CO_2 plume extent, and must consider the following methods to detect the shape of CO_2 saturation of the pore space in the sequestration zone:

(1) Time-lapse three-dimensional surface seismic surveys;

(2) Downhole, time-lapse three-dimensional vertical seismic profiling surveys;

(3) Wireline-based saturation, sonic, and gravity logging;

(4) Electrical resistivity tomography (surface or downhole); and

(5) An alternative test approved by the Executive Officer.

(d) Monitoring pressure development: CCS Project Operators must monitor the elevated pressure of the CO_2 plume. The CCS Project Operator must consider the following methods and provide an estimate of the site-specific quality of detection for each chosen method:

(1) Satellite based synthetic aperture radar (InSAR) monitoring (satellite-based);

(2) Pressure gauges (downhole);

(3) Tilt meters or inclinometers (surface and well-based); and

(4) Alternative methods approved by the Executive Officer.

(e) Plume and elevated pressure-tracking data must be reported quarterly (subsection C.1.1.3) for methods in which data are collected continuously or monthly, and annually for methods in which data are collected yearly (or longer), based on the monitoring timeline pursuant to subsection C.*4.3.2.1*(b). Reports must include, at a minimum:

(1) Tabular data of all measurements and a description and interpretation of the data aided with charts, graphs, and maps of the three-dimensional extent of the CO_2 plume;

(2) A description of the measurement methodology, noting any differences from what was established in the Testing and Monitoring Plan, and a justification of why a different methodology was used;

(3) An assessment of any deviations from the modeled three-dimensional extent of the CO_2 plume, if observed, and the determination of whether or not the results trigger corrective action pursuant to subsection C.2.4.3;

(4) The monitoring approach and equipment should periodically be reevaluated to determine if (1) the methods are useful and produce accurate data, and (2) if improved methods are available; and

(5) Any identified necessary changes to the CCS project Testing and Monitoring Plan and the justification for those changes.

4.3.2.2. Surface and Near-Surface Monitoring

(a) The CCS Project Operator must monitor the surface and near-surface of a CCS project to detect potential atmospheric CO_2 leakage.

(b) The CCS Project Operator must design surface and near-surface monitoring based on potential risks to atmospheric CO_2 leakage within the surface projection of the storage complex.

(c) The monitoring frequency and spatial distribution of surface and near-surface monitoring must be decided by analysis of baseline data pursuant to subsection C.2.5. Methods must be able to distinguish between leakage signals and other variations, such as land use, climate, and ecosystems changes. Methods must be able to (1) attribute the source of leakage, (2) potentially manage or reduce future leakage, and (3) quantify the losses, including any CO_2 leakage.

(d) Surface monitoring of point sources: CCS Project Operators must monitor and quantify CO_2 or other gases associated with the storage complex (e.g. CH_4, in the case of injection into a hydrocarbon reservoir) in the atmosphere in order to detect potential releases from wellbores, faults, and other migration pathways. Broad aerial monitoring should focus on the footprint of the free-phase CO_2 plume, while more targeted monitoring can occur at wells and pipelines. CCS Project Operators must use both intermittent and continuous monitoring methods, must use one or more of the following tools to detect atmospheric CO_2 leakage:

(1) Optical sensors;

(2) Infrared (IR) open-path detectors;

(3) Forward looking infrared (FLIR) cameras;

(4) Multi-spectral imaging;

(5) Atmospheric tracers, including natural and injected chemical compounds;

(6) Eddy covariance flux measurement techniques; and

(7) Alternative methods approved by the Executive Officer.

(e) Monitoring of all wellbores: The CCS Operator must monitor all wells that intersect the storage complex at depth. Monitoring should include direct observation of the wells, if possible, and surface air monitoring around the wellbore. Monitoring should focus on identifying CO_2 flux in the vicinity of the wellbore that may indicate a catastrophic leak.

(f) Ecosystem stress monitoring: CCS Project Operators must conduct annual vegetation surveys to measure potential vegetative stress resulting from elevated CO_2 in soil. CCS Project Operators must consider methods such as satellite imagery, aerial photography, and spectral imagery. Any indications of anomalous change from remote sensing must be subject to ground-based verification and, if necessary, soil gases must be analyzed to determine the presence or absence of sequestration zone brine or characteristics of injected CO_2, including any introduced tracers.

(g) If deep subsurface or atmospheric monitoring suggests that atmospheric CO_2 leakage may occur or has occurred, the CCS Project Operator must perform continuous and intermittent geochemical monitoring of the soil and vadose zone, including sampling of CO_2, ratios of CO_2 to other gasses, natural chemical tracers, and introduced tracers, in order to detect potential releases from wellbores, faults, and other migration pathways, and separate ecosystem variability from leakage signal. CCS Project Operators must use one or more of the following methods:

(1) Flux accumulation chamber methods;

(2) Active sample collection methods including shallow monitoring wells, ground probes and permanent soil gas probes;

(3) Passive sample collection methods; and

(4) Alternative methods approved by the Executive Officer.

(h) If deep subsurface or atmospheric monitoring suggests that atmospheric CO_2 leakage may occur or has occurred, CCS Project Operators must consider using near-surface electrical conductivity surveys to measure variations in soil salinity to determine the presence or absence of brine from potential brine leakage from the sequestration zone.

(i) Surface and near-surface monitoring data must be reported and interpreted annually. Reports must include, at a minimum:

(1) Tabular data of all measurements and a description and interpretation of the data aided with charts, graphs, and maps of sample collection locations;

(2) A description of the measurement methodology, noting any differences from what was established in the Testing and Monitoring Plan, and a justification of why a different methodology was used;

(3) If leakage is detected, it must be attributed, quantified, and assessed for potential corrective action, and CCS Project Operators must appropriately manage, stop, and mitigate leakage;

(4) Any identified necessary changes to the CCS project Testing and Monitoring Plan and the justification for those changes; and

(5) If data indicate a surface leak of CO_2 from the storage complex, the CCS Project Operator must perform all actions necessary to identify and remediate the leak following the Emergency and Remedial Action Plan in subsection C.6.

4.3.2.3. Seismicity Monitoring

(a) The CCS Project Operator must deploy and maintain a permanent, downhole seismic monitoring system in order to determine the presence or absence of any induced micro-seismic activity associated with all wells and near any discontinuities, faults, or fractures in the subsurface.

(1) The design of the array should consider the seismic risk. Location of small events can be helpful in risk reduction, but sufficient planning is needed to collect and analyze the data. Analysis of the microseismicity must consider if the risk of triggering an earthquake of Richter magnitude 2.7,[10] or greater, is significantly increased by injection. If an increase in risk is detected and determined, mitigation of the risk is required; and

(2) The array should be calibrated with check-shots, preferably at depth.

[10] Updated Underground Injection Control Regulations Pre-Rulemaking Discussion Draft, 04-26-17, Division of Oil, Gas, and Geothermal Resources. Available at http://www.conservation.ca.gov/dog/general_information/Pages/UICupdate.aspx

(b) From commencement of injection activity to its completion, the CCS Project Operator must continuously monitor for indication of an earthquake of magnitude 2.7 or greater occurring within a radius of one mile of injection operations.

(1) A CCS Project Operator in California must continuously monitor the California Integrated Seismic Network, or other equivalent jurisdictional network; or

(2) For CCS projects located out of California, the CCS Project Operator must continuously monitor the U.S. Geological Survey's National Earthquake Information Center and Advanced National Seismic System, or equivalent.

(c) If an earthquake of magnitude 2.7 or greater is identified under subsection C.*4.3.2.3*(b), the following requirements apply:

(1) The CCS Project Operator must immediately notify the Executive Officer when and where (i.e., the epicenter and hypocenter) the earthquake occurred;

(2) CARB, in consultation with the CCS Project Operator and the California Geological Survey, or local geological survey or equivalent, will conduct an evaluation of the following:

(A) Whether there is indication of a causal connection between the injection activity and the earthquake;

(B) Whether there is a pattern of seismic activity in the area that correlates with nearby injection activity; and

(C) Whether the mechanical integrity of any well, facility, or pipeline within the radius specified in subsection C.*4.3.2.3*(b) has been compromised.

(d) If the CCS Project Operator obtains evidence that an earthquake has caused a failure of the mechanical integrity of wells, facilities, or pipelines, which may cause potential CO_2 emissions to the atmosphere, the CCS Project Operator must implement the Emergency Remedial Response Plan pursuant to subsection C.6.

(e) The preliminary results of the seismic evaluation must be reported to the Executive Officer within 30 days following the earthquake, with a final report submitted within 120 days. The report must include, at a minimum:

(1) The date, time, and magnitude of the earthquake;

(2) The location and distance of the epicenter from the CCS project;

(3) The results of the investigation into the link between the injection activity and the earthquake or pattern of seismicity;

(4) Any emergency and remedial actions taken pursuant to subsection C.6;

(5) A description of any investigations and tests conducted to assess the mechanical integrity of wells and other surface equipment, and a demonstration that the well and equipment were either not damaged by the earthquake or that mechanical integrity was restored prior to the re-initiation of injection; and

(6) Any identified changes necessary to the CCS project Testing and Monitoring Plan.

4.3.2.4. Verification

(a) CCS projects must be verified pursuant to sections 95500 through 95503 of the LCFS Regulation, and the requirements of the CCS protocol.

(b) Each verification team must include:

(1) A CARB-accredited oil and gas systems specialist pursuant to the Regulation for the Mandatory Reporting of Greenhouse Gas Emissions section 95131(a); and

(2) A professional geologist licensed under Chapter 12.5 of Division 3 of the California Business and Professions Code §§ 7800 – 7887, or equivalent professional geologist approved by the Executive Officer. An explanation demonstrating that the verification team includes a professional geologist with the required experience and expertise must be included in the Notice of Verification Services.

(3) The required experience and expertise may be demonstrated by a single individual, or by a combination of individuals.

(c) Verification must include a review of the following:

(1) Documentation and maps to verify the boundaries of the project, including the location of monitoring and measurement equipment, and procedures for data quality assurance and quality control; and

(2) The operator's CCS project's risk rating for determining its contribution to the LCFS Buffer Account as calculated under Appendix G.

(3) All plans, assessments, and reports for conformance with the LCFS Regulation and the requirements of this protocol.

(d) Verification of CO_2 leakage.

(1) Within six months of an event that triggers CO_2 leakage, the operator must submit the verified mass of CO_2 leakage as calculated under section C.2.4.4(d). The verification team must review the quantification and methods for determining CO_2 leakage reported by the project operator under section C.2.4.4(d). To verify the mass of CO_2 leakage a full verification must be conducted pursuant to sections 95500 through 95503, including a site visit. The verified mass of CO_2 leakage may be submitted as a separate verification service, or incorporated into a chapter of the detailed verification report submitted pursuant to section 95501(c)(3)(A), if the timing of the verification coincides with annual verification being conducted for the CCS project.

5. Well Plugging and Abandonment and Post-Injection Site Care and Site Closure

5.1. Well Plugging and Abandonment

(a) Well Plugging and Abandonment Plan: The CCS Project Operator must prepare, maintain, and comply with a plan to plug all injection, production, and monitoring wells associated with the CCS project that is acceptable to the Executive Officer.

(b) The CCS Project Operator must demonstrate in the plan that each well will be plugged in a manner that prevents the well from serving as a conduit for fluid or CO_2 leakage out of the storage complex.

(c) The Well Plugging and Abandonment Plan must be submitted as part of the application for Sequestration Site Certification, and the plan must be updated as needed throughout the life of the CCS project.

(d) The Well Plugging and Abandonment Plan must include the following information:

(1) Appropriate tests or measures for determining bottom-hole pressure. Bottom-hole pressure must be used to determine the appropriate density of plugging fluids to achieve static equilibrium prior to plug placement;

(2) Appropriate testing methods to ensure external mechanical integrity as specified in subsection C.4.2. External mechanical integrity testing is required to ensure that the long-string casing and cement left in the ground after the well is plugged will maintain their integrity over time;

(3) The type and number of plugs to be used;

(4) A description and depiction of the placement of each plug, including the elevation of the top and bottom of each plug;

(5) The type, grade, and quantity of material to be used in plugging. The material must be compatible with the CO_2 stream; and

(6) The method of plug placement.

(e) The CCS Project Operator must consider the following when developing the Well Plugging and Abandonment Plan:

(1) The location and thickness of the lowermost sequestration zone and freshwater aquifer-containing strata, which dictate the location of all plugs;

(2) Well construction details, particularly the depth of the bottom of the intermediate and surface casings, which would affect the number of plugs and the types and amount of cement needed;

(3) Types of subsurface formations penetrated by the well and their geochemistry, which may influence both plugging methods and the types of cement needed (for open-hole plugging); and

(4) The composition of the CO_2 stream and formation fluid geochemistry, including any geochemical changes anticipated during the post-injection period, which can affect appropriate plugging and cementing materials.

(f) Prior to the well plugging, the CCS Project Operator must flush each CCS injection well with a buffer fluid, determine bottom-hole pressure, and perform a final external mechanical integrity test.

(g) Prior to plugging each well, the CCS Project Operator must consider the operational and monitoring history of the CCS project and identify whether any information or events warrant amendment of the original Well Plugging and Abandonment Plan. Data that must be considered include:

(1) Monitoring data related to chemistry of the CO_2 plume and formation fluids;

(2) Mechanical integrity testing, including any mechanical integrity problems that may have occurred during the injection phase of the CCS project;

(3) Operational data, such as injection rates or volumes; and

(4) Any significant changes to the CCS project that may affect plugging of a well.

(h) Notice of intent to plug: The CCS Project Operator must notify the Executive Officer in writing pursuant to subsection C.1.1.2, at least 30 days before plugging, conversion, or abandonment of a well. At the discretion of the Executive Officer, a shorter notice period may be allowed.

(i) Amending the Well Plugging and Abandonment Plan: If the CCS Project Operator finds it necessary to change the Well Plugging and Abandonment Plan, a revised plan must be submitted at the same time as providing the notice of intent, pursuant to subsection C.1.1.2, to the Executive Officer for written approval.

(j) The CCS Project Operator must receive written approval from the Executive Officer before plugging the well, and must plug and abandon the well in accordance with subsections C.5.1(d) through C.5.1(g) in this section, as provided in the Well Plugging and Abandonment Plan.

(k) Plugging report: Within 60 days after plugging, the CCS Project Operator must submit, pursuant to subsection C.1.1.2, a plugging report to the Executive Officer. The report must be certified as accurate by the CCS Project Operator and by the person who performed the plugging operation (if other than the CCS Project Operator). The CCS Project Operator must retain the well plugging and abandonment report for 10 years following site closure. The report must include:

(1) A statement that the well was plugged in accordance with the Well Plugging and Abandonment Plan previously approved by the Executive Officer; or

(2) If the actual plugging differed from the approved plan, a statement describing the actual plugging and an updated plan specifying the differences from the plan previously submitted; and

(3) A statement that the well was inspected using approved detection methods and found to have no leaks.

(l) Temporary Abandonment: The CCS Project Operator must continue to comply with the conditions of the Permanence Certification, including all monitoring and reporting requirements according to the frequencies outlined in the Permanence Requirements and documentation. The well must also be tested to ensure that it maintains mechanical integrity, according to the requirements and frequency specified in subsection C.4.2.

(1) After a cessation of operations of 24 months, the CCS Project Operator must plug and abandon the well, or group of wells, in accordance with the Executive Officer-approved Well Plugging and Abandonment Plan unless he or she:

(A) Provides notice to CARB; and

(B) Describes actions or procedures, satisfactory to CARB, which the CCS Project Operator will take to ensure that the well will not endanger public health and/or the environment during the period of temporary abandonment. These actions and procedures must include compliance with the technical requirements applicable to active wells unless waived by CARB.

5.2. Post-Injection Site Care and Site Closure

(a) The CCS Project Operator must prepare, maintain, and comply with a plan for post-injection site care and site closure that meets the requirements of subsection C.5.2(a)(2).

(1) The CCS Project Operator must submit the Post-Injection Site Care and Site Closure Plan as a part of the application for Sequestration Site Certification.

(2) Post-Injection Site Care and Site Closure Plan. The plan for site care and closure must include the following information:

(A) The pressure differential between pre-injection and predicted post-injection pressures in the sequestration zone, and the predicted timeframe in which pressure is expected to reach a stable level;

(B) A depiction of the predicted three-dimensional extent of the CO_2 free-phase CO_2 plume and associated elevated pressure at the time of site closure as demonstrated in the final validated computational model required at subsections C.2.4 and C.2.4.1;

(C) A description of post-injection monitoring location, methods, and proposed frequency; and

(D) A proposed schedule for submitting post-injection site care monitoring results to the Executive Officer.

(3) Upon injection completion, the CCS Project Operator must either submit an amended Post-Injection Site Care and Site Closure Plan or demonstrate to the Executive Officer through monitoring data and modeling results that no amendment to the plan is needed. Any amendments to the Post-Injection Site Care and Site Closure Plan must be approved by the Executive Officer and incorporated into the Permanence Certification.

(4) At any time during the life of the CCS project, the CCS Project Operator may modify and resubmit the Post-Injection Site Care and Site Closure Plan for the Executive Officer's approval.

(b) Post-injection site care and monitoring:

(1) The CCS Project Operator must monitor the site following injection completion to determine the three-dimensional extent of the free-phase CO_2 plume and elevated pressure, and demonstrate that no CO_2 leakage is occurring, as specified in the Testing and Monitoring Plan and the Post-Injection Site Care and Site Closure Plan.

(2) After injection is complete, the CCS Project Operator must continue to conduct monitoring as specified in this section and Post-Injection Site Care and Site Closure Plan for a minimum of 100 years.

(3) Post-injection site care and monitoring requirements are as follows:

(A) Within 24 months after the CCS project enters into the post-injection site care period, all injection (and production, if applicable) wells associated with the CCS project must be plugged and abandoned pursuant subsection C.5.1(d), with the exception of any wells that the CCS Project Operator plans to transition into observation or monitoring wells.

(B) Monitoring and observation wells may remain open, and in active monitoring mode, until the Executive Officer approves of the CCS Project Operator's demonstration that plume stabilization has occurred pursuant to subsection C.5.2(b)(3)(C). Risk reduction must be prioritized, and remote sensing methods and surveillance outside and above the CO_2 plume must be adopted as wells that penetrate the plume are plugged.

(C) No sooner than 15-years post injection completion, the CCS project operator may submit evidence to CARB that plume stabilization has occurred. Such evidence must include modeling pursuant to subsection C.2.4.4, updated using operational and post-injection monitoring measurements. The evidence must also include measured plume migration rates. In order for CARB to determine that plume stabilization has occurred, the evidence must show that plume migration over a 100-year period would not result in CO_2 leakage, that the modeling shows good conformance with measurements, and that overall CO_2 leakage risk is reduced. Following verification, CARB will use the submitted evidence to determine whether plume stabilization has occurred.

(D) If a monitoring well is discovered to be leaking at any time during the post-injection monitoring period, the CCS Project Operator must take all necessary measures to identify the cause of the leak and remediate it. If the leak cannot be remediated, the well must immediately be plugged and abandoned pursuant to subsection C.5.1(d). If necessary, a new well must be drilled to continue monitoring for plume stabilization.

(E) As part of post-injection monitoring, and pursuant to the monitoring timeline as specified in the Post-Injection Site Care and Site Closure Plan, the CCS Project Operator must:

1. Perform quarterly bottom-hole pressure measurements in the monitoring wells in order to track pressure changes. Frequency of measurement may be adjusted based on the previously measured rate of change, provided the CCS Project Operator provides a justification for an alternative monitoring strategy;

2. Use appropriate best-practice methods to map the three dimensional extent of the free-phase CO_2 plume and elevated pressure ; and

3. Periodically update the plume extent modeling pursuant to subsection C.2.4 to determine if any corrective action is necessary and to establish if the CO_2 plume has stabilized.

(F) Once plume stabilization has been determined by CARB to have occurred, pursuant to subsection 5.1(b)(3)(C), all CCS project wells may be abandoned following subsection C.5.1(d).

(G) For the remainder of the post-injection site care and monitoring period following Executive Officer approval of the demonstration of plume stabilization, the CCS Project Operator must implement a leak detection strategy:

1. In the near surface strategically located near plugged and abandoned wells, using ground-based methods. Aerial technologies with a likelihood of detecting leakage from wells in the near-surface equivalent to that of ground-based methods may be used, pending approval of the Executive Officer;

2. At areas of concern determined by the risk assessment (following subsection C.2.2) to be potential pathways for the preferential migration of CO_2 or brine to surface, during the post-injection site care and monitoring period at a frequency based on monitoring and verification data collected during injection and using methods approved by the Executive Officer, at a minimum of once every five years;

3. Using methods that can be verified and provide the following data, at a minimum:

   i. Date and time of site visit or visual inspection;

ii. GPS coordinates for any samples collected, measurements recorded, and locations of pertinent areas/points of concern (e.g., plugged and abandoned wells);

iii. Photographs documenting site conditions on date of inspection; and

iv. Appropriate baseline and background measurements collected prior to reaching plume stability.

4. If the inspection checks suggest a potential leak may have occurred, the area must be tested pursuant to subsection C.4.3.2.

(H) The CCS Project Operator must submit the results of all monitoring performed according to the schedule identified in the Post-Injection Site Care and Site Closure Plan.

(c) Notice of intent for site closure. The CCS Project Operator must notify the Executive Officer at least 120 days before site closure. At this time, if any changes have been made to the original Post-Injection Site Care and Site Closure Plan, the CCS Project Operator must also provide the revised plan.

(d) After the Executive Officer has authorized site closure, the CCS Project Operator must plug all monitoring wells as specified in the Post-Injection Site Care and Site Closure Plan, in a manner in which will not allow movement of injection or formation fluids out of the storage complex. At the direction of the Executive Officer, the CCS Project Operator must also restore the site to a condition agreed to with the Executive Officer, as close to pre-injection conditions as practicable.

(e) The CCS Project Operator must submit a site closure report to the Executive Officer within 90 days of site closure, which must thereafter be retained at a location designated by the Executive Officer for 10 years. The report must include:

(1) Documentation of appropriate injection and monitoring well plugging and abandonment as specified in subsections C.5.1, C.5.2(b)(3)(A), and C.5.2(b)(3)(G). The CCS Project Operator must provide a copy of a survey plat, which has been submitted to the local zoning authority designated by the Executive Officer. The plat must indicate the location of the injection well relative to permanently surveyed benchmarks;

(2) Documentation of appropriate notification and information to such state, federal, local, and tribal authorities that have authority over drilling activities to enable such state, federal, local, and tribal authorities to impose appropriate conditions on subsequent drilling activities that may penetrate the storage complex; and

(3) Records reflecting the nature, composition, and volume of the CO_2 stream.

(f) Within six months after completion of injection, each CCS Project Operator must record a notation on the deed to the CCS project property or any other document that is normally examined during title search that will in perpetuity provide any potential purchaser of the property the following information:

(1) The fact that land has been used to sequester CO_2;

(2) The name of the state agency and local authority with which the survey plat was filed; and

(3) The volume of fluid injected, the sequestration zone into which it was injected, and the period over which injection occurred.

(g) The CCS Project Operator must retain for 10 years following site closure, records collected during the post-injection site care period.

6. Emergency and Remedial Response

(a) As part of the application for Sequestration Site Certification, the CCS Project Operator must provide the Executive Officer with an Emergency and Remedial Response Plan that describes actions the CCS Project Operator must take in the event of an emergency at the site that has the potential to endanger public health or the environment during construction, operation, and post-injection site care periods.

(b) If the CCS Project Operator obtains evidence any CCS project operations have the potential to endanger public health or the environment, either by surface injection facility operations or CO_2 or formation fluid leakage, the CCS Project Operator must:

(1) Immediately cease injection in affected well(s) and any other wells that may exacerbate risk of leakage in the affected well(s);

(2) Take all steps reasonably necessary to identify, characterize, and quantify any CO_2 leakage;

(3) Notify the Executive Officer in writing within 24 hours; and

(4) Implement the Emergency and Remedial Response Plan.

(c) The Executive Officer may allow the CCS Project Operator to resume injection prior to remediation if the CCS Project Operator demonstrates that the injection operation will not endanger public health and the environment.

(d) The CCS Project Operator must periodically review the Emergency and Remedial Response Plan developed under subsection C.6(a), which must include:

(1) At a frequency specified in the Storage Complex and Corrective Action Plan, or more frequently when monitoring, operational, or other relevant conditions warrant, the CCS Project Operator must review and update the Emergency and Remedial Response Plan or demonstrate to the Executive officer that no update is needed. The CCS Project Operator must also incorporate monitoring, operational data, or other relevant data and in response to storage complex reevaluations required under subsection C.2.4.4 or demonstrate to the Executive Officer that no update is needed. The amended Emergency and Remedial Response Plan or demonstration must be submitted to the Executive Officer as follows:

(A) Within one year of a storage complex reevaluation;

(B) Following any significant changes to the CCS project, such as addition of injection or monitoring wells, on a schedule determined by the Executive Officer; or

(C) When required by the Executive Officer.

(e) Following each update of the Emergency and Remedial Response Plan or a demonstration that no update is needed, the CCS Project Operator must submit the resultant information to the Executive Officer for review and confirmation of the results.

6.1. Emergency and Remedial Response Requirements

(a) The Emergency and Remedial Response Plan must describe the response actions that would be necessary in the event of an emergency at the site. The plan must ensure that site operators know which entities and individuals are to be notified and what actions need to be taken to mitigate an emergency situation and protect public health and safety and the environment. The Emergency and Remedial Response Plan must be based on the site risk assessment pursuant to subsection C.2.2.

(b) Response actions should depend on the severity of the event(s) that triggered an emergency response. Emergency events are characterized in Table 3.

Table 2. Degrees of risk for emergency events

Emergency Condition	Description
Major Emergency	Event poses immediate substantial risk to human health, resources, or infrastructure. Emergency actions involving local authorities (evacuation or isolation of areas) should be initiated.
Serious Emergency	Event poses potential serious (or significant) near term risk to human health, resources, or infrastructure if conditions worsen or no response actions are taken.
Minor Emergency	Event poses no immediate risk to human health, resources, or infrastructure.

(c) The Emergency and Remedial Response Plan must include the following:

(1) A list and description of possible risk scenarios that could potentially call for emergency response at the site, including but not limited to:

(A) Injection, production, or monitoring well integrity failure;

(B) Well injection or monitoring equipment failure;

(C) Fluid (e.g., CO_2 or formation fluid) leakage to the land surface and atmosphere;

(D) A natural disaster with effects that could impact site operations (e.g. earthquake or lightning strike); or

(E) Induced seismic event.

(2) A list and description of the potential consequences of the risk scenarios.

(3) A list and description of local resources and infrastructure that may be impacted as a result of an emergency at the CCS project site, including but not limited to:

(A) Freshwater aquifers, potable water wells, surface water such as rivers or lakes, farmland, and public land or nature preserves; and

(B) Residential areas, commercial properties, recreational facilities, topographic depressions, and basements.

(4) A list and description of any steps needed to identify, characterize, and respond to each potential risk scenario listed pursuant to subsection C.6.1(a)(1) in this section, including:

(A) Emergency identification, for example:

1. Activation of automatic shutdown devices due to well integrity failure;

2. Malfunction of monitoring equipment for pressure or temperature that may indicate a problem with the injection well and possible endangerment of public health and the environment;

3. Detections of elevated concentrations of CO_2 or other evidence of CO_2 leakage to the land surface;

4. Detections of elevated values of indicator parameters in groundwater samples or other evidence of brine or CO_2 leakage into freshwater aquifers or surface water; or

5. A natural disaster such as a weather-related disaster that may impact surface facilities or an earthquake that may disturb subsurface facilities.

(B) Response actions planned, including but not limited to:

1. Notification to the site supervisor or designee;

2. Notification to the Executive Officer in writing within 24 hours of the emergency event, per subsection C.6(b)(3);

3. Initial assessment of the situation by the site supervisor or designee and the determination of which other CCS project personnel to notify;

4. The determination of the severity of the event, based on the information available by the site supervisor or designee, within 24 hours of the event; and

5. Emergency and remedial actions to be taken to stop or limit the risk of endangerment to public health and the environment due to the type and severity of the event.

(5) A list of site personnel, CCS project personnel, and local authorities, and their contact information.

(6) A list of any special equipment needed in the event of an emergency. The type of equipment needed in the event of an emergency, as remedial response varies depending on the triggering event. Response actions (e.g., injection completion or hiatus, well shut-in, or evacuation) will generally not require specialized equipment to implement. Where specialized equipment

(such as a drilling rig) is required, the designated Project Manager must be responsible for its procurement.

(7) A site-specific emergency communications plan, including the designation of a public and media communications liaison, which must be developed and maintained throughout the life of the CCS project.

(8) The timeline for review of the Emergency and Remedial Response Plan, no less than once every five years following its approval by the permitting agency, within one year following a storage complex reevaluation, and within a prescribed period to be determined by CARB following any significant changes to the injection process or CCS project. If the review indicates that no amendments to the Emergency and Remedial Response Plan are necessary, the CCS Project Operator must provide the Executive Officer with documentation supporting such a determination. If the review indicates that amendments to the Emergency and Remedial Response Plan are necessary, amendments must be made and submitted to the CARB within one year following an event that initiates the Emergency and Remedial Response Plan review procedure.

7. Financial Responsibility

(a) The CCS Project Operator of a certified CCS project must demonstrate and maintain financial responsibility and resources as determined by the Executive Officer that meets the following conditions:

(1) The financial responsibility instrument(s) used must be from the following list of qualifying instruments:

(A) Trust Funds;

(B) Surety Bonds;

(C) Letter of Credit;

(D) Insurance;

(E) Self-Insurance (i.e., Financial Test and Corporate Guarantee);

(F) Escrow Account; and

(G) Any other instrument(s) satisfactory to the Executive Officer.

(2) The qualifying instrument(s) must be sufficient to cover the cost of:

(A) Corrective action (that meets the requirements of subsection C.2.4.3);

(B) Well plugging and abandonment (that meets the requirements of subsection C.5.1);

(C) Post-injection site care and site closure (that meets the requirements of subsection C.5.2); and

(D) Emergency and remedial response (that meets the requirements of subsection C.6).

(3) The financial responsibility instrument(s) must be sufficient to address the potential endangerment of public health and the environment via atmospheric CO_2 leakage.

(4) The qualifying financial responsibility instrument(s) must comprise protective conditions of coverage.

(A) Protective conditions of coverage must include at a minimum: cancellation, renewal, and continuation provisions, specifications on when the provider becomes liable following a notice of cancellation if there is a failure to renew (with a new qualifying financial instrument), as well as requirements for the provider to meet a minimum rating, minimum capitalization, and ability to pass the bond rating when applicable.

1. For purposes of this part, a CCS Project Operator must provide that their financial mechanism may not cancel, terminate or fail to renew except for failure to pay such financial instrument. If there is a failure to pay the financial instrument, the financial institution may elect to cancel, terminate, or fail to renew the instrument by sending notice by certified mail and an electronic format to the CCS Project Operator and the Executive Officer. The cancellation must not be final for 120 days after receipt of cancellation notice. The CCS Project Operator must provide an alternate financial responsibility demonstration within 60 days of notice of cancellation, and if an alternate financial responsibility demonstration is not acceptable (or possible), any funds from the instrument being cancelled must be released within 60 days of notification by the Executive Officer to complete required activities that the financial responsibility instrument are expected to cover, as described in subsection C.7(a)(2).

2. For purposes of this part, the CCS Project Operator must renew all financial instruments, if an instrument expires, for the entire term of the CCS project. The instrument may be automatically renewed as long as the CCS Project Operator has the option of renewal at the face amount of the expiring instrument. The automatic renewal of the

instrument must, at a minimum, provide the holder with the option of renewal at the face amount of the expiring financial instrument.

3. Cancellation, termination, or failure to renew may not occur and the financial instrument will remain in full force and effect in the event that on or before the date of expiration: (1) the Executive Officer deems the CCS project abandoned, (2) the permit is terminated or revoked or a new permit is denied, (3) closure is ordered by the Executive Officer or a U.S. district court or other court of competent jurisdiction, (4) the CCS Project Operator is named as debtor in a voluntary or involuntary proceeding under Title 11 (Bankruptcy), U.S. Code, or (5) the amount due is paid.

(5) The qualifying financial responsibility instrument(s) must be approved by the Executive Officer.

(A) The financial responsibility demonstration must be considered and approved by the Executive Officer for all phases of the CCS project prior to Permanence Certification following subsection C.1.1.

(B) The CCS Project Operator must provide updated information related to their financial responsibility instrument(s) when/if there are any changes. This information must be provided to the Executive Officer within 30 days of such a change. The Executive Officer will evaluate, within a reasonable time, the financial responsibility demonstration to confirm that the instrument(s) used remain adequate for use. The CCS Project Operator must maintain financial responsibility requirements regardless of the status of the Executive Officer's review of the financial responsibility demonstration.

(C) The Executive Officer may disapprove the use of a financial instrument if they determine that it is not sufficient to meet the requirements of this section.

(6) The CCS Project Operator must demonstrate financial responsibility by using one or multiple qualifying financial instruments for specific phases of the CCS project.

(A) In the event that the CCS Project Operator combines more than one instrument for a specific CCS phase (e.g., well plugging), such combination must be limited to instruments that are not based on financial strength or performance (i.e., self-insurance or performance bond), for example trust funds, surety bonds guaranteeing payment into a trust fund, letters of credit, escrow account, and insurance. In this case, it is the combination of mechanisms, rather than the single mechanism, which must provide financial responsibility for an amount at least equal to the current cost estimate.

(B) When using a third-party instrument to demonstrate financial responsibility, the CCS Project Operator must provide a proof that the third-party providers either have passed financial strength requirements based on credit ratings, or has met a minimum rating, minimum capitalization, and ability to pass the bond rating when applicable.

(C) A CCS Project Operator using certain types of third-party instruments must establish a standby trust to enable CARB to be party to the financial responsibility agreement without CARB being the beneficiary of any funds. The standby trust fund must be used along with other financial responsibility instruments (e.g., surety bonds, letters of credit, or escrow accounts) to provide a location to place funds if needed.

(D) A CCS Project Operator may deposit money to an escrow account to cover financial responsibility requirements, and this account must segregate funds sufficient to cover estimated costs for CCS project financial responsibility from other accounts and uses.

(E) A CCS Project Operator or its guarantor may use self-insurance to demonstrate financial responsibility for CCS projects. In order to satisfy this requirement the CCS Project Operator must meet a tangible net worth of an amount approved by the Executive Officer, have a Net working capital and tangible net worth each at least six times the sum of the current well plugging, post injection site care and site closure cost, have assets located in the United States amounting to at least 90 percent of total assets or at least six times the sum of the current well plugging, post injection site care and site closure cost, and must submit a report of its bond rating and financial information annually. In addition the CCS Project Operator must either: Have a bond rating test of AAA, AA, A, or BBB as issued by Standard & Poor's, Aaa, Aa, A, or Baa as issued by Moody's, or meet all of the following five financial ratio thresholds:

1. A ratio of total liabilities to net worth less than 2.0;

2. A ratio of current assets to current liabilities greater than 1.5;

3. A ratio of the sum of net income plus depreciation, depletion, and amortization to total liabilities greater than 0.1;

4. A ratio of current assets minus current liabilities to total assets greater than −0.1; and

5. A net profit (revenues minus expenses) greater than 0.

(F) A CCS Project Operator who is not able to meet corporate financial test criteria may arrange a corporate guarantee by demonstrating that its corporate parent meets the financial test requirements on its behalf. The parent's demonstration that it meets the financial test requirement is insufficient if it has not also guaranteed to fulfill the obligation for the CCS Project Operator.

(G) A CCS Project Operator may obtain an insurance policy to cover the estimated costs of CCS activities requiring financial responsibility. This insurance policy must be obtained from a third-party provider.

(b) The CCS Project Operator must maintain financial responsibility and resources until:

(1) The Executive Officer receives and approves the completed Post-Injection Site Care and Site Closure Plan; and

(2) The Executive Officer approves site closure.

(c) The CCS Project Operator may be released from financial instrument in the following circumstances:

(1) The CCS Project Operator has completed the phase of the CCS project for which the financial instrument was required and has fulfilled all its financial obligations as determined by the Executive Officer, including obtaining financial responsibility for the next phase of the CCS project, if required; or

(2) The CCS Project Operator has submitted a replacement financial instrument and received written approval from the Executive Officer accepting the new financial instrument and releasing the CCS Project Operator from the previous financial instrument.

(d) The CCS Project Operator must have a detailed written estimate, in current dollars, of the cost of performing corrective action on all wells that either penetrate the storage complex or are within the surface projection of the storage complex, plugging the well(s), post-injection site care and site closure, and emergency and remedial response.

(1) The cost estimate must be performed for each phase separately and must be based on the costs to the regulatory agency of hiring a third party to perform the required activities. A third party is a party who is not within the corporate structure of the CCS Project Operator.

(2) During the active life of the CCS project, the CCS Project Operator must adjust the cost estimate for inflation within 60 days prior to the anniversary

date of the establishment of the financial instrument(s) used to comply with subsection C.7(a) and provide this adjustment to the Executive Officer. The CCS Project Operator must also provide the Executive Officer written updates of adjustments to the cost estimate within 60 days of any amendments to the Corrective Action Plan, the Well Plugging and Abandonment Plan, the Post-Injection Site Care and Site Closure Plan, and the Emergency and Remedial Response Plan.

(3) Any decrease or increase to the initial cost estimate must be approved by the Executive Officer. During the active life of the CCS project, the CCS Project Operator must revise the cost estimate no later than 60 days after the Executive Officer has approved the request to modify the Corrective Action Plan, the Injection Well Plugging and Abandonment Plan, the Post-Injection Site Care and Site Closure Plan, and the Emergency and Remedial Response Plan, if the changes in the plan increases the cost. If the change to the plans decreases the cost, any withdrawal of funds must be approved by the Executive Officer. Any decrease to the value of the financial assurance instrument must first be approved by the Executive officer. The revised cost estimate must be adjusted for inflation as specified at subsection C.7(c)(2).

(4) Whenever the current cost estimate increases to an amount greater than the face amount of a financial instrument currently in use, the CCS Project Operator, within 60 days after the increase, must either cause the face amount to be increased to an amount at least equal to the current cost estimate and submit evidence of such increase to the Executive Officer, or obtain other financial responsibility instruments to cover the increase. Whenever the current cost estimate decreases, the face amount of the financial assurance instrument may be reduced to the amount of the current cost estimate only after the CCS Project Operator has received written approval from the Executive Officer.

(e) The CCS Project Operator must notify the Executive Officer by an electronic format and certified mail of adverse financial conditions such as bankruptcy that may affect the ability to carry our injection well plugging and post-injection site care and site closure.

(1) In the event that the CCS Project Operator or the third-party provider of a financial responsibility instrument is going through a bankruptcy, the CCS Project Operator must notify the Executive Officer by certified mail and an electronic format of the commencement of a voluntary or involuntary proceeding under Title 11 (Bankruptcy), U.S. Code, naming the CCS Project Operator as debtor, within 10 days after commencement of the proceeding.

(2) A guarantor of a corporate guarantee must make such a notification to the Executive Officer if he/she is named as debtor, as required under the terms of the corporate guarantee.

(3) A CCS Project Operator who fulfills the requirements of subsection C.7(a) by obtaining a trust fund, surety bond, letter of credit, escrow account, or insurance policy will be deemed to be without the required financial assurance in the event of bankruptcy of the trustee or issuing institution, or a suspension or revocation of the authority of the trustee institution to act as trustee of the institution issuing the trust fund, surety bond, letter of credit, escrow account, or insurance policy. The CCS Project Operator must establish other financial assurance within 60 days after such an event.

(f) The CCS Project Operator must provide an adjustment of the cost estimate to the Executive Officer within 60 days of notification by the Executive Officer, if the Executive Officer determines during the annual evaluation of the qualifying financial responsibility instrument(s) that the most recent demonstration is no longer adequate to cover the cost of corrective action (as required by subsection C.2.4.3), well plugging and abandonment (as required by subsection C.5.1), post-injection site care and site closure (as required by subsection C.5.2), and emergency and remedial response (as required by subsection C.6).

(g) The use and length of pay-in-periods for trust funds or escrow accounts must be approved by the Executive Officer.

8. Modification or Revocation and Reissuance of Permanence Certification

(a) When the Executive Officer receives any information, including but not limited to, (1) information submitted by the CCS Project Operator as required by the Permanence Certification, (2) receives a request for modification or evocation and reissuance of the Permanence Certification, or (3) inspects the facility or conducts a review of the Permanence Certification, he or she may determine whether or not one or more of the causes listed in subsections C.8(b) and C.8(c) of this section exist requiring a modification or revocation and reissuance of the Permanence Certification, or both. If cause exists, the Executive Officer may modify or revoke and reissue the Permanence Certification accordingly, and may request an updated Permanence Certification if necessary. When a Permanence Certification is modified, only the conditions subject to modification are reopened. If a Permanence Certification is revoked and reissued, the entire Permanence Certification is reopened and subject to revision and the permit is reissued for a new term. If a Permanence Certification modification satisfies the criteria in subsection C.8.2 for “minor modifications,” the Permanence Certification may be modified without a draft Permanence Certification and public review. Otherwise, the Executive Officer will post the draft Permanence Certification for public comment for at least 15 days, address those comments if considered valid, and then issue an executive order endorsing the permanence of the CCS project, if appropriate.

(b) Causes for modification or revocation and reissuance.

(1) Alterations. There are material and substantial alterations or additions to the certified CCS project or activity which occurred after issuance of the Permanence Certification, and which justify the application of conditions that are different or absent in the existing Permanence Certification.

(2) Information. Permanence Certifications may be modified during their terms for this cause only if the information was not available at the time of issuance of the Permanence Certification (other than revised regulations, guidance, or test methods) and would have justified the application of different conditions of Permanence Certification at the time of issuance.

(3) New regulations. The standards or regulations on which the Permanence Certification was based have been changed by promulgation of new or amended standards or regulations or by judicial decision after the Permanence Certification was issued.

(4) Compliance schedules. The Executive Officer determines good cause exists for modification of a compliance schedule, such as a strike, flood, or materials shortage or other events over which the certified CCS Project Operator has little or no control and for which there is no reasonably available remedy. (See also subsection C.8.2(a)(3)).

(5) Basis for modification of Permanence Certifications. Additionally, whenever the Executive Officer determines that changes to the Permanence Certification are necessary, based on:

(A) Storage complex reevaluations under subsection C.2.4.4;

(B) Any amendments to the Testing and Monitoring Plan under subsection C.4.1;

(C) Any amendments to the Well Plugging and Abandonment Plan under subsection C.5.1;

(D) Any amendments to the Post-Injection Site Care and Site Closure Plan under subsection C.5.2;

(E) Any amendments to the Emergency and Remedial Response Plan under subsection C.6;

(F) A review of monitoring and/or testing results conducted in accordance with Permanence Certification requirements.

(c) Causes for modification or revocation and reissuance of Permanence Certification. Cause exists to modify or, alternatively, revoke and reissue Permanence Certification if the Executive Officer determines cause exists for termination under subsection C.8.1(a), and the Executive Officer determines that modification or revocation and reissuance is appropriate.

8.1. Termination of Permanence Certifications

(a) The Executive Officer may terminate a Permanence Certification during its term, or deny a Permanence Certification renewal application for the following causes:

(1) Noncompliance by the CCS Project Operator with any condition of the Permanence Certification;

(2) The CCS Project Operator’s failure in the application or during the Permanence Certification issuance process to disclose fully all relevant facts, or the CCS Project Operator's misrepresentation of any relevant facts at any time; or

(3) A determination that any CCS injection activity endangers public health or the environment via CO_2 or formation fluid leakage, and can only be regulated to acceptable levels by modification or termination of Permanence Certification.

8.2. Minor Modification of Permanence Certifications

(a) Upon the consent of the CCS Project Operator, the Executive Officer may modify a Permanence Certification to make the corrections or allowances for changes in the certified CCS project activity listed in this section, without following the procedures of subsection C.8(a). Any modification to the Permanence Certification not processed as a minor modification under this section must be made for cause and pursuant to draft Permanence Certification and public notice as required in subsection C.8(a). Minor modifications may only:

(1) Correct typographical errors;

(2) Require more frequent monitoring or reporting by the CCS Project Operator;

(3) Change an interim compliance date in a schedule of compliance, provided the new date is not more than 120 days after the date specified in the existing Permanence Certification and does not interfere with attainment of the final compliance date requirement; or

(4) Allow for a change in ownership or operational control of a CCS project where the Executive Officer determines that no other change in Permanence Certification is necessary, provided that a written agreement containing a specific date for transfer of responsibility, coverage, and liability between the

current and new CCS Project Operator has been submitted to the Executive Officer.

(5) Change quantities or types of fluids injected which are within the capacity of the facility as certified and, in the judgment of the Executive Officer, would not interfere with the operation of the CCS project or its ability to meet conditions described in the Permanence Certification.

(6) Change in construction requirements approved by the Executive Officer, provided that any such alteration must comply with the requirements of this section and subsection C.3.1.

(7) Amend a plugging and abandonment plan which has been updated under subsection C.5.

(8) Amend a CCS Well Testing and Monitoring Plan, Plugging Plan, Post-Injection Site Care and Site Closure Plan, or Emergency and Remedial Response Plan where the modifications merely clarify or correct the plan, as determined by the Executive Officer.

9. Legal Understanding, Contracts, and Post-Closure Care

(a) The CCS Project Operator must show proof of exclusive right to use the pore space in the sequestration zone for storing CO_2 permanently;

(b) Full disclosure must be made to inform future land management or development within the surface projection of the storage complex. For example, the restrictions and disclosure must be recorded on the deeds of the land when no regulations are in place to address this issue; and

(c) The CCS Project Operator must show proof that there is binding agreement among relevant parties that drilling or extraction that penetrate the storage complex are prohibited to ensure public safety and the permanence of stored CO_2.

This Page Left Intentionally Blank

Appendix A. Fugitive and Vented GHG Emissions: Injection into Depleted Oil and Gas and Saline Formations

(a) Fugitive CO_2 Emissions: Equipment Count Method

Count each component (e.g., valves, connectors, open-ended lines) individually for the facility and multiply with default emission factors specific to component type. Alternatively, count the number of major pieces of equipment and multiply by the average number of components per major piece of equipment to arrive at the total number of each component for a facility. Calculate fugitive CO_2 emissions using Equation A.1.

$$E_{s,i} = \sum Count_i \times EF_i \times C_{CO2} \times T_s \quad \text{(A.1)}$$

Where:

$E_{s,i}$ = Annual volumetric fugitive CO_2 emissions at standard conditions from i^{th} component in cubic feet.

$Count_i$ = Total number of i^{th} component at the facility.

EF_i = Emission factor for i^{th} component (scf/hour). Use a default CO_2 emission factor if available. Methane emission factors can be used as proxy for CO_2 emission factors.

C_{CO2} = CO_2 concentration (%).

T_s = Total time that each component type associated with the equipment leak emission was operational per year, in hours, using engineering estimate based on best available data.

$E_{s,i}$ must be converted to MT CO_2/year using the method described in Appendix C to obtain estimate $CO_{2_{fugitive}}$ included in previous equations.

(b) Vented Emissions: Event-Based Approach

Calculate vented CO_2 emissions by measuring/estimating CO_2 emissions per venting event, and account for CH_4 emissions for all venting events at storage site per year using Equation A.2.

$$GHG_{vent} = \sum_{i=1}^{n} Vi \quad \text{(A.2)}$$

Where:

GHG_{vent} = Annual vented CO_2 and CH_4 emissions (MT CO_2e/year).

Vi = Vented CO_2 and CH_4 emissions for i^{th} vented event (MT CO_2e/event).

This Page Left Intentionally Blank

Appendix B. CO_2 Venting and Fugitive Emissions from CO_2-EOR Operations

(a) Metered natural gas pneumatic device and pump vented CO_2 emissions.

(1) Calculate CO_2 emissions from a natural gas-powered continuous high bleed control device and pneumatic pump vented using the method specified in section 95153(a) in the Regulation for the Mandatory Reporting of Greenhouse Gas Emissions (MRR)[11] when the natural gas flow to the device is metered.

(b) Non-metered natural gas pneumatic device vented emissions.

(1) Calculate CO_2 emissions from all non-metered natural gas-powered pneumatic intermittent bleed and continuous low and high bleed devices using the equation in section 95153(a) of MRR.

(c) Acid gas removal vents.

(1) For AGR vents (including processes such as amine, membrane, molecular sieve or other absorbents and adsorbents), calculate emissions for CO_2 only (not CH_4) vented directly to the atmosphere or emitted through a flare, engine (e.g., permeate from a membrane or de-adsorbed gas from a pressure swing adsorber used as fuel supplement), or sulfur recovery plant using the applicable calculation methodologies described in section 95153(c) of MRR.

(d) Dehydrator vents.

(1) Calculate annual CO_2 emissions using any of the calculation methodologies described in section 95153(d) of MRR.

(e) Gas well vented CO_2 emissions during well completions and workovers.

(1) Use either the Methodology 1 or 2 described in section 95153(f) of MRR.

(f) Equipment and pipeline blowdowns.

(1) Calculate CO_2 blowdown emissions from depressurizing equipment and natural gas pipelines to reduce system pressure for shutdowns resulting from human intervention or to take equipment out of service for maintenance (excluding depressurizing to a flare, over-pressure relief, operating pressure control vented and blowdown of non-GHG gases using the methods described in 95153(g). Desiccant dehydrator blowdown vented before reloading is covered in section 95153 (d) of MRR.

---

[11] Final Regulation Order, Amendments to the Regulation, Mandatory Reporting of Greenhouse Gas Emissions Regulation. CARB, filed with Secretary of State September 1, 2017.

(g) Dump valves.

(1) Calculate CO_2 emissions from gas-liquid separator liquid dump valves not closing by using the method found in section 95153(i) of MRR.

(h) Well testing vented emissions.

(1) Calculate CO_2 vented from oil well testing using the methods found in section 95153(j) of MRR.

(i) Associated gas.

(1) Calculate CO_2 in associated gas vented not in conjunction with well testing using the methods found in section 95153(k) of MRR.

(j) Centrifugal compressor vented emissions.

(1) Calculate CO_2 emissions from both wet seal and dry seal centrifugal compressor using the methods described in section 95153(m) of MRR.

(k) Reciprocating compressor vented emissions.

(1) Calculate CO_2 emissions from all reciprocating compressor vents using the methods described in section 95153 of MRR.

(l) EOR injection pump blowdown emissions.

(1) Calculate CO_2 pump blowdown emissions from EOR operations using critical CO_2 injection using Equation 33 as described in section 95153(u) of MRR.

(m) Fugitive CO_2 emissions from valves, connectors, open ended lines, pressure relief valves, pumps, flanges, and other equipment leak sources (such as instruments, loading arms, stuffing boxes, compressor seals, dump lever arms, and breather caps).

(1) Perform leak detection tests in accordance with procedures as described in the MRR. If CO_2 leakage is detected from the equipment listed above during annual leak detection tests, calculate fugitive emissions (CO_2) per component type in which leak is detected using Equation 25 in section 95153(o) of MRR for each component type. Default fugitive emission factors for Equation 25 are reported in Tables E4 to E6; or

(2) Calculate fugitive emissions from all equipment using the population count and emission factors as described in section 95153(p) of MRR.

Appendix C. Converting Volume of CO_2 to Mass

(a) When volumetric emissions of CH_4 and CO_2 are measured at actual temperatures and pressures, convert them to volumetric emissions at standard conditions (25˚C and 1 atm) using Equation30 in MRR.

(b) Calculate GHG mass emissions by converting the GHG volumetric emissions at standard conditions into mass emissions using Equation 32 described in section 95153(t) of MRR.

This Page Left Intentionally Blank

Appendix D. Data Measurement/Generation and Reporting for Energy and Chemical Inputs

(a) Amounts of fuels used:

(1) Fuel receipts/invoices or flow meter readings whichever applicable;

(2) The flow meter readings must be corrected for temperature and pressure. Density estimates used for emission quantification purposes must be adjusted to corrected standardized temperatures and pressures;

(3) Flow meters must be placed based on manufacturer recommendations and must operate within manufacturers specified operating conditions at all times; and

(4) Flow meters must be calibrated according to manufacturer specifications and must be checked and calibrated at regular intervals according to these specifications.

(5) In cases where the same fuel is used for CCS and other unrelated activities and share the same meter or receipts/invoices, or when fuel receipts/invoices or metered data are not available, estimates with justification for the chosen methodology can be used with approval from the Executive Officer.

(b) Electricity consumption:

(1) Utility receipts/invoices or metered data for off-grid electricity use. In the absence of these data, maximum power rating for each type of equipment and operating hours can be used to estimate electricity use with approval from the Executive Officer.

(2) In certain cases, other loads may be tied into the same electricity meter. In such instances, estimates with justification for the chosen methodology can be used with approval from the Executive Officer.

(3) Electricity meters must be calibrated in accordance with manufacturer specifications and must be checked and calibrated at regular intervals according to these specifications.

(c) Steam consumption:

(1) Utility receipts/invoices or metered data for on-site steam production whichever applicable.

(2) In the absence of utility receipts/invoices or metered data, estimates with justification for the chosen methodology can be used with approval from the Executive Officer.

(3) If metered data are used, meters must be calibrated in accordance with manufacturer specifications and must be checked and calibrated at regular intervals according to these specifications.

(d) Cogeneration:

If any part of the CCS project uses electricity and thermal energy supplied directly by co-generation, the amount of fuel use associated with the electricity and thermal energy must be estimated using Equation D.1.

$$Fuel_i = Total\ Fuel_{cogen} \times \frac{Heat_{CCS} + Electricity_{CCS}}{Heat_{cogen} + Electricity_{cogen}} \quad \text{(D.1)}$$

Where:

$Fuel_i$ = Proportionate volume or mass of each type of fuel, by fuel type *i*, combusted by cogeneration unit to supply electricity or thermal energy to the CCS project (e.g., gallons/year or metric tons/year).

$Total\ Fuel_{cogen}$ = Total volume or mass of each type of fuel, by fuel type *i*, combusted by the cogeneration unit supplying electricity or thermal energy to the CCS project (e.g., gallons/year or metric tons/year).

$Heat_{CCS}$ = Quantity of thermal energy supplied to the CCS project by the cogeneration unit (MJ/year).

$Electricity_{CCS}$ = Quantity of electricity supplied to the CCS project by the cogeneration unit (MWh/year).

$Heat_{cogen}$ = Total quantity of thermal energy generated by the cogeneration unit (MJ/year).

$Electricity_{cogen}$ = Total quantity of electricity generated by the third party cogeneration unit (MWh/year).

(e) Chemical inputs:

(1) Purchase receipts/invoices or flow meter readings whichever applicable.

Appendix E. Emission Factors and Component Counts

Note: Stationary emissions factors in Tables E1 to E3 may be used only if they are not available in CA-GREET.

Table E1. Stationary Emission Factors for Fossil Fuel Combustion[12]

Coal and Coke	**kg CO_2/ton**	**g CH_4/ton**	**g N_2O/ton**
Anthracite (coal)	2602	276	40
Bituminous (coal)	2325	274	40
Sub-bituminous (coal)	1676	190	28
Lignite	1389	156	23
Mixed (commercial)	2016	235	34
Mixed (electric power sector)	1885	217	32
Mixed (industrial sector)	2468	289	42
Mixed (commercial)	2116	246	36
Coal Coke	2819	273	40
Fossil-derived Fuels (solid)	**kg CO_2/ton**	**g CH_4/ton**	**g N_2O/ton**
Municipal Solid Waste	902	318	42
Petroleum Coke (Solid)	3072	960	126
Plastics	2850	1216	160
Tires	2407	896	118
Fossil-derived Fuels (gaseous)	**kg CO_2/scf**	**g CH_4/scf**	**g N_2O/scf**
Blast Furnace Gas	0.02524	0.000002	0.000009
Coke Oven Gas	0.02806	0.000288	0.00006
Fuel Gas	0.08189	0.004164	0.000833
Propane Gas	0.15463	0.000055	0.000252

Note: Ton refers to short ton. While using Tables E1 to E3, CO and VOC emissions may need to be estimated if possible.

[12] U.S. EPA. Direct Emissions from Stationary Combustion Sources. (2016). Available at https://www.epa.gov/sites/production/files/2016-03/documents/stationaryemissions_3_2016.pdf

Table E2. Stationary Emission Factors for Petroleum Fuel Combustion[12]

Petroleum Products	kg CO_2/gal	g CH_4/gal	g N_2O/gal
Asphalt and Road Oil	11.91	0.47	0.09
Aviation Gasoline	8.31	0.36	0.07
Butane	6.67	0.31	0.06
Butylene	7.22	0.32	0.06
Crude Oil	10.29	0.41	0.08
Distillate Fuel Oil No .1	10.18	0.42	0.08
Distillate Fuel Oil No .2	10.21	0.41	0.08
Distillate Fuel Oil No. 4	10.96	0.44	0.09
Ethane	4.05	0.2	0.04
Ethylene	3.83	0.17	0.03
Heavy Gas Oils	11.09	0.44	0.09
Isobutane	6.43	0.3	0.06
Isobutylene	7.09	0.31	0.06
Kerosene	10.15	0.41	0.08
Kerosene-Type Jet Fuel	9.75	0.41	0.08
Liquefied Petroleum Gases (LPG)	5.68	0.28	0.06
Lubricants	10.69	0.43	0.09
Motor Gasoline	8.78	0.38	0.08
Naphtha (<401 deg F)	8.5	0.38	0.08
Natural Gasoline	7.36	0.33	0.07
Other Oil (>401 deg F)	10.59	0.42	0.08
Pentanes Plus	7.7	0.33	0.07
Petrochemical Feedstocks	8.88	0.38	0.08
Petroleum Coke	14.64	0.43	0.09
Propane	5.72	0.27	0.05
Propylene	6.17	0.27	0.05
Residual Fuel Oil No. 5	10.21	0.42	0.08
Residual Fuel Oil No. 6	11.27	0.45	0.09
Special Naphtha	9.04	0.38	0.08
Unfinished Oils	10.36	0.42	0.08
Used Oil	10.21	0.41	0.08

Table E3. Stationary Emission Factors for Petroleum Fuel Combustion[12]

Biomass-Derived Fuels (Solid)	**kg CO_2/ton**	**g CH_4/ton**	**g N_2O/ton**
Agricultural Byproducts	975	264	35
Peat	895	256	34
Solid Byproducts	1096	332	44
Wood and Wood Residuals	1640	126	63
Biomass -Derived Fuels (gaseous)	**kg CO_2/scf**	**g CH_4/scf**	**g N_2O/scf**
Landfill Gas	0.025254	0.001552	0.000306
Other Biomass Gases	0.034106	0.002096	0.000413
Biomass Fuels (liquid)	**kg CO_2/gal**	**g CH_4/gal**	**g N_2O/gal**
Biodiesel (100%)	9.45	0.14	0.01
Ethanol (100%)	5.75	0.09	0.01
Rendered Animal Fat	8.88	0.14	0.01
Vegetable Oil	9.79	0.13	0.01
Biomass Fuels (Kraft Pulping Liquor by Wood Furnish)	**kg CO_2/MMbtu**	**g CH_4/MMbtu**	**g N_2O/MMbtu**
North American Softwood	94.4	1.9	0.42
North American Hardwood	93.7	1.9	0.42
Bagasse	95.5	1.9	0.42
Bamboo	93.7	1.9	0.42
Straw	95.1	1.9	0.42

Table E4. Default CO_2 Emission Factors for Onshore Petroleum and Natural Gas Production[11]

Onshore Petroleum and Natural Gas Production	Emission Factor[g] (scf/hour/component)
Western US Population Emission Factors for all Components, Gas Service[a]	
Valve	0.121
Connector	0.017
Open-ended Line	0.031
Pressure Relief Valve	0.193
Low Continuous Bleed Pneumatic Device Vents[b]	1.39
High Continuous Bleed Pneumatic Device Vents[b]	37.3
Intermittent Bleed Pneumatic Device Vents[b]	13.5
Pneumatic pumps[c]	13.3
Population Emission Factors – All Components, Light Crude Service[d]	
Valve	0.05
Flange	0.003
Connector	0.007
Open-Ended Line	0.05
Pump	0.01
Other[e]	0.30
Population Emission Factors – All Components, Heavy Crude Service[f]	
Valve	0.0005
Flange	0.0009
Connector (Other)	0.0003
Open-Ended Line	0.006
Other[5]	0.003

[a] For multi-phase flow that includes gas, use the gas service emission factors.
[b] Emission factor is in units of "scf/hour/device."
[c] Emission Factor is in units of "scf/hour/pump."
[d] Hydrocarbon liquids greater than or equal to 20°API are considered "light crude."
[e] "Other" category includes instruments, loading arms, pressure relief valves, stuffing boxes, compressor seals, dump lever arms, and vents.
[f] Hydrocarbon liquids less than 20°API are considered "heavy crude."
[g] If the CO_2 volume percent in the gaseous stream flowing through the equipment is ≤ 80%, the emissions factors in Table E4 may be adjusted by multiplying them with the CO_2 volume percent.

Table E5. Default Average Component Counts for Major Crude Oil Production Equipment[11]

Major Equipment	Valves	Flanges	Connectors	Open-Ended Lines	Other Components
Wellhead	5	10	4	0	1
Separator	6	12	10	0	0
Heater-Treater	8	12	20	0	0
Header	5	10	4	0	0

Table E6. Default Average Component Counts for Major Onshore Natural Gas Production Equipment[11]

Major Equipment	Valves	Connectors	Open-Ended Lines	Pressure Relief Valves
Wellheads	11	36	1	0
Separators	34	106	6	2
Meters/Piping	14	51	1	1
Compressors	73	179	3	4
In-Line Heaters	14	65	2	1
Dehydrators	24	90	2	2

This Page Left Intentionally Blank

Appendix F. Emissions from CO_2 Entrained in Produced Oil and Gas

(a) Annual CO_2 Fugitive Emissions Entrained in Produced Oil and Gas[13]

$$CO_{2_{entrained}} = (V_{gas} \times \%CO_{2_{gas}} \times \rho CO_2 \times 0.001) + (M_{water} \times F_{CO2-water}) + (M_{oil} \times F_{CO2-oil}) \quad (F.1)$$

Where:

$CO_{2_{entrained}}$	=	Emissions or other losses of CO_2 entrained or dissolved in crude oil/other hydrocarbons, produced water and natural gas that have been separated from the produced CO_2 for sale or disposal. Calculated based on quantities of crude oil, water and gas produced and the CO_2 content of each product (MT CO_2/year).
V_{gas}	=	Volume of natural gas or fuel gas, produced from the formation that CO_2 is being injected into, that is sold to third parties or input into a natural gas pipeline in year y (m^3 /year), measured at standard conditions.
ρCO_2	=	Density of CO_2 at standard conditions (1.899 kg/m^3 or 0.0538 kg/ft^3).
$\%CO_{2_{gas}}$	=	% CO_2 in the natural gas or fuel gas that is sold to third parties or input into a natural gas pipeline, in year y (% volume).
M_{water}	=	Mass of water produced from the formation that CO_2 is being injected into, that is disposed of or otherwise not re-injected back into the formation (MT/year).
$F_{CO2-water}$	=	Mass fraction of CO_2 in the water produced from the formation.
M_{oil}	=	Mass of crude oil and other hydrocarbons produced from the formation that CO_2 is being injected into (MT/year).
$F_{CO2-oil}$	=	Mass fraction of CO_2 in the crude oil and other hydrocarbons produced from the formation (MT/year).

[13] The American Carbon Registry "Methodology for Greenhouse Gas Emission Reductions from Carbon Capture and Storage Projects," Version 1 (2015). Available at http://americancarbonregistry.org/carbon-accounting/standards-methodologies/carbon-capture-and-storage-in-oil-and-gas-reservoirs/acr-ccs-methodology-v1-0-final.pdf.

This Page Left Intentionally Blank

Appendix G. Determination of a CCS Project's Risk Rating for Determining its Contribution to the LCFS Buffer Account

A percentage of a CCS project's LCFS credits must be contributed to the LCFS Buffer Account pursuant to the Regulation. The specific percentage of the contribution is determined by a CCS project's risk rating, based on the potential for CO_2 leakage associated with different types of risks and project-specific circumstances.

(a) The CCS Project Operator is required to determine the project's invalidation risk rating prior to submitting their application for CCS project certification, and to recalculate it every time the CCS project undergoes verification.

(b) When estimated risk values and associated mitigation measures are updated, any adjustments to the invalidation risk ratings will affect only the current and future year contributions to the Buffer Account.

(c) Factors that contribute to CCS project risk rating are classified into the categories identified in Table G1.

(d) The CCS project risk rating must be determined using the tables and methods in this appendix. The CCS Project Operator must determine the contribution to the invalidation risk rating for each risk type in Table G1.

Table G.1. CCS project contribution to CCS project risk rating based on risk types

Risk type	**Risk category**	**Risk Rating Contribution**
Financial	*Low Financial Risk:* CCS project operators that demonstrate their company has: • a Moody's rating of A or better; or • an equivalent rating from Standard & Poor's, and Fitch	0%
	Medium Financial Risk: CCS project operators that demonstrate their company has: • a Moody's rating of B or better meets; or • an equivalent rating from Standard & Poor's, and Fitch	1%
	High Financial Risk: CCS project operators that cannot make one of the two demonstrations above	2%

Social	*Low Social Risk:* CCS projects located in countries or regions ranked among the top 20th percentile based on the World Justice Project Rule of Law Index	0%
	Medium Social Risk: CCS projects located in countries or regions ranked between the 20th and 50th percentile based on the World Justice Project Rule of Law Index	1%
	High Social Risk: CCS projects located in countries or regions that are not ranked, or are ranked below the 50th percentile based on the World Justice Project Rule of Law Index	3%
Management	*Low Management Risk:* Demonstrated surface facility access control, e.g., injection site is fenced and well protected	1%
	Higher Management Risk: Poor or no surface facility access control, e.g., injection site is open, or not fenced or protected	2%
Site	*Low Site Risk:* Selected site has more than two good quality confining layers above the sequestration zone and a dissipation interval below the sequestration zone	1%
	Higher Site Risk: Selected site meets the minimum site selection criteria but does not meet the above site criteria	2%
Well integrity	*Low Well Integrity Risk:* All wells for the CCS project meet USEPA class VI well or equivalent requirements	1%
	Higher Well Integrity Risk: The CCS project has wells that do not meet USEPA class VI well or equivalent requirements	3%

(e) A Project Operator must use Table G2 to summarize and report to CARB the CCS project's risk rating and contribution to the Buffer Account for each risk type.

Table G2. CCS Project Contribution to the Buffer Account for Each Risk Type

Risk type	Risk category	Risk Rating Contribution
Financial	□ Low Financial Risk □ Medium Financial Risk □ High Financial Risk	

Social	□ Low Social Risk □ Medium Social Risk □ High Social Risk	
Management	□ Low Management Risk □ Higher Management Risk	
Site	□ Low Site Risk □ Higher Site Risk	
Well integrity	□ Low Well integrity Risk □ Higher Well integrity Risk	

(f) The CCS project's overall risk rating and contribution to the Buffer Account is calculated using Equation G.1, below:

$$
\begin{aligned}
\mathit{CCS\ Project\ Risk\ Rating} &= 105\% \\
&- \left[(100\% - Risk_{Financial}) \times (100\% - Risk_{Social}) \right. \\
&\times \left(100\% - Risk_{Management}\right) \times (100\% - Risk_{Site}) \\
&\left. \times \left(100\% - Risk_{Well\ Integrity}\right)\right]
\end{aligned}
\tag{G.1}
$$

FOREST BIOMASS ENERGY IS A FALSE SOLUTION

Wheelabrator Shasta Energy biomass plant, photo by Trip Jennings

UNDERSTANDING WHY INCINERATING FORESTS TO GENERATE ELECTRICITY IS A BAD IDEA IS AS EASY AS P-I-E

Forest biomass power is:

- **Polluting,** emitting greenhouse gases, worsening the climate crisis, and harming vulnerable communities
- **Ineffective** for protecting communities during wildfires
- **Expensive** and dependent on subsidies that take resources away from truly clean energy alternatives

Instead of promoting biomass energy that harms our climate, communities, and forests, legislators and policy-makers should:

- Stop mandating, subsidizing, or otherwise incentivizing biomass power production, and instead direct investments toward truly clean energy production such as solar and wind.
- Fully account for the smokestack emissions from biomass power plants and stop incorrectly treating biomass power as "carbon neutral."
- Create climate-smart wildfire and forest policy that invests in proven home and community-focused approaches to wildfire safety rather than forest-cutting, while increasing forest protections that keep carbon stored in forest ecosystems as an essential climate solution.

Polluting for the Climate — Biomass is currently categorized as a "renewable" energy source along with solar and wind, but the reality is that biomass energy has more in common with fossil fuels. Like coal and oil, biomass is a carbon-burning form of energy production that emits carbon dioxide and contributes to the climate crisis. In fact, biomass power plants are California's dirtiest electricity source—releasing more carbon at the smokestack than coal. Adding to these harms, cutting trees for biomass energy reduces the forest's ability to sequester and store carbon. All in all, biomass power is a double whammy for the climate: it emits more carbon at the smokestack and leaves less carbon stored in the forest.

Polluting for Communities— Biomass power plants are also a significant source of air pollutants, harming the vulnerable communities where biomass facilities are located and worsening environmental injustice.

Ineffective — Biomass energy is often promoted as a tool to incentivize large-scale tree-cutting ("thinning") under the claim that this will protect communities and forests during wildfires. However, this approach is ineffective at protecting houses and communities, which is best achieved through a home-focused fire-safety strategy that helps communities safely coexist with inevitable wildfires. Although biomass energy is promoted as a means for disposing of debris piles from forest thinning projects, it is mostly lumber mill residues from commercial logging that end up being subsidized. Meanwhile, biomass extraction does significant ecological damage to forests.

Expensive —The inefficiency of using forest biomass to generate electricity makes it particularly costly. In fact, biomass power is California's most expensive energy source. Biomass power plants rely heavily on regulatory incentives and subsidies paid for by taxpayers and ratepayers. These biomass subsidies consume resources that would be better spent on cheaper and truly clean solar and wind energy alternatives and the jobs they create.

Each of these points is explained and supported in the factsheets accompanying this overview.

On close inspection, it's clear that biomass energy is not the solution – and would in fact impede California's ability to build a truly clean energy economy, all while endangering Californians along the way. The resources the state could pour into biomass would be put to better use pursuing truly clean solar and wind energy that will protect Californians, our health, our forests, and our climate well into the future.

For more information, contact Shaye Wolf and Brian Nowicki at the Center for Biological Diversity: swolf@biologicaldiversity.org and bnowicki@biologicaldiversity.org.
Last updated: March 2021.

CENTER for BIOLOGICAL DIVERSITY

Wheelabrator Shasta Energy biomass plant, photo by Trip Jennings

BIOMASS ENERGY IS POLLUTING: A FALSE CLIMATE SOLUTION THAT WORSENS THE CLIMATE CRISIS

Biomass is currently categorized as a "renewable" energy source along with solar and wind, but the reality is that biomass energy has more in common with fossil fuels. Like coal and oil, biomass is a carbon-burning form of energy production that emits carbon dioxide and contributes to the climate crisis. In fact, biomass power plants are California's dirtiest electricity source—releasing more carbon at the smokestack than coal. Adding to these harms, cutting trees for biomass energy reduces the forest's ability to sequester and store carbon. All in all, biomass power is a double whammy for the climate: it emits more carbon at the smokestack and leaves less carbon stored in the forest.

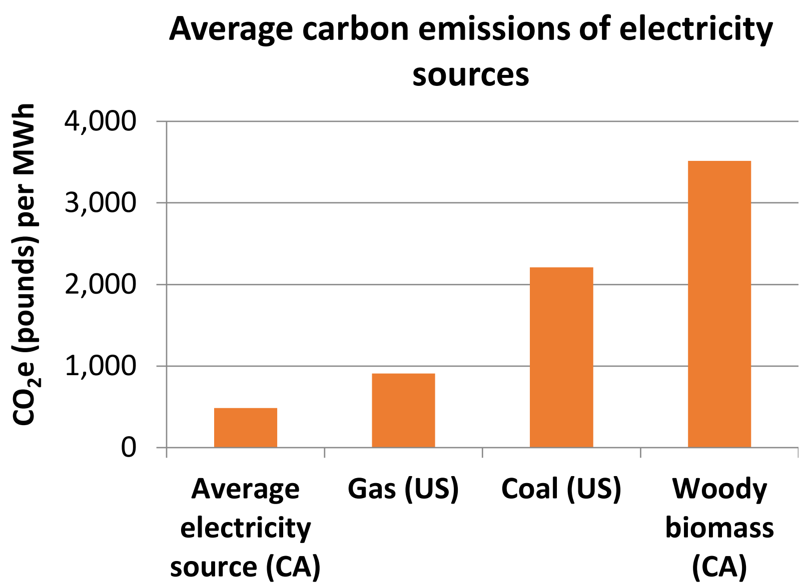
Biomass power plants are California's dirtiest electricity source.

Biomass power plants are ***much more*** climate-polluting than other electricity sources in California. The average greenhouse gas emission rate for California's current electricity portfolio is about 485 pounds carbon dioxide equivalent (CO_2e) per megawatt hour (MWh).[1] In 2018 woody biomass power plants in California emitted more than seven times that amount, averaging 3,500 pounds CO_2e per net MWh for the non-cogeneration facilities.[2] Smaller-scale biomass power plants using gasification technology are similarly carbon-intensive.[3]

Biomass power plant emissions in 2018	Capacity (MW)	Total CO_2e (pounds) per net MWh
Ampersand Chowchilla Biomass Power	12.5	2,996
Burney Forest Products (BioRAM) (cogen)	31	3,768
Collins Pine Biomass Power (cogen)	12	19,120
DG Fairhaven	15	3,877
DTE Stockton Biomass Power (cogen)	50	3,298
HL Power (BioRAM)	35.5	2,980
Humboldt Sawmill Company (cogen)	32.5	5,016
Merced Power	12.5	3,220
Mt. Poso Cogeneration (cogen)	63.6	2,507
Pacific Ultrapower Chinese Station (BioRAM)	25.7	4,418
Rio Bravo Fresno Biomass Power (BioRAM)	27.8	3,150
Rio Bravo Rocklin Biomass Power (BioRAM)	27.8	3,435
Roseburg Forest Products (cogen)	13.4	4,967
SPI Anderson Biomass Power II (cogen)	30.1	4,480
SPI Burney Biomass Power (cogen)	20	4,736
SPI Lincoln Biomass Power (cogen)	19.2	5,314
SPI Quincy Biomass Power (cogen)	35.3	6,215
SPI Sonora Standard Biomass Power (cogen)	7.5	11,540
Wheelabrator Shasta Energy (BioRAM)	62.8	3,900
Woodland Biomass Power	28	3,464
Average for non-cogeneration plants		**3,515**

Biomass energy is more climate-polluting than coal.

At the smokestack, biomass power plants release more carbon pollution than coal for the same amount of electricity produced.[4] Woody biomass energy generation in California emits more than one-and-a-half times the carbon pollution of coal-fired power per unit of electricity—and almost four times the carbon pollution of gas-generated power.[5] This is because incinerating trees is a remarkably inefficient way to generate electricity, resulting in high carbon emissions and high costs of production. In contrast, solar and wind energy provide truly carbon-free sources of power.



Biomass energy is not carbon neutral.

Despite the substantial carbon pollution from biomass power, biomass proponents claim that cutting and incinerating forests is inherently "carbon neutral"—that it does not cause net greenhouse gas emissions. The reality is biomass energy worsens carbon pollution, at a time when global emissions must be cut in half in the next decade to limit the worst damages of the climate crisis.

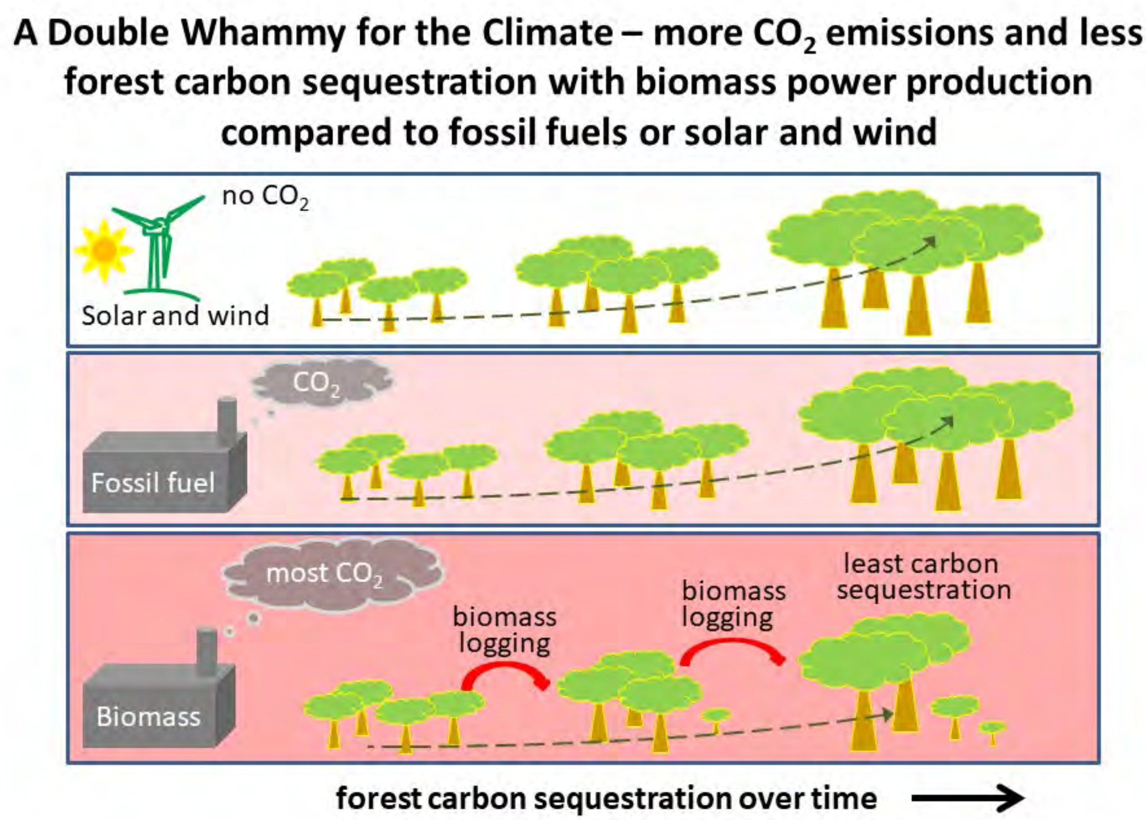
To claim biomass energy is carbon neutral, biomass proponents try to discount the carbon released by biomass power plants by taking credit for the carbon absorbed by future tree growth. But there is no requirement that forests cut down for biomass energy be allowed to regrow instead of being cut again and again, and or that forests won't be developed into other land uses. In short, there is no guarantee that new forests will be allowed to grow large enough to sequester as much carbon as the older, complex, carbon-rich forests that were cut.

Even if trees are allowed to regrow, numerous studies show that it takes many decades to more than a century, if ever, for new trees to grow large enough to capture the carbon that was released. [6] One study concluded that the increase in atmospheric greenhouse gases may be permanent.[7] In the meantime, that carbon pollution worsens the climate crisis and contributes to the probability of surpassing climate tipping points, causing irreversible harms.

Biomass energy reduces carbon stored in forests.

Cutting trees for biomass energy reduces the forest's ability to sequester and store carbon. When trees are cut to fuel a power plant, it ends their carbon sequestration. If these trees had instead been allowed to continue growing, they would have continued to pull carbon out of the atmosphere and increased the total amount of carbon stored in the forest. Even dead trees left in the forest will continue storing much of their carbon for decades or even centuries, while also providing important wildlife habitat, and eventually becoming soil that nourishes more forest growth. All these benefits are lost when a tree is hauled away to a biomass facility. Thus, biomass power is a double-whammy for the climate—it emits more carbon at the smokestack and it leaves less carbon stored in the forest than if the trees had not been cut.

Intact forests are a vital part of the climate solution because they pull carbon out of the air and provide long-term, natural storage.[8] Instead of cutting our natural carbon stores, we should support genuine forest protection, allowing trees to keep growing and sequestering carbon, in addition to the many other benefits that intact forests provide such as wildlife habitat, recreation, flood control, clean air and water.



Adapted from figure by Partnership for Policy Integrity

Promoting biomass energy to avoid wildfire emissions is damaging to the climate.

The bioenergy industry promotes cutting forests and incinerating forest materials for bioenergy as a way to avoid carbon emissions from forest fire. However, this claim is contradicted by scientific research and practical realities. Studies show that thinning forests to control fire actually reduces forest carbon stocks and increases overall carbon emissions.[9] Because the probability of a fire occurring on any given acre of forest is relatively low, many more acres must be thinned than will actually burn during the timeframe in which the thinning has an effect, so thinning ends up removing more carbon than would be released in a fire. One study estimated that thinning operations typically tend to remove about three times as much carbon from the forest as would be avoided in wildfire emissions.[10] Furthermore, field studies of large fires find only about 11% of forest carbon is consumed in a fire, and only 3% of the carbon in trees,[11] and vigorous post-fire regrowth returns forests to carbon sinks within several years.[12] In contrast, when forest biomass is extracted for bioenergy production, 100% of that carbon is immediately emitted to the atmosphere.

California's current policies do not account for greenhouse gas pollution from biomass energy, undermining the state's climate goals.

Despite the high carbon emissions from biomass power, California policies avoid accounting for this greenhouse gas pollution, implicitly treating the cutting and incinerating of forests as carbon neutral. For example, California's greenhouse gas cap-and-trade program does not count bioenergy emissions when calculating the amount of carbon pollution that electricity companies are allowed to emit. California's renewable portfolio standard treats biomass energy as an eligible energy source indistinguishable from non-carbon-burning energy like solar and wind,[13] completely ignoring the fact that biomass energy is extremely carbon intensive. California's Forest Carbon Action Plan and Vegetation Treatment Program both promote biomass energy as an economic driver for forest thinning projects that remove trees from the forest. Each of these policies includes a de facto assumption that biomass energy is carbon neutral, without explicitly stating that assumption or providing any analysis of the actual carbon impacts of forest bioenergy. The reality is that incinerating trees to make electricity increases carbon pollution in the atmosphere and undermines California's ability to meet its climate goals.

For more information, contact Shaye Wolf and Brian Nowicki
at the Center for Biological Diversity: swolf@biologicaldiversity.org
and bnowicki@biologicaldiversity.org.
Last updated: March 2021.

[1] California Air Resources Board, California Greenhouse Gas Emissions for 2000 to 2018, Trends of Emissions and Other Indicators (2020 Edition) at Figure 9 (GHG Intensity of Electricity Generation); *See also* California Air Resources Board, 2000-2018 Emissions Trends Repot Data (2020 Edition) at Figure 9, showing the overall GHG Intensity of Electricity Generation in 2018 of 0.22 tonnes CO_2e per MWh, which is equal to 485 pounds per MWh.

[2] Total CO_2e emissions for each facility in 2018 come from California Air Resources Board Mandatory GHG Reporting Emissions data, available at https://ww2.arb.ca.gov/mrr-data. Data on net MWh produced by each facility in 2018 come from the California Energy Commission California Biomass and Waste-To-Energy Statistics and Data, available at https://ww2.energy.ca.gov/almanac/renewables_data/biomass/index_cms.php. Total CO_2e produced by the 9 electricity-only, non-cogeneration active woody biomass facilities with available data totaled 2,127,693 metric tons, and net MWh in 2018 from these 9 facilities totaled 1,334,346 MWh, for an average of 1.59 metric tons CO_2e per net MWh, equal to 3,515 pounds CO_2e per net MWh. The average of 3,515 pounds CO_2e per MWh includes electricity-only plants; cogeneration plants are excluded because some of their CO_2 emissions are from heat-related fuel consumption.

[3] For example, the Cabin Creek bioenergy project approved by Placer County would have an emissions rate of more than 3,300 lbs CO_2/MWh. *See* Ascent Environmental, Cabin Creek Biomass Facility Project Draft Environmental Impact Report, App. D (July 27, 2012) (describing 2 MW gasification plant with estimated combustion emissions of 26,526 tonnes CO_2e per year and generating 17,520 MWh per year of electricity, resulting in emissions of 3,338 lbs CO_2e per MWh).
[4] Searchinger, Timothy D. et al., Europe's renewable energy directive poised to harm global forests, 9 Nature Communications 3741 (2018); Sterman, John D. et al., Does replacing coal with wood lower CO2 emissions? Dynamic lifecycle analysis of wood bioenergy, 13 Environmental Research Letters 015007 (2018)
[5] Overall average GHG Intensity of electricity generation in California comes from California Air Resources Board, 2000-2018 Emissions Trends Repot Data (2020 Edition); Average CO_2 emissions per MWh for gas and coal in the United States in 2019 are from U.S. Energy Information Administration, How much carbon dioxide is produced per kilowatt hour of U.S. electricity generation?
[6] Searchinger, T.D. et al., Fixing a critical climate accounting error, 326 Science 527 (2009); Gunn, J., et al., Manomet Center for Conservation Sciences, Massachusetts Biomass Sustainability and Carbon Policy Study: Report to the Commonwealth of Massachusetts Department of Energy Resources (2010); Hudiburg, T.W. et al., Regional carbon dioxide implications of forest bioenergy production, 1 Nature Climate Change 419 (2011); Law, B.E. and M.E. Harmon, Forest sector carbon management, measurement and verification, and discussion of policy related to climate change, 2 Carbon Management 73 (2011); Campbell, J.L. et al., Can fuel-reduction treatments really increase forest carbon storage in the western US by reducing future fire emissions? 10 Frontiers in Ecology and Environment 83 (2012); Holtsmark, Bjart, The outcome is in the assumptions: Analyzing the effects on atmospheric CO_2 levels of increased use of bioenergy from forest biomass, 5 GCB Bioenergy 467 (2012); Mitchell, S.R. et al., Carbon debt and carbon sequestration parity in forest bioenergy production, 4 Global Change Biology Bioenergy 818 (2012); Schulze, E.-D. et al., Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral, 4 Global Change Biology Bioenergy 611 (2012); Booth, Mary S., Not carbon neutral: Assessing the net emissions impact of residues burned for bioenergy, 13 Environmental Research Letters 035001 (2018); Sterman, John D. et al., Does replacing coal with wood lower CO_2 emissions? Dynamic lifecycle analysis of wood bioenergy, 13 Environmental Research Letters 015007 (2018)
[7] Holtsmark, Bjart, The outcome is in the assumptions: Analyzing the effects on atmospheric CO_2 levels of increased use of bioenergy from forest biomass, 5 GCB Bioenergy 467 (2012)
[8] Moomaw, William R. et al, Intact forests in the United States: proforestation mitigates climate change and serves the greatest good, Frontiers in Forests and Global Change, doi: 10.3389/ffgc.2019.00027 (2019)
[9] Mitchell, S.R. et al., Forest fuel reduction alters fire severity and long-term carbon storage in three Pacific Northwest ecosystems, 19 Ecological Applications 643 (2009); Campbell, J.L. and A.A. Ager, Forest wildfire, fuel reduction treatment, and landscape carbon stocks: a sensitivity analysis, 121 Journal of Environmental Management 124 (2013); DellaSala, D.A. and M. Koopman, Thinning Combined with Biomass Energy Production Impacts Fire-Adapted Forests in Western United States and May Increase Greenhouse Gas Emissions, Reference Module in Earth Systems and Environmental Sciences (2016).
[10] Campbell, J.L. et al., Can fuel-reduction treatments really increase forest carbon storage in the western US by reducing future fire emissions? 10 Frontiers in Ecology and Environment 83 (2012).
[11] Campbell, J., et al., Pyrogenic carbon emission from a large wildfire in Oregon, United States, 112 Journal of Geophysical Research Biogeosciences G04014 (2007)
[12] Meigs, G., et al., Forest fire impacts on carbon uptake, storage, and emission: The role of burn severity in the Eastern Cascades, Oregon, 12 Ecosystems 8 (2009)
[13] The bill that set the RPS in 2002—AB 1078 (Sher)—deferred to the existing definition of "in-state renewable electricity generation technology" in the Public Utilities code: Cal. Pub. Utilities Code § 3.99.12(e) [def of "renewable source"]; Cal. Pub. Resources Code § 25741(a)(1) ("The facility uses biomass, solar thermal, photovoltaic, wind, geothermal, fuel cells using renewable fuels, small hydroelectric generation of 30 megawatts or less, digester gas, municipal solid waste conversion, landfill gas, ocean wave, ocean thermal, or tidal current, and any additions or enhancements to the facility using that technology.").

BIOMASS ENERGY IS POLLUTING: BIOMASS POWER PLANT POLLUTION HARMS VULNERABLE COMMUNITIES, WORSENING ENVIRONMENTAL INJUSTICE

Biomass power plants are a significant source of air pollutants, harming the vulnerable communities where biomass facilities are located and worsening environmental injustice.

Biomass power plants emit large amounts of air pollutants that harm public health.

Biomass power plants emit toxic air pollutants, including particulate matter (PM), nitrogen oxides (NOx), carbon monoxide (CO), sulfur dioxide (SO_2), lead, mercury, and other hazardous air pollutants that harm public health.[1] Biomass power plant pollution can exceed that of coal-fired power plants even when the best available control technology is used.[2]

In California, biomass power plants are among the worst emitters of particulate matter and NOx.[3] Fine particulate matter (PM 2.5)—which can get deep into the lungs and even enter the bloodstream—is linked to serious health problems including heart disease, premature death, stroke, and aggravated asthma.[4] In the San Joaquin Valley air district, two biomass plants—Mount Poso Cogeneration Company and Rio Bravo Fresno—were the 11th and 13th biggest stationary source of fine particulate matter (PM 2.5) in 2017 out of 153 sources. In the Sacramento Valley air district, 7 out of the 10 worst PM 2.5 polluters were biomass plants.[5]

Biomass power plants also emit hazardous air pollutants, including hydrochloric acid, dioxins, benzene, formaldehyde, arsenic, chromium, cadmium, lead, and mercury.[6] In 2017 Humboldt Redwood Company's Scotia biomass cogeneration facility reported emitting a whopping 11,574 pounds of the carcinogen benzene and 12,364 pounds of the toxin formaldehyde.[7]

California's biomass plants are often located in vulnerable communities already overburdened with pollution, worsening environmental injustice.

Many of California's biomass power plants are concentrated in vulnerable communities already suffering from high pollution burdens, worsening environmental injustice. The San Joaquin Valley is one of the nation's most polluted air basins. Currently, Bakersfield, Fresno-Madera-Hanford, and Visalia are the top three most polluted cities for year-round particulate pollution levels *in the country*.[8] In the San Joaquin Valley, 4 of 5 active biomass plants and 4 of 5 idle biomass plants are located in disadvantaged communities.[9] Most of these communities are within the ninetieth percentile for air pollution burden, and some are in the top percentile. For example, the 25 MW Rio Bravo biomass plant in Fresno is located less than a half-mile from the Malaga Elementary School, Malaga Community Park, and surrounding homes, in a majority Hispanic neighborhood with a pollution burden score of 100.[10]

California's biomass plants have repeated air pollution violations.

California's biomass power plants are guilty of repeated air quality violations.[11] In 2016 the now idle Blue Lake Power plant, located near Blue Lake Rancheria Indian Tribal lands, was cited and fined for multiple air pollution violations.[12] Tribal members, especially children and the elderly, reported severe health harms from the air pollution from the plant.[13] Merced Power and Ampersand Chowchilla Biomass in the San Joaquin Valley have been levied large fines for the excess emission of nitrogen oxides and fine particulate matter.[14]

Biomass power plants produce continuous air pollution.

The air pollution from biomass power plants can be continuous, heavily impacting nearby communities and degrading the entire air basin around the clock and throughout the year with the incineration of woody biomass from throughout the region. In comparison, leaving woody materials in the forest to decompose naturally cycles carbon and nutrients and helps increase forest growth, aiding in future carbon sequestration. Even when cut materials are pile-burned in the forest, the burning occurs for a limited period of time and dispersed through the forest, in contrast to biomass plants which emit pollution continuously in or near particular communities.

For more information, contact Shaye Wolf and Brian Nowicki
at the Center for Biological Diversity: swolf@biologicaldiversity.org
and bnowicki@biologicaldiversity.org.
Last updated: March 2021.

[1] Partnership for Policy Integrity, Air pollution from biomass energy (updated April 2011), https://www.pfpi.net/wp-content/uploads/2011/04/PFPI-air-pollution-and-biomass-April-2011.pdf

[2] Partnership for Policy Integrity, Air pollution from biomass energy (updated April 2011), https://www.pfpi.net/wp-content/uploads/2011/04/PFPI-air-pollution-and-biomass-April-2011.pdf

[3] For example, Roseburg Forest Products ranked as the 21st biggest stationary source of fine particulate matter out of 591 sources state-wide in 2017, according to facility-level emissions data from the California Air Resources Board Pollution Mapping Tool, https://ww3.arb.ca.gov/ei/tools/pollution_map/pollution_map.htm

[4] U.S. Environmental Protection Agency, Health and Environmental Effects of Particulate Matter, https://www.epa.gov/pm-pollution/health-and-environmental-effects-particulate-matter-pm

[5] Based on facility-level emissions data in each air district from the California Air Resources Board Pollution Mapping Tool, https://ww3.arb.ca.gov/ei/tools/pollution_map/pollution_map.htm

[6] Partnership for Policy Integrity, Air pollution from biomass energy (updated April 2011), https://www.pfpi.net/wp-content/uploads/2011/04/PFPI-air-pollution-and-biomass-April-2011.pdf

[7] Based on facility-level emissions data from the California Air Resources Board Pollution Mapping Tool, https://ww3.arb.ca.gov/ei/tools/pollution_map/pollution_map.htm

[8] American Lung Association, State of the Air 2020: Most Polluted Cities, http://www.stateoftheair.org/city-rankings/most-polluted-cities.html

[9] Four active biomass plants (Rio Bravo Fresno, DTE Stockton, Merced Power, and Ampersand Chowchilla) and four idle biomass plants (Community Recycling Madera Power, Covanta Mendota, Dinuba Energy, and Covanta Delano) are in census tracts designated as disadvantaged under SB 535, https://oehha.ca.gov/calenviroscreen/sb535

[10] Data from CalEnviroScreen 3.0. https://oehha.ca.gov/calenviroscreen.

[11] Based on the EPA Enforcement and Compliance History Online Database, https://echo.epa.gov/, and other public records.

[12] EPA Enforcement and Compliance History Online Database, https://echo.epa.gov/enforcement-case-report?id=09-2014-0502

[13] Blue Lake Rancheria, Environmental Programs, https://bluelakerancheria-nsn.gov/about/departments/environmental-programs-2/; Blue Lake Power Under Fire From Residents, Tribe Over Alleged Pollution Violations, Clean Power Exchange (Nov. 29, 2016), https://cleanpowerexchange.org/blue-lake-power-under-fire-from-residents-tribe-over-alleged-pollution-violations/

[14] Green, Ronnie, "Green" Biomass Isn't Always So Clean, Center for Public Integrity (April 26, 2011, updated May 19, 2014), https://publicintegrity.org/environment/green-biomass-isnt-always-so-clean/

Biomass logging, Stanislaus National Forest, 2019, photo by Chad Hanson

LOGGING FOR BIOMASS ENERGY IS INEFFECTIVE FOR PROTECTING COMMUNITIES DURING WILDFIRES

Biomass energy is often promoted as a tool to incentivize large-scale tree-cutting ("thinning") under the claim that this will protect communities and forests during wildfires. However, this approach is ineffective at protecting houses and communities, which is best achieved through a home-focused fire-safety strategy that helps communities safely coexist with inevitable wildfires. Although biomass energy is promoted as a means for disposing of debris piles from forest thinning projects, it is mostly lumber mill residues from commercial logging that end up being subsidized. Meanwhile, biomass extraction does significant ecological damage to forests.

Effectively protecting communities from wildfire requires preparing houses and the area immediately surrounding them—not large-scale forest thinning.

Research and experience show that the most effective way to prevent homes from igniting during wildfires is to make the homes themselves more fire safe. Home safety retrofits and vegetation pruning in the "home-ignition zone" within 60 to 100 feet of a house provide the most direct and effective way to prevent wildfire from going from the forest to the home.[1] In communities in fire-prone areas, California should invest in helping communities implement proven home fire-safety measures: retrofitting homes and other structures with fire-resistant roofing, rain gutter guards, ember-proof vent screens, and pruning vegetation in the defensible space immediately surrounding them. To avoid putting communities in harm's way, California should also stop allowing new developments in highly fire-prone wildlands.

In contrast to the "from the home outward" approach, biomass proponents promote large-scale forest-cutting—"thinning" or "fuels reduction"—as a way to alter wildfire behavior and reduce community fire risk. Yet the best-available science indicates that thinning forests far from communities is not a good way to protect people and property from wildfire. The probability that thinned forest areas will overlap with a wildfire is very small.[2] Thinning is ineffective in altering fire behavior under the hot, windy, extreme fire weather conditions that have caused largest losses of homes and lives in recent years.[3] And thinning more than 100 feet from homes is largely irrelevant to home fire safety. A properly prepared home—with home fire-safety retrofits and defensible space pruning—will generally not ignite even if high-intensity fire occurs nearby. By the same token, an improperly prepared house can burn from contact with wind-blown embers from distant fires.[4] Furthermore, the majority of California communities most vulnerable to wildfire are not in forests but in chaparral and grasslands, making forest thinning irrelevant for their safety. All in all, the ineffective forest-cutting approach of biomass proponents takes resources away from proven home-focused fire-safety strategies that protect our communities.

Bioenergy facilities primarily consume commercial lumber mill refuse, not forest thinning residues.

Biomass energy is often promoted as a means to incentivize the removal of residual forest material cut during thinning projects, but the reality is that biomass facilities select to get their material mainly from other sources, even when receiving state subsidies intended to promote thinning. Commercial lumber mill refuse is more reliable, easier to obtain, and cheaper to transport than material taken from the forest. Only about a third of the forest-sourced biomass being consumed in biomass plants is forest thinning residues, while the majority—more than two-thirds, on average—is residues from commercial lumber mills.[5] For the seven biomass plants that utilize the BioRAM program subsidy, in 2017, only 30% of their feedstock came from forest thinning residues.[6]

Dead trees do not increase wildfire and should not be sent to bioenergy facilities.

In response to California's widespread tree mortality during drought, Governor Brown in 2015 issued an Emergency Declaration calling for the removal of dead trees along with incentives to bioenergy facilities to burn them.[7] The justification was that dead trees were feared to increase wildlife risk. However, numerous scientific studies show that dead trees do not increase wildfire—including no increase in fire severity, rate of spread, or extent.[8] Meanwhile, dead trees—standing or fallen—provide numerous ecological benefits such as wildlife habitat, soil stabilization, water quality, and carbon storage.[9] These ecological benefits are lost when dead trees are removed and incinerated in biomass power plants.

Biomass extraction harms forests.

Cutting forests for biomass energy is often promoted as helping protect forests from "catastrophic" wildfire, but this misrepresents the important role of wildfire—including high-intensity fire—in California's forest ecosystems. Fire of all intensities, called "mixed-severity" fire, is a natural and necessary part of California's forests.[10] Forests are adapted to mixed-severity fire and need fire to rejuvenate. In fact, patches of high-severity fire create some of the most diverse wildlife habitat of any forest type.[11] And numerous studies show that there is currently less fire of all severities now than there was prior to modern fire suppression,[12] depriving forests of the ecological benefits produced by intense fires, such as habitat creation and nutrient cycling. California's focus on logging and fire suppression degrades wildlife habitat, results in a net loss of carbon storage, and takes resources away from proven fire-safety solutions focused on homes and communities.

For more information, contact Shaye Wolf and Brian Nowicki
at the Center for Biological Diversity: swolf@biologicaldiversity.org
and bnowicki@biologicaldiversity.org.
Last updated: March 2021.

[1] Cohen, J.D., Preventing disaster: home ignitability in the Wildland-Urban Interface, 98 Journal of Forestry 15 (2000); Cohen, J.D. & R.D. Stratton, Home destruction examination: Grass Valley Fire, U.S. Forest Service Technical Paper R5-TP-026b (2008); Gibbons, P. et al., Land management practices associated with house loss in wildfires, 7 PLoS ONE e29212 (2012); Syphard, A.D. et al., The role of defensible space for residential structure protection during wildfires, 23 International Journal of Wildland Fire 1165 (2014); Scott, J.H. et al., Examining alternative fuel management strategies and the relative contribution of National Forest System land to wildfire risk to adjacent homes – A pilot assessment on the Sierra National Forest, California, USA, 362 Forest Ecology and Management 29 (2016); Syphard, Alexandra D. et al., The importance of building construction materials relative to other factors affecting structure survival during wildfire, 21 International Journal of Disaster Risk Reduction 140 (2017); Syphard, Alexandra D. et al., The relative influence of climate and housing development on current and projected future fire patterns and structure loss across three California landscapes, 56 Global Environmental Change 41 (2019); Cohen, Jack, A more effective approach for preventing wildland-urban fire disasters, *In* A New Direction for California Wildfire Policy—Working from the Home Outward, Leonardo DiCaprio Foundation (February 11, 2019)

[2] Schoennagel, Tania et al., Adapt to more wildfire in western North American forests as climate changes, 114 PNAS 4582 (2017)

[3] Dellasala, Dominick A., Accommodating mixed-severity fire to restore and maintain ecosystem integrity with a focus on the Sierra Nevada of California, USA, 13 Fire Ecology 148 (2017); Abatzoglou, John T. et al., Human-related ignitions concurrent with high winds promote large wildfires across the USA, 27 International Journal of Wildland Fire (2018); Syphard, Alexandra D. et al., The relative influence of climate and housing development on current and projected future fire patterns and structure loss across three California landscapes, 56 Global Environmental Change 41 (2019)

[4] Cohen, J.D., Preventing disaster: home ignitability in the Wildland-Urban Interface, 98 Journal of Forestry 15 (2000); Cohen, J.D. & R.D. Stratton, Home destruction examination: Grass Valley Fire, U.S. Forest Service Technical Paper R5-TP-026b (2008); Cohen, Jack, A more effective approach for preventing wildland-urban fire disasters, *In* A New Direction for California Wildfire Policy—Working from the Home Outward, Leonardo DiCaprio Foundation (February 11, 2019)

[5] CalRecycle, SB 498 Reporting, 2018 Biomass Conversion (2018), file:///C:/Users/swolf/Downloads/SB498DataRpt2018.pdf. (According to CalRecycle (2018), the 25 biopower facilities operating in 2018 incinerated approximately 4.1 million bone-dry tons (BDT) of biomass annually. On average, forest residues accounted for 15% of this total, mill residues for about 35%, and the remainder derived from agricultural and urban waste streams.)

[6] MB&G and the Beck Group, High Hazard Fuels Availability Study, Prepared for the High Hazard Fuel Study Committee and PG&E (June 13, 2019), https://fmtf.fire.ca.gov/media/2180/hhzfuelstudy_final_20190613.pdf. (This analysis reported that the cost of qualifying fuel is more than 2.5 times the cost of non-qualifying fuel, and that even with the subsidized power price provided by BioRAM contracts, some BioRAM plants are struggling to obtain enough qualifying fuel.)

[7] Governor Edmund G. Brown, Proclamation of a State of Emergency (Oct. 30, 2015), https://www.caloes.ca.gov/RecoverySite/Documents/Governor's%20Proclamation%20Tree%20Mortality%202015-05.pdf

[8] Bond, M.L. et al., Influence of pre-fire tree mortality on fire severity in conifer forests of the San Bernardino Mountains, California, 2 The Open Forest Science Journal 41 (2009); Hart, S.J., et al., Area burned in the western United States is unaffected by recent mountain pine beetle outbreaks, 112 PNAS 14 (2015); Meigs, G.W., et al., Do insect outbreaks reduce the severity of subsequent forest fires? 11 Environmental Research Letters 4 (2016); Hart, S.J. & D.L. Preston, Fire weather drives daily area burned and observations of fire behavior in mountain pine beetle affected landscapes, 15 Environmental Research Letters 054007 (2020)

[9] Swanson, M.E. et al., The forgotten stage of forest succession: early-successional ecosystems on forested sites, 9 Frontiers in Ecology and Environment 117 (2011); DellaSala, D.A. et al., Complex early seral forests of the Sierra Nevada: what are they and how can they be managed for ecological integrity? 34 Natural Areas Journal 310 (2014); Hutto, R.L. et al., Toward a more ecologically informed view of severe forest fires, 7 Ecosphere e01255 (2016)

[10] Odion, D.C. et al., Examining historical and current mixed-severity fire regimes in Ponderosa pine and mixed-conifer forests of western North America, 9 Plos One e87852 (2014)

[11] Swanson, M.E. et al., The forgotten stage of forest succession: early-successional ecosystems on forested sites, 9 Frontiers in Ecology and Environment 117 (2011); DellaSala, D.A. et al., Complex early seral forests of the Sierra Nevada: what are they and how can they be managed for ecological integrity? 34 Natural Areas Journal 310 (2014)

[12]Mouillot, F. & C. Field, Fire history and the global carbon budget: a 1° x 1° fire history reconstruction for the 20th century, 11 Global Change Biology 398 (2005); Stephens, S.L. et al., Prehistoric fire area and emissions from California's forests, woodlands, shrublands and grasslands, 251 Forest Ecology and Management 205 (2007); Marlon, J.R., Long-term perspective on wildfires in the western USA, 109 PNAS E535 (2012); Odion, D.C. et al., Examining historical and current mixed-severity fire regimes in Ponderosa pine and mixed-conifer forests of western North America, 9 Plos One e87852 (2014); Parks, S.A., et al., Wildland fire deficit and surplus in the western United States, 1984-2012, 6 Ecosphere 275 (2015)

BIOMASS POWER IS EXPENSIVE AND DEPENDS ON TAXPAYER SUBSIDIES THAT TAKE RESOURCES AWAY FROM TRULY CLEAN ENERGY

The inefficiency of using forest biomass to generate electricity makes it particularly costly. In fact, biomass power is California's most expensive energy source. Biomass power plants rely heavily on regulatory incentives and subsidies paid for by taxpayers and ratepayers. These biomass subsidies consume resources that would be better spent on cheaper and truly clean solar and wind energy alternatives and the jobs they create.

Biomass power is California's most expensive energy source.

Incinerating trees is a highly inefficient way to make electricity, which makes it very expensive. In fact, biomass power is the most expensive of California's common electricity sources.[1] In 2018, the levelized cost of biomass power averaged $166 per megawatt hour compared to $49 per megawatt hour for photovoltaic solar and $57 for wind.[2]

Biomass power plants in California are not competitive with other electricity sources and depend on being propped up by state policies.

As of 2019, there were 23 bioenergy power plants operating in California fueled by wood and other biomass[3] which contribute less than 2% of the state's total electric power.[4] Many California bioenergy power plants have been closed or idled since the peak of more than 60 plants in the 1980s because bioenergy is not competitive with other energy sources.[5] Because biomass energy is expensive and inefficient, bioenergy power plants depend heavily on regulatory incentives and subsidies in order to be economically viable.

Recent legislation has required electric utilities to purchase electricity from bioenergy power plants at high costs that are passed on to customers. In 2012 under SB 1122 (Rubio), California required public utilities to collectively purchase 250 MW (megawatts) of electricity from bioenergy plants, including 50 MW from forest-sourced woody biomass.[6] As a result, in 2014, the Public Utilities Commission established the BioMAT program (Bioenergy Market Adjusting Tariff), a feed-in-tariff that effectively requires California's three investor-owned utilities—PG&E, SCE, and SDG&E—to purchase bioenergy at a price set by the CPUC. In other words, it provides a guaranteed above-market price to bioenergy facilities less than 5 MW in size. This is effectively a subsidy to bioenergy plants, the cost of which is passed through to ratepayers.

In 2016, SB 859 required that all utilities serving more than 100,000 customers must collectively procure 125 MW of power from existing bioenergy plants for which 80% of the biomass feedstock must be a byproduct of "sustainable" forestry management—defined as any logging other than clearcutting—60% of which must derive from Tier 1 and Tier 2 high hazard zones.[7]

Also in 2016, the CPUC initiated the BioRAM program (Bioenergy Renewable Auction Mechanism), which requires California's three investor-owned utilities to collectively procure at least 50 MW of biomass energy and to pay above-market rates for that electricity, provided that at least 50% of a biomass facility's feedstock derives from wildfire high-hazard zones (HHZs). This proportion was raised to 60% in 2018, and 80% for 2019 and beyond. However, because this program does not distinguish between forest thinning projects and commercial logging, so long as the wood comes from hazard zone areas, the majority of the material comes from commercial timber operations and lumber mills.

Californians bear the costs of propping up the biomass industry.

California lawmakers provide subsidies to the biomass industry without directly using state funds in two ways: by including biomass energy under the Renewable Portfolio Standard and through legislation requiring electric utilities to purchase forest-sourced biomass power. Californians wind up shouldering the cost of these subsidies when they pay for the high cost of biomass power through their electricity bills. Meanwhile, lawmakers claim that they are addressing forest fire without allocating any actual funds for community wildfire protection.

For comparison, the average wholesale price of power on the California grid is $50 per megawatt hour (Mwh).[8] The price for forest biomass energy through the BioMAT program is four times as much—$199.72 per Mwh based on the price cap set by the Public Utilities Commission[9]—and more than twice as much through the BioRAM program at $115 per Mwh.[10] In practice, California residents and electric utility ratepayers are subsidizing forest biomass facilities at a rate of $150 per Mwh above market price through the BioMAT program, and $65 per Mwh above market price through the BioRAM program. Furthermore, BioMAT power is four times as expensive as photovoltaic solar power and 3.5 times as expensive as wind power. BioRAM power is more than twice as expensive as solar or wind power.

California policies that incentivize forest bioenergy divert resources away from truly clean energy solar and wind energy and the jobs they create.

State policies that mandate that electric utilities purchase electricity from forest-sourced woody biomass divert investment away from zero-carbon sources like solar and wind, impeding the urgently needed transition to truly clean energy. Because the Renewable Portfolio Standard is used as the means for providing subsidies to biomass, every increase in biomass energy means a direct reduction in the amount that utilities companies invest in solar or wind power.

In addition, costly forest thinning projects to fuel biomass power plants are heavily dependent on taxpayer subsidies. On national forests, the federal timber sale program operates at a net loss to taxpayers of nearly $2 billion each year.[11] In California, the state government subsidizes tree-cutting in various ways, including a billion dollars over five years allocated by SB 901. These resources were intended to increase public safety during wildfires. Instead of first paying for the forest projects and then paying a second time to burn the residues in biomass facilities, these resources would be much more effectively used to directly help communities implement wildfire-safety actions right around houses, with vastly greater public safety benefits.

Redirecting resources to home fire safety work and solar and wind energy would also be better for job creation, bolstering rural communities. While bioenergy proponents tout biomass power plants as a source of jobs, the reality is that these facilities are highly automated, so they produce few jobs for the massive subsidies necessary to prop them up. In contrast, fire-safety work directed at homes and the zone right around them requires much more intensive involvement by well-trained workers, and thus generates far more jobs per dollar spent. One study found that an equal amount of government investment could produce two to three times as many jobs—and better paying jobs—if those funds were used to support fire-safety work right around homes rather than subsidizing forest-cutting projects to fuel biomass power plants.[12] In addition, solar and wind energy are driving massive job creation with relatively high, family-sustaining wages.[13]

For more information, contact Shaye Wolf and Brian Nowicki
at the Center for Biological Diversity: swolf@biologicaldiversity.org
and bnowicki@biologicaldiversity.org.
Last updated: March 2021.

---

[1] California Energy Commission, Staff Report, Estimated Cost of New Utility-Scale Generation in California: 2018 Update (May 2019), https://ww2.energy.ca.gov/2019publications/CEC-200-2019-005/CEC-200-2019-005.pdf at 40

[2] California Energy Commission, Staff Report, Estimated Cost of New Utility-Scale Generation in California: 2018 Update (May 2019), https://ww2.energy.ca.gov/2019publications/CEC-200-2019-005/CEC-200-2019-005.pdf at B-12 (levelized mid-level cost of Solar PV: C-Si, Tracking 100 MW is $49), at B-18 (levelized mid-level cost of Wind 80 m Hub Height 100 MW is $57), and B-21 (levelized mid-level cost of Biomass fluidized bed boiler 20 MW is $166). The levelized cost estimates reflect the average cost per megawatt-hour for an independent developer to build and operate a power plant over the lifetime of the facility.

[3] University of California, Division of Agriculture and Natural Resources, Woody Biomass Utilization, https://ucanr.edu/sites/WoodyBiomass/Project/California_Biomass_Power_Plants/. The 23 operational plants burning woody biomass and other organic materials are ARP Loyalton Biomass Power, Burney Forest Power, Chowchilla Biomass Power, Collins Pine Biomass Power, DG Fairhaven, DTE Mt. Poso Cogen, DTE Stockton Biomass Power, DTE Woodland Biomass Power, Greenleaf Desert View Power, Honey Lake Power, Humboldt Redwood Company Scotia Power, Merced Power, Pacific Ultrapower Chinese Station Power, Rio Bravo Fresno Biomass Power, Rio Bravo Rocklin Biomass Power, Roseburg Forest Products Biomass Power, SPI Anderson Biomass Power II, SPI Burney Biomass Power, SPI Lincoln Biomass Power, SPI Quincy Biomass Power, SPI Sonora Standard Biomass Power, Wadham Biomass Power, Wheelabrator Shasta Energy. In addition, three small-scale gasification plants are operating as pilot/demonstration projects: Dixon Ridge Farms Gasifier Power Pilot, Ortigalita Power Company, and Cal Forest Nursery Gasifier.

[4] California Energy Commission, California Biomass and Waste-To-Energy Statistics and Data, https://ww2.energy.ca.gov/almanac/renewables_data/biomass/index_cms.php. In 2017, 22 operational bioenergy plants produced 3,205 GW, which was 1.6% of the state total 206,387 GW produced.

[5] Morris, Gregory, Biomass Energy Production in California: The Case for a Biomass Policy Initiative, Final Report, NREL (2000), https://www.nrel.gov/docs/fy01osti/28805.pdf at 5

[6] Forest-sourced woody biomass is eligible for up to 50 MW of the total, along with 110 MW from landfills and wastewater sources, and 90 MW from dairy and agricultural sources.

[7] Cal. Pub. Utilities Code § 3.99.20.3(a). (In addition to the requirements of subdivision (f) of Section 399.20, by December 1, 2016, electrical corporations shall collectively procure, through financial commitments of five years, their proportionate share of 125 megawatts of cumulative rated generating capacity from existing bioenergy projects that commenced operations prior to June 1, 2013. At least 80 percent of the feedstock of an eligible facility, on an annual basis, shall be a byproduct of sustainable forestry management, which includes removal of dead and dying trees from Tier 1 and Tier 2 high hazard zones and is not that from lands that have been clear cut. At least 60 percent of this feedstock shall be from Tier 1 and Tier 2 high hazard zones.)

[8] California ISO, 2018 Annual Report on Market Issues & Performance (May 2019), http://www.caiso.com/Documents/2018AnnualReportonMarketIssuesandPerformance.pdf at 1

[9] PG&E reported executed BioMAT contracts with three biomass facilities at a price of $199.72 per MWh: North Fork Community Power (2 MW), Blue Mountain Electricity Company (3 MW), and Hat Creek Bioenergy (2.88 MW), *See* BioMAT Executed PPAs Awarded, 10 Day Report, https://pgebiomat.accionpower.com/biomat/doccheck.asp?doc_link=biomat/docs/FIT/2015/documents/d.%20PPAs%20Awarded/2.%20PPAs%20Awarded-10-Day%20Report/BioMAT_ExecutedPPAs_10DayReport.xlsx

[10] MB&G and The Beck Group, High Hazard Fuels Availability Study, Prepared for The High Hazard Fuel Study Committee and PG&E, (June 13, 2019), https://fmtf.fire.ca.gov/media/2180/hhzfuelstudy_final_20190613.pdf at 63

[11] Center for Sustainable Economy, Environmentally Harmful Subsidies in the U.S.: Issue #1: The federal logging program (May 2019), https://sustainable-economy.org/wp-content/uploads/2019/05/CSE-Federal-logging-report-May-2019.pdf

[12] Natural Resource Economics, Potential Jobs and Wages from Investments in Defensible-Space Approaches to Wildfire Safety (April 2018), http://nreconomics.com/reports/2018-04-28_EnvNow_Report.pdf
[13] Muro, Mark et al., Advancing Inclusion Through Clean Energy Jobs, Metropolitan Policy Program at Brookings (April 2019), https://www.think-asia.org/bitstream/handle/11540/10116/2019.04_metro_Clean-Energy-Jobs_Report_Muro-Tomer-Shivaran-Kane_updated.pdf?sequence=1

19 July 2021

To: The Honorable Joseph R. Biden, Jr., President of the United States
The Honorable Nancy Pelosi, Speaker of the House of Representatives
The Honorable Charles Schumer, Majority Leader, United States Senate

cc: The Honorable Jennifer Granholm, Secretary, Department of Energy
Dr. Jennifer Wilcox, Principal Deputy Assistant Secretary for Fossil Energy, Department of Energy
Brenda Mallory, Chair, White House Council on Environmental Quality
Richard Moore, Chair, White House Environmental Justice Advisory Council
Peggy Shepard, Chair, White House Environmental Justice Advisory Council

Re: Carbon capture is not a climate solution

Dear President Biden, Speaker Pelosi, and Majority Leader Schumer,

On behalf of our millions of members and supporters across the United States, Canada, and globally, we are writing to express deep concerns about our governments' support for carbon capture and storage (CCS) technologies. Despite occupying center stage in the "net zero" climate plans trumpeted by the United States, Canada, and other countries at the Leaders' Summit on Climate, in government spending programs and in bills pending before Congress, carbon capture is <u>not</u> a climate solution. To the contrary, investing in carbon capture delays the needed transition away from fossil fuels and other combustible energy sources, and poses significant new environmental, health, and safety risks, particularly to Black, Brown, and Indigenous communities already overburdened by industrial pollution, dispossession, and the impacts of climate change.

Pledges to achieve "net zero" emissions through the use of CCS technologies rely on the flawed premise that we can continue burning fuels indefinitely by capturing some of the carbon emissions and offsetting the rest. As explained below, CCS does not halt the core drivers of the climate crisis — fossil fuel production and consumption — or meaningfully reduce greenhouse gas emissions. Instead, it prolongs reliance on fossil fuels and, perversely, increases oil production through "enhanced oil recovery." CCS is neither economically sound nor feasible at scale. And most alarmingly, it threatens the communities affected by carbon capture infrastructure and the underlying sources of emissions to which the technology is attached.

Simply put, technological carbon capture is a dangerous distraction. We don't need to *fix* fossil fuels, we need to *ditch* them. To avoid catastrophic climate change, we need to deploy resources to replace the fossil fuel industry, not prop it up. Directing government support to CCS diverts resources from the most sustainable and job-creating solutions to the climate crisis: phasing out oil, gas, and coal; investing in energy efficiency and non-combustion renewable energy sources; and nurturing forests, wetlands, and other natural landscapes that function as carbon sinks.

The buildout of CCS infrastructure presents serious health, safety, and environmental risks, particularly for marginalized communities, already

overburdened by industrial hazards, that are being targeted for CCS. These dangers are systematically overlooked in discussions on carbon capture. Transporting and storing carbon dioxide (CO_2) involves a massive network of perilous pipelines connected to underground injection sites, each with their own set of dangers. Pipelines can leak or rupture; compressed CO_2 is highly hazardous upon release and can result in the asphyxiation of humans and animals. Underground storage poses additional risks, such as potential leakage, contamination of drinking water, and stimulation of seismic activity. These hazards apply to all the current and proposed variants utilizing CCS technologies, including carbon capture utilization and storage (CCUS), fossil hydrogen with CCS ("blue" or decarbonized hydrogen), bioenergy with CCS (BECCS), coal-bioenergy systems with CCS (CBECCS), waste-to-energy with CCS (WtE-CCS), and direct air capture (DAC), which depends on CCS or CCUS to manage the captured carbon.

CCS is not consistent with the principles of environmental justice. As the U.S. White House Environmental Justice Advisory Council's Interim Final Recommendations made clear, CCS will not benefit communities. Yet pollution-burdened communities are being targeted for CCS, which brings new risks and threats, ironically in the name of environmental justice. The U.S. Gulf Coast, including the Louisiana petrochemical corridor known as "Cancer Alley," northern plains, and California Central Valley, as well as the provinces of Alberta and Saskatchewan in Canada, are among those areas being targeted for CCS development. Such a buildout would impose new pollution and safety hazards on Black, Brown, and Indigenous communities already suffering the disproportionate and deadly impacts of environmental racism.

Rather than replacing fossil fuels, carbon capture technology prolongs our dependence on them. By design, carbon capture is parasitic on the underlying sources of emissions to which it is attached. Putting carbon capture technology on greenhouse-gas emitting facilities enables those facilities to continue operating, effectively providing those emitters with a license to pollute indefinitely. In practice, CCS at best captures only a fraction of carbon emissions and fails to address other harmful pollution from fuel combustion, such as fine particulate matter (PM2.5), as well as other contaminants from the underlying activities to which CCS was applied. The additional energy required to power the carbon capture process generates even more emissions if supplied by fossil fuels.

Worse still, the majority of captured carbon is used to pump more oil out of the ground, in a practice known as "enhanced oil recovery" (EOR). Almost all existing CCS projects are tied to EOR, whereby CO_2 is injected into depleted underground oil reservoirs to boost oil production. EOR is currently the primary market driver for captured CO_2; no other markets exist at the scale proposed by many of the technology's proponents. EOR is disastrous for the climate, as it results in more oil extraction and more carbon emissions when that oil is burned. And yet, the public in the United States is currently paying for EOR through the Section 45Q tax credit, of which oil companies are the biggest beneficiaries. In Canada, the oil and gas industry is lobbying for a similar tax break.

There is no economic rationale for the massive deployment of CCS. Attaching carbon capture technology to an emitting source makes operating that source both more expensive and more energy-intensive. As costs of clean energy like solar and wind plummet, fossil fuel and biomass power plants are becoming less competitive, and adding carbon capture just makes them more costly. Even in heavy-emitting industrial sectors such as plastic or petrochemical manufacturing, applying CCS at scale makes little climate or economic sense. The push to deploy CCS in the industrial sector ignores the most important alternative methods for curtailing the *vast* majority of the sector's emissions, which are available and scalable: replacing fossil fuels with non-carbon emitting renewable energy to supply power and heat, adapting production processes and methods, reducing and ultimately ending production of wasteful and unsustainable materials like disposable plastics, and reusing materials in manufacturing to reduce the production of virgin material. Investing in CCS infrastructure add-ons to existing facilities locks those facilities and their current energy technologies in place, and diverts resources from non-polluting alternatives that are compatible with a safe climate future.

CCS does not *remove* CO_2 from the atmosphere. At best, it prevents some carbon emissions from entering the atmosphere. But even there it falls short: CCS projects implemented to date have systematically overpromised and under-delivered on emissions reductions. Advertisements from some fossil fuel companies that compare CCS to a living plant are deeply misleading. Industry claims that BECCS is a negative emissions technology are based on the flawed and scientifically discredited premise that burning biomass is carbon neutral. In fact, burning wood for energy can increase greenhouse gas impacts for decades to centuries compared to fossil fuels.

The promise of "permanent" storage or sequestration of captured carbon is not backed by science or existing regulations. Current U.S. federal regulations, for example, only require storage of CO_2 for 50 years to qualify for subsidies. But CO_2 lingers in the atmosphere and environment on a geological time scale — for many hundreds or even thousands of years. Considering CO_2 injected underground or used in the manufacture of plastics, cement, or other goods to be safely contained in perpetuity is irresponsible at best, as it merely kicks the can down a very short road, to be a burden to the next generation.

Deploying CCS at any climate-relevant scale, in the short timeframe we have to avert climate catastrophe, without posing substantial risks to communities on the frontlines of the buildout, is a pipe dream. Despite the billions of taxpayer dollars spent by governments in both the United States and Canada on CCS over the last ten-plus years, the technology has not made a dent in CO_2 emissions. Continuing to sink federal funds into technological carbon capture is choosing to chase a fossil-fueled fantasy rather than deal with the root of the problem.

Therefore, we, the undersigned organizations, urge you to:

1. **Ensure that the environmental justice and human rights impacts and the significant safety risks of CCS are front and center in any hearings and policy discussions regarding the technology**. Representatives from communities disproportionately harmed by systemic environmental racism, including Black, Brown and Indigenous communities,

and the environmental justice organizations accountable to them, should be invited to testify in all congressional or parliamentary hearings and formal policy discussions on CCS. All decisions regarding CCS policy must respect and uphold the rights of Indigenous Peoples.

2. **Reject proposals to provide, extend, or increase government funding and subsidies for CCS/CCUS and related infrastructure.** Rather than funding CO_2 pipelines and expensive retrofits to dirty power and industrial plants, public resources should be invested in sustainable infrastructure that serves people, not polluters. From replacing lead pipes to ensure safe drinking water and ensuring access to safe drinking water for all First Nations, to upgrading public transit and accelerating deployment of electric vehicles and non-polluting energy sources, to sustaining natural ecosystems and supporting communities impacted by climate change, there are many areas deserving of government investment that are a "win-win" for people and the planet. CCS is not one of them.

3. **Prohibit the use of 45Q tax credits in the U.S. or other national subsidies in the U.S. or Canada for enhanced oil recovery.** Federal funds deployed to address the climate crisis and accelerate the transition to a non-polluting energy future must not be used to produce more of the oil and gas that are choking our planet. Using government funds to give handouts to polluters is bad enough; doing it in the name of 'climate action' adds insult to injury.

4. **Investigate how existing U.S. and Canadian subsidies for CCS technologies have been used to date and close loopholes in tax policy that allow polluters to claim the credits without demonstrating compliance with monitoring, reporting, and verification requirements.** The U.S. Treasury's Inspector General for Tax Administration, for example, found that fossil fuel companies improperly claimed nearly $900 million in tax credits under 45Q. No further support for CCS technologies should be approved at all, let alone while questions loom over the use of funds to date.

5. **Reject national energy strategies that rely on or anticipate CCS.** Current legislative proposals, including proposals for a national Clean Electricity Standard in the United States and Canada's hydrogen strategy, are designed to promote or accelerate the deployment of CCS. National strategies should focus on eliminating the use of fossil fuels and other combustible sources in our energy system, not simply reducing their emissions intensity.

Conclusion: Carbon capture schemes are unnecessary, ineffective, exceptionally risky, and at odds with a just energy transition and the principles of environmental justice. We ask that you reject federal funding for CCS technologies, immediately end subsidies for enhanced oil recovery, and instead prioritize investments in safe and sustainable climate solutions and equitable and just transitioning of workers and communities to a fossil-free, clean energy economy.

Signed,

International
350.org
Ben & Jerry’s
Catholic Divestment Network
Citizens’ Resistance at Fermi 2
Coalition for a Nuclear Free Great Lakes
EcoHealth Network
Global Alliance for Incinerator Alternatives
GreenFaith
International Marine Mammal Project
Just Transition Alliance
Network of Spiritual Progressives
North American Climate, Conservation, and Environment
Ocean Conservation Research
Oceanic Preservation Society
Oil Change International
Reconstructionist Rabbinical Association
Sisters of Charity Federation
Social Eco Education Los Angeles
Stand.earth
The Enviro Show
Waterkeeper Alliance

United States
198 methods
2 Degrees Northampton
350 Bay Area Action
350 Brooklyn
350 Butte County
350 Central Mass
350 Colorado
350 Conejo / San Fernando Valley
350 Corvallis
350 Eugene
350 Hawaii
350 Juneau
350 Kishwaukee
350 Maine
350 Massachusetts
350 Merced
350 Montana
350 New Hampshire
350 New Orleans
350 NYC
350 Sacramento
350 Seattle

350 Spokane
350 Tacoma
350 Triangle
350 Wenatchee
A Community Voice
Action Center on Race & the Economy
ActionAid USA
Advocacy & Training Center
Advocates for Springfield
AFGE Local 704
Alabama Interfaith Power & Light
Algalita
Alliance for a Green Economy
Alliance for Affordable Energy
Amazon Watch
American Environmental Health Studies Project
American Family Voices
American Indian Movement Southern California
Animals Are Sentient Beings
Animas Valley Institute
Anthropocene Alliance
Atchafalaya Basinkeeper
Athens County's Future Action Network
Atlantic Coast Conference Climate Justice Coalition
Ban Single-Use Plastics
Bergen County Green Party
Berks Gas Truth
Better Path Coalition
Beyond Extreme Energy
Beyond Plastics
Biofuelwatch
Black Mesa Trust
Black Voters Matter Fund
Bold Alliance
Breathe Project
Bronx Climate Justice North
Buckeye Environmental Network
Bucks County Concerned Citizens Against the Pipelines
Bucks Environmental Action
Businesses for a Livable Climate
California Businesses for a Livable Climate
California Democratic Party Environmental Caucus
California Environmental Justice Alliance
California River Watch
California Safe Schools
Call to Action Colorado

Cape Downwinders
Carrie Dickerson Foundation
CatholicNetwork US
Catskill Mountainkeeper
Cedar Lane Unitarian Universalist Church Environmental Justice Ministry
Center for Biological Diversity
Center for Climate Integrity
Center for Coalfield Justice
Center for Environmental Health
Center for Environmentally Recycled Building Alternatives
Center for International Environmental Law
Center on Race, Poverty & the Environment
CEO Pipe Organs
Change the Chamber
Chicago Area Peace Action
Choctawhatchee Riverkeeper
Church Women United in New York State
Citizen Power
Citizens Action Coalition
Citizens Awareness Network
Ciudadanos Del Karso
Clean Air Action Network of Glens Falls
Clean Air Now
Clean Energy Action
Clean Energy Now Texas
Climate Action Now Western Mass
Climate Action Rhode Island / 350 Rhode Island
Climate Hawks Vote
Climate Justice Alliance
Climate Reality Project New Orleans
Coal River Mountain Watch
Coalition Against Death Alley
Coalition Against Pilgrim Pipeline New Jersey
Coalition for Outreach, Policy, Education
Colorado Businesses for a Livable Climate
Colorado Small Business Coalition
Columbus Community Bill of Rights
Comite Pro Uno
Common Ground Community Trust
Community Action Works
Community Church of New York
Concerned Citizens for Nuclear Safety
Concerned Citizens of Saint John
Concerned Health Professionals of New York
Concerned Ohio River Residents
Conejo Climate Coalition

Congregation of Sisters of Saint Agnes
Conservation Congress
Conservation Council for Hawaii
Cool Effect
Cooperative Energy Futures
Corporate Accountability
Cottonwood Environmental Law Center
Council on Intelligent Energy & Conservation Policy
Courage California
Damascus Citizens for Sustainability
DC Environmental Network
Deep Green Resistance New York
Deep South Center for Environmental Justice
Democratic Environmental Caucus of St. Bernard Parish
Descendants Project
Detroit Hamtramck Coalition for Advancing Healthy Environments
Dis Organization for Solar Power
Dogwood Alliance
Don't Gas the Meadowlands Coalition
Don't Waste Arizona
Don't Waste Michigan
Drawdown Bay Area
Dryden Resource Awareness Coalition
Earth Action
Earth Care
Earth Day Initiative
Earth Day Network
Earthworks
EcoEquity
Education, Economics, Environmental, Climate & Health Organization
Electric Auto Association of Central Coast California
Elgin Green Groups 350
Empower Our Future
Endangered Species Coalition
Environmental Communion New Jersey Association United Church of Christ
Environmental Protection Information Center
Environmental Transformation Movement of Flint
Environmental Working Group
Escambia County Democratic Environmental Caucus of Florida
Extinction Rebellion New Orleans
Extinction Rebellion San Francisco Bay Area
Fairmont Peace Group
Family Farm Defenders
Fenceline Watch
First Presbyterian Church of Brooklyn
First Unitarian Universalist Church of New Orleans

Five Calls Civic Action
Florida Student Power Network
Food & Water Watch
Food Shift
Forest Unlimited
Fossil Free California
Fossil Fuel Divest Harvard
Fox Valley Citizens for Peace & Justice
FrackBusters New York
FracTracker Alliance
Franciscan Action Network
FreshWater Accountability Project
Fridays for Future USA
Friends of Buckingham
Friends of the Earth U.S.
Fuerza Mundial
Genesis Farm
Global Justice Ecology Project
Global Witness
Golden Ponds Farm
Grassroots Environmental Education
Grassroots Global Justice Alliance
Great Egg Harbor Watershed Association
Great Old Broads for Wilderness
Great Plains Action Society
Greater Grand Rapids NAACP
Greater New Orleans Housing Alliance
Greater New Orleans Interfaith Climate Coalition
Green Education & Legal Fund
Green New Deal Virginia
Green Newton
Green Retirement
Green State Solutions
Greenaction for Health and Environmental Justice
GreenARMY
GreenLatinos
Greenpeace USA
GreenRoots
Greenvest
Gulf Coast Center for Law & Policy
Haiti Cholera Research Funding Foundation USA
Harambee House
Harvard Solar Gardens
Healthy Gulf
Heirs To Our Oceans
Homewise Realty

Hudson River Sloop Clearwater
Idle No More SoCal
In the Shadow of the Wolf
Indian Point Safe Energy Coalition
Indigenous Environmental Network
Indivisible CA-43
Indivisible Pittsfield
Inland Ocean Coalition
INOCHI / Women for Safe Energy
Institute for Agriculture and Trade Policy
Institute for Policy Studies Climate Policy Program
Interfaith Council for Peace & Justice
International Indigenous Youth Council Los Angeles
Iowa Citizens for Community Improvement
Ironbound Community Corporation
John Muir Project
Justice & Beyond
Klamath Forest Alliance
KyotoUSA
LaPlaca & Associates
Living Rivers
Local Environmental Action Demanded Agency
Long Beach 350
Long Island Progressive Coalition
Longmeadow Pipeline Awareness Group
Los Padres ForestWatch
Louisiana Bucket Brigade
Louisiana League of Conscious Voters
Lower 9th Ward Neighborhood Watch
Lynn Canal Conservation
Manhattan Project for a Nuclear-Free World
Maryland Legislative Coalition
Mass Peace Action
Massachusetts Forest Watch
Maternal & Child Health Access
Metro New York Catholic Climate Movement
Michigan Alliance for Justice in Climate
Michigan Environmental Justice Coalition
Michigan Interfaith Power & Light
Mid-Missouri Peaceworks
Milwaukee Riverkeeper
Mission Blue
Moral ReSources
Mothers Out Front
Mothers Out Front Tompkins
Movement Rights

MoveOn.org Hoboken
Nassau Hiking & Outdoor Club
Nature Rhythms
Network in Solidarity with the People of Guatemala
Nevada Nuclear Waste Task Force
New Energy Economy
New Jersey State Industrial Union Council
New Mexico Environmental Law Center
New York / New Jersey Environmental Watch
New York Climate Action Group
New York Lawyers for the Public Interest
Ní Btháska Stand Collective
Nobody Leaves Mid-Hudson
North American Water Office
North Bronx Racial Justice
North Carolina Council of Churches
North Carolina Interfaith Power & Light
North Country Earth Action
North Range Concerned Citizens
Northern Michigan Environmental Action Council
Northridge Indivisible
No Waste Louisiana
Nuclear Age Peace Foundation
Nuclear Information & Resource Service
Nuclear Watch South
NY-16 Indivisible
NYC Environmental Justice Alliance
Occupy Bergen County
Ohio Valley Environmental Coalition
Oil & Gas Action Network
On Behalf of Planet Earth
Organized Uplifting Resources & Strategies
Our Climate Education Fund
Our Place in the World: A Journal of Ecosocialism
Our Revolution Minnesota
Our Santa Fe River
Partnership for Policy Integrity
Pax Christi USA New Orleans
Peace Action Wisconsin
Peak Plastic Foundation
Peninsula Interfaith Climate Action
People Over Petro Coalition
People's Solar Energy Fund
People's Party
Peoples Climate Movement New York
Physicians for Social Responsibility Arizona

Physicians for Social Responsibility Iowa
Physicians for Social Responsibility Pennsylvania
Pipe Line Awareness Network for the Northeast
Plastic Free Delaware
Plastic Pollution Coalition
PlasticFreeRestaurants.org
Plymouth Friends for Clean Water
Post Carbon Institute
Powder River Basin Resource Council
Power Past Fracked Gas
Power Shift Network
Presentation Sisters
Preserve Montgomery County Virginia
Progressive Democrats of America
Proposition One Campaign
Public Citizen
Public Goods Institute
Publish What You Pay United States
Pueblo Action Alliance
Rachel Carson Council
Rainforest Action Network
Rapid Shift Network
RedTailed Hawk Collective
Redwood Justice Fund/ Prison Radio
Renewable Energy Long Island
Resistance Action Tuesdays & Thursdays Pack
Resource Renewal Institute
RESTORE: The North Woods
Rio Grande Valley Great Old Broads for Wilderness
RISE St. James
River Guardian Foundation
River Valley Organizing
Riverdale Jewish Earth Alliance
RootsAction
Safe Energy Rights Group
San Luis Obispo Mothers for Peace
Sane Energy Project
Sanford-Oquaga Area Concerned Citizens
Santa Barbara Standing Rock Coalition
Santa Cruz Climate Action Network
Save Our Illinois Land
Save RGV from LNG
Save the Frogs!
Science & Environmental Health Network
Sequoia ForestKeeper
Seven Circles Foundation

Shenandoah Energy Services
Sierra Club Delta Chapter
Sisters of Charity of Nazareth Congregational Leadership
Sisters of Charity of Nazareth Western Province Leadership
Sisters of Charity of New York
Sisters of Saint Dominic of Blauvelt
Snake River Alliance
Socially Responsible Agriculture Project
Society of Native Nations
Solidarity Info Service
Sonoma County Climate Activist Network
South Shore Audubon Society
Southeast Faith Leaders Network
SouthWings
Spirit of the Sun
Spottswoode Winery
Springfield Climate Justice Coalition
Stop Fracking Long Beach
Stop SPOT & Texas Gulflink: Save Our Gulf Coast
Stop the Algonquin Pipeline Expansion
Sullivan Alliance for Sustainable Development
Sunflower Alliance
Sunrise Knoxville
Sunrise Movement Baltimore
Sunrise Movement New Orleans
Sustainable Belmont
Sustainable Medina County
Syracuse Cultural Workers
Texas Campaign for the Environment
Texas Environmental Justice Advocacy Services
Texas Grassroots Alliance
The Borneo Project
The Climate Center
The Climate Mobilization
The Forest Foundation
The Freedom BLOC
The Future Left
The Green House Connection Center
The Last Beach Cleanup
The Last Plastic Straw
The Lilies Project
The River Project
The Wei
Three Mile Island Alert
Toledo Coalition for Safe Energy
Transition Sebastopol

Tucson Climate Action Network
Turtle Island Restoration Network
Unitarian Universalist Congregation of Binghamton Green Sanctuary
Unitarian Universalist Mass Action
Unitarian Universalists for a Just Economic Community
Unite North Metro Denver
United Church of Christ Environmental Justice Ministry
Utah Valley Earth Forum
Valley Watch
Verde
Veterans For Peace Climate Crisis & Militarism Project
Wall of Women
Wasatch Clean Air Coalition
Washington Physicians for Social Responsibility
Washtenaw350
Water and Air Team Charlevoix
Waterspirit
Wendell State Forest Alliance
West Dryden Residents Against Pipeline
Western Organization of Resource Councils
Western Rural + Plains States Project
Western Watersheds Project
White Rabbit Grove RDNA
Wild Nature Institute
WildEarth Guardians
Women Watch Afrika
Women's Earth and Climate Action Network
Working Families Joliet
Young Democrats of America Environmental Caucus
Youth United for Climate Crisis Action
Youth Vs. Apocalypse
Zero Hour

Canada
Alberta Liability Disclosure Project
Below 2ºC
British Columbia Hydro Ratepayers Association
Canadian Association of Physicians for the Environment
Canadian Environmental Law Association
Canadian Health Association for Sustainability & Equity
Canadian Unitarians for Social Justice
Canadian Voice of Women for Peace
Canadians for Tax Fairness
Chemainus Climate Solutions
Climate Action Powell River
Climate Emergency Unit

Climate Justice Montreal
Climate Justice Ottawa
ClimateFast
Committee for Human Rights in Latin America
Community Climate Council
Comox Valley Council of Canadians
Council of Canadians / Le Conseil des Canadiens
Courage Montreal
Curr Dynasty Creative
Ecologos Water Docs
Environmental Defence Canada
ENvironnement JEUnesse
Environnement Vert Plus
Équiterre
Extinction Rebellion New Brunswick
For Our Grandchildren
For Our Kids North Shore British Columbia
For Our Kids Toronto
Fridays for Future Toronto
Friends of the Earth Canada
Georgia Strait Alliance
Glasswaters Foundation
Global Peace Alliance BC Society
Grand(m)others Act to Save the Planet
Grandmothers Advocacy Network
Just Earth
Leadnow
MiningWatch Canada
My Sea to Sky
Nature Canada
Parents for Climate
People's Health Movement Canada
Réseau Québécois sur l'Intégration Continentale
Respecting Aboriginal Values & Environmental Needs
Seniors For Climate Action Now!
Shift: Action for Pension Wealth & Planet Health
Sierra Club Canada Foundation
Simcoe County Environmental Youth Alliance
Simcoe County Greenbelt Coalition
Sustainable Orillia Youth Council
TBL Communications
The Climate Reality Project Canada
Wilderness Committee
Wildsight
Women's Healthy Environments Network

Confronting the Myth of Carbon-Free Fossil Fuels

Why Carbon Capture Is Not a Climate Solution

The world is confronting a climate emergency. Avoiding climate catastrophe requires immediate and dramatic reductions in greenhouse gas (GHG) emissions that are possible only with a significant investment of public resources in proven mitigation measures, beginning with eliminating fossil fuel use and halting deforestation. Carbon capture and storage (CCS) and carbon capture, utilization, and storage (CCUS) will not address these core drivers of the climate crisis or meaningfully reduce GHG emissions, and should not distract from real climate solutions.

CCS and CCUS technologies are not only *unnecessary* for the rapid transformation required to keep warming under 1.5°C, they *delay* that transformation, providing the fossil fuel industry with a license to continue polluting. This brief argues that carbon capture technologies:

- Do not remove carbon from the atmosphere, and in fact worsen the climate crisis when used to boost oil production.
- Have not been proven feasible or economic at scale and can only contain a fraction of source emissions.
- Prolong dependence on fossil fuels and delay their replacement with renewable alternatives.
- Create environmental, health, and safety risks for communities saddled with CCS infrastructure, such as pipelines and underground storage.

CCS Isn't Carbon Negative, or Even Carbon Neutral

CCS and CCUS refer to processes that collect or "capture" carbon dioxide generated by high-emitting activities — such as coal- and gas-fired power production or plastics manufacturing — and then transport those captured emissions to sites where they are either used for industrial processes or stored underground.[1]

CCS does not *remove* carbon from the atmosphere, although it is often erroneously conflated with "CO_2 removal" or "negative emission" technology. At best, CCS prevents some emissions caused by the combustion of carbon-based fuels from reaching the atmosphere — provided that the captured gases are not later released.

In practice, however, CCS masks the harmful carbon emissions from the underlying source, enabling that source to continue operating rather than being replaced altogether, while creating additional risks, impacts, and costs associated with the CCS infrastructure itself. Moreover, the injection of captured carbon into oil wells to enhance oil recovery — the most pervasive use of CCS today — exacerbates global warming by boosting oil production and prolonging the fossil fuel era.[2]

Large-Scale CCS is Neither Viable Nor Necessary

The unproven scalability of CCS technologies and their prohibitive costs mean they cannot play any significant role in the rapid reduction of global emissions necessary to limit warming to 1.5°C. Despite the existence of the technology for decades and billions of dollars in government subsidies to date, deployment of CCS at scale still faces insurmountable challenges of feasibility, effectiveness, and expense.

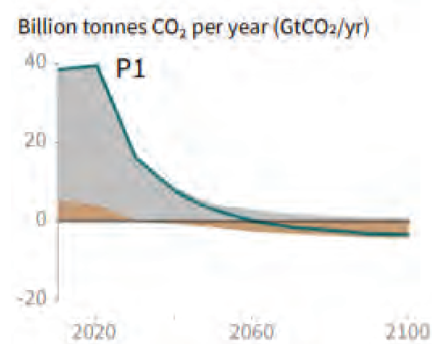
Existing CCS facilities capture less than 1 percent of global carbon emissions. The 28 CCS facilities currently operating globally have a capacity to capture only 0.1 percent of fossil fuel emissions, or 37 megatons of CO_2 annually. Of that capacity, just 19 percent, or 7 megatons, is being captured for actual geological sequestration.[3] The vast majority, as discussed ahead, is being used to produce more oil.

CCS pilot projects have repeatedly overpromised and underdelivered. The Petra Nova carbon capture facility installed at a coal-fired power station near Houston, Texas, in 2017 illustrates the failure of CCS to deliver meaningful emissions reductions and the folly of deploying CCS in service of fossil fuel extraction and use.

During its operation, the CCS system only captured 7 percent of the power plant's total CO_2 emissions, well below the company's promises to reduce CO_2 emissions by 90 percent.[4] The captured carbon from Petra Nova had been used for enhanced oil recovery, but the 2020 collapse in oil price and demand rendered this uneconomic. The CCS operation and the gas plant used to power it have been shut down indefinitely, leaving the coal-fired plant as emissions-intensive as ever.[5]

The surest approach to avoiding climate catastrophe does not involve CCS. According to the Intergovernmental Panel on Climate Change (IPCC), the emissions reduction pathway with the best chance of keeping warming at or below 1.5°C makes *limited to no* use of engineered carbon capture technologies. This pathway involves a rapid phaseout of fossil fuels along with limited carbon removal by *natural sources* such as reforestation

FIGURE 1
IPCC 1.5°C Pathway 1



P1: A scenario in which social, business, and technological innovations result in lower energy demand up to 2050 while living standards rise, especially in the global South. A down-sized energy system enables rapid decarbonisation of energy supply. Afforestation is the only CDR option considered; neither fossil fuels with CCS nor BECCS are used.

Graphic Source: IPCC

and enhanced soil carbon uptake.[6] The IPCC points to "uncertainty in the future deployment of CCS,"[7] and cautions against reliance on the technology, given "concerns about storage safety and cost"[8] and the "non-negligible risk of carbon dioxide leakage from geological storage and the carbon dioxide transport infrastructure."[9]

In January 2021, the 1,500 member-organizations of Climate Action Network (CAN) International adopted a shared position statement that the largest network of climate organizations worldwide "does not consider currently envisioned CCS applications as proven sustainable climate solutions." The organizations warned that CCS "risks distracting from the need to take concerted action across multiple sectors in the near-term to dramatically reduce emissions." Accordingly, CAN urged that "[a]ll government subsidies, loans, grants, tax credit, incentives, and financial support for fossil fuels and technologies that use or otherwise support the continued use of fossil fuels, including CCS, should be phased out as soon as possible."[10]

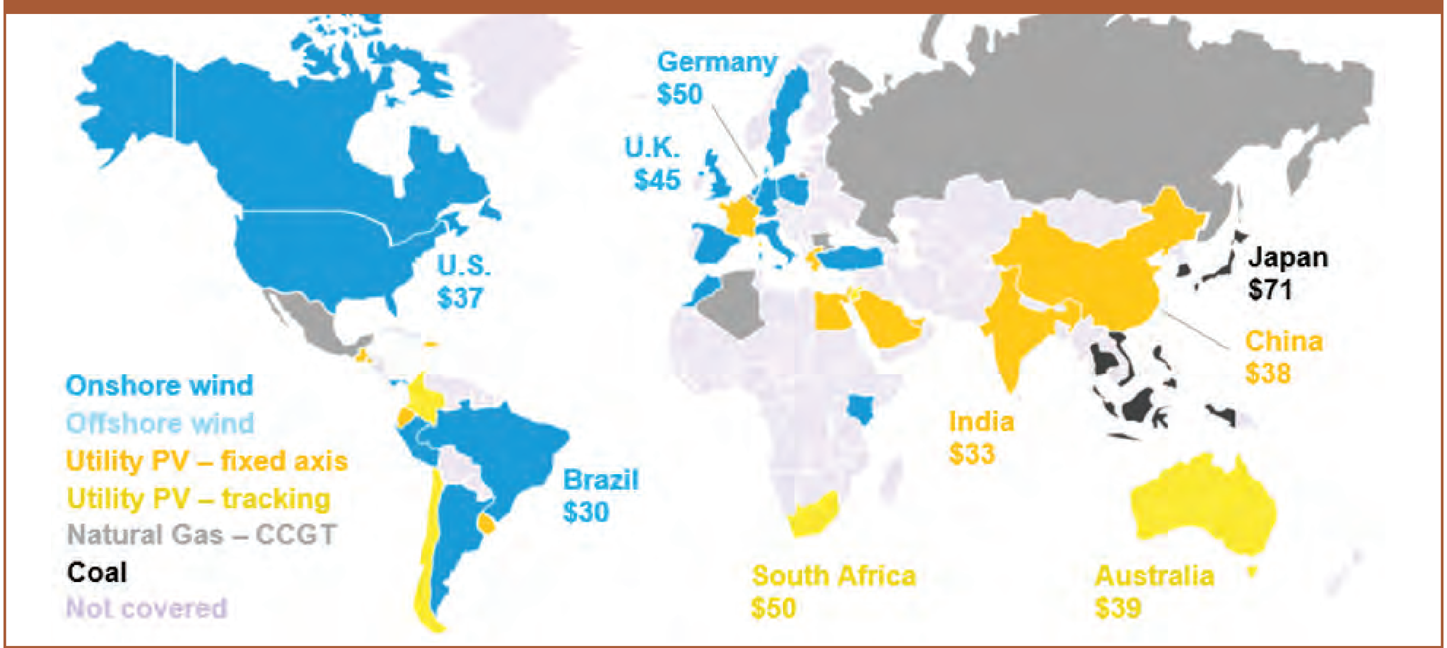
A 1.5°C pathway is possible without CCS. By transitioning the transportation, industry, and building sectors to 100 percent clean, renewable energy through rapid electrification and phase out of fossil fuels, and enhancing natural carbon sequestration through improved land management and restoration, it is possible to keep warming at or below 1.5° C *without* CCS.[11]

Clean energy is also cheaper energy. Plummeting renewable energy costs are rapidly making electrification with clean sources like solar and wind less expensive than producing power with fossil fuels.[12] A 2020 analysis by Bloomberg New Energy Finance found that solar and wind are already the cheapest energy sources for two-thirds of the world's population. Rapidly declining costs make renewable energy cheaper than continuing to operate existing coal and gas facilities in many places.[13]

Similarly, plummeting costs are quickly making battery storage a cheaper option for ensuring grid reliability than new gas peaker plants.[14] The US Energy Information Administration (EIA) projects that renewables will account for 71 percent of new US electricity generating capacity in 2021.[15]

The failure to account for the energy transition's market and technological disruptions to coal- and gas-fired power plants means not only that they are outcompeted

FIGURE 2
Cheapest Source of New Bulk Electricity Generation by Country



Source: *BloombergNEF.* Note: Levelized cost of energy (LCOE) calculations exclude subsides or tax credits. Graph shows benchmark LCOE for each country in US dollars per megawatt-hour. CCGT: Combined-cycle gas turbine.

Photo by Fabrice Duprez via Pixabay

by alternatives and systematically overvalued,[16] but also that "the overwhelming majority of these conventional facilities will become financially unviable and their assets stranded over the next decade or so."[17] Tacking CCS onto these soon-to-be stranded power plants is as economically ill-founded as it is environmentally unsound.

From a purely economic perspective, CCS does not make sense. Economists and energy analysts note that CCS projects are "prohibitively expensive compared to other GHG emissions mitigation options, such as renewable energy and energy storage technologies."[18] Adding CCS onto a fossil-fueled power plant inevitably makes operating the underlying source more expensive. As the authors of the energy transition study summarized above observed, "Coal and gas power plants with integrated carbon capture and storage (CCS) are doubly mispriced (overvalued)."[19] With coal- and gas-fired power stations already becoming more costly than renewable alternatives, adding CCS simply makes them even less economic and even less necessary.

A recent assessment of the economic viability of using CCS with gas-fired power plants demonstrates this reality, noting that mature carbon capture technologies are poorly suited to gas and pose an even larger energy penalty for fossil gas than for coal.[20] For a new-build gas-fired plant, CCS could more than double the construction costs and increase the cost of energy produced (known as levelized cost of energy) by up to 61 percent.[21]

As a result, CCS is not economic for gas-fired power plants even when it takes full advantage of existing federal subsidies, as discussed below, and when the captured carbon is used to produce more oil.[22] The authors of the study proposed a solution of injecting even more federal funding into CCS.

The simpler, surer, and cheaper solution is to end this and similar subsidies for the fossil fuel economy and invest the savings in accelerating the transition to clean energy.

Even for the Hard-to-Decarbonize Industrial Sector, CCS Is Not the Answer

The industrial sector accounted for 27 percent of US GHG emissions in 2019.[23] As the rationale for wide CCS deployment in the energy sector rapidly fades, CCS proponents are increasingly arguing that CCS will be needed to reduce emissions in heavy-emitting industries like steel, cement, petrochemicals, and aluminum. While the challenges to decarbonizing these industries are real, the potential for CCS to contribute to major emission reductions is routinely and often dramatically overstated. All too frequently, the advocacy for industrial CCS overlooks or downplays considerations like cost, alternatives to fossil fuel inputs, and the risks posed by transporting and storing captured carbon underground.

Applying CCS to high-emitting industrial activities, like petrochemical, steel, or cement manufacturing, is not economical. GHG emissions from these industries come from a diverse array of sources, including electricity consumption, on-site fossil fuel combustion, and process emissions, which make installing and operating CCS even more complex and generally more costly than it is in the power sector.

A recent analysis co-authored by a Chevron researcher highlights how these costs and complexities weaken the case for significant CCS deployment in the industrial sector. Beginning with a candidate pool of more than 1,500 US industrial facilities identified by the Environmental Protection Agency, the researchers immediately eliminated nearly 700 facilities, accounting for roughly half of all US industrial emissions, because the industries involved — including oil, gas, and coal production — "are not suitable for carbon capture retrofit."[24] By contrast, a transition away from fossil fuels would dramatically curtail such emissions.

From the remaining 656 facilities, the researchers identified only 123 facilities, less than 10 percent of the 1,500 facilities in the initial pool, that could capture carbon economically, even with full use of available federal subsidies and enhanced oil recovery.[25] And among that handful of facilities, many major sources of GHG emissions could not be captured.

For example, the petroleum refining industry is the largest source of industrial emissions other than fossil fuel production itself, yet less than 19 percent of refinery emissions were amenable to carbon capture. For metals processing, including steel, only a quarter of process emissions were amenable to CCS.[26] In total, the researchers identified only 68.5 metric tons of CO_2 per year from industrial process emissions that could be economically captured,[27] representing just 8 percent of all industrial emissions in the US.

Even this figure significantly overstates the potential of CCS in the industrial sector because the analysis excluded the indirect energy inputs that account for the largest single component of industrial sector emissions.[28] The authors did so on the grounds that the energy provided comes from the electrical grid, meaning associated emissions can be reduced more directly through other means, such as renewable energy.

Renewable sources for electricity and heat can dramatically reduce industrial emissions. Most industrial sector emissions are created by burning fossil fuels to produce the electricity and heat that power

FIGURE 3

Breakdown of the Number of Facilities and Their Emissions by Industrial Sector, Type of Emissions, and CO_2 Capture Potential

	refining[a]	chemicals	bioethanol	metals	minerals	pulp & paper	total
All Facilities in the Continuous U.S. Non-Suppliers of CO_2							
number of facilities	123	360	174	289	369	214	**1529**
total emissions [$MtCO_2$-eq/yr]	163	138	60	93	114	38	**606**
SC[b] [$MtCO_2$-eq/yr]	101	70	19	55	30	28	**303**
PE[b] [$MtCO_2$-eq/yr]	57	68	41[c]	37	84	10	**297**[c]
Facilities Considered for Carbon Capture Retrofit							
Number of facilities	97	104	174	118	163	0	**656**
total emissions [$MtCO_2$-eq/yr]	163	82	60	73	96	0	**473**
SC[b] [$MtCO_2$-eq/yr]	107	39	19	45	15	0	**225**
PE[b] [$MtCO_2$-eq/yr]	56	39	39	27	81	0	**242**
captured emissions [$MtCO_2$/yr]	40	26	37	19	72	0	**195**
Facilities Qualifying for the 45Q Tax Credit							
number of facilities	75	62	155	37	129	0	**458**
captured emissions [$MtCO_2$/yr]	39	24	36	17	71	0	**188**

[a]Refining category includes the emissions from the refining process and the hydrogen production at refineries. [b]SC = emissions from stationary combustion; PE = process emissions. [c]Process emissions from the ethanol industry are not reported by the EPA, the total process emissions reported by the EPA would thus equal to 256 $MtCO_2$/yr. In addition, this number excludes emissions from wastewater treatment and landfills that are not studied for point-source carbon capture in this work. Details are available in the Supporting Information.

Photo by HHakim via iStockphoto

manufacturing processes. Thus, decarbonizing the electricity grid by shifting to renewable sources provides the most direct route to slashing emissions in these industries. For example, the World Economic Forum estimates that 60 percent of carbon emissions from electricity-intensive aluminum production could be eliminated simply by producing that electricity from renewable sources.[29] In March 2021, a report by the International Aluminum Institute agreed that decarbonizing electricity grids provides the surest, most direct, and likely most cost-effective pathway to significant emission reductions in this energy-intensive industry.[30]

As currently equipped, the industrial sector uses fossil fuels not only for electricity, but for the heat that fuels industrial processes. Fossil fuel combustion for that heat accounts for about 58 percent of US industrial emissions and about 10 percent of overall global GHG emissions.[31] Electricity from clean power sources like solar and wind has the potential to provide low-carbon heat to many industrial systems.[32]

Concentrated solar thermal systems, for example, use solar energy for generating heat. One company has demonstrated this system works for reaching temperatures of more than 1,000°C.[33] From the heat used in kilns during the process of making cement,[34] to the high energy demand from electricity that goes into producing aluminum,[35] clean sources of electricity could displace fossil fuels consumed in a growing array of industrial processes, dramatically curtailing the largest single source of industrial GHG emissions and, with it, the purported benefits of CCS deployment in those industries.

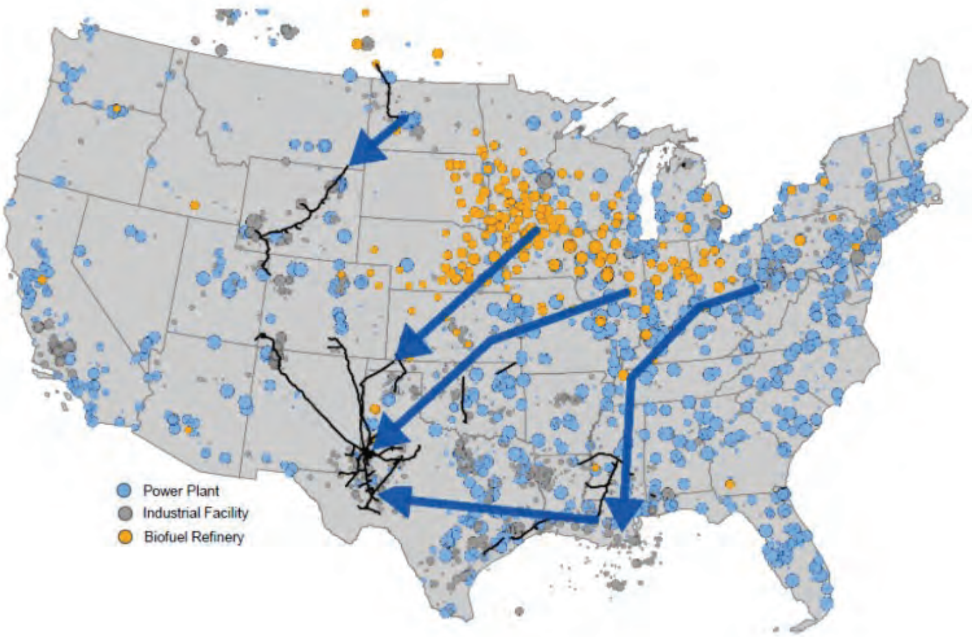
CCS obscures the role of reduction, reuse, and recycling in lowering industrial emissions. Proponents of industrial CCS routinely ignore that one of the most effective ways to reduce industrial emissions from high-emitting sectors like steel, aluminum, and plastics is to reuse existing materials, increase recycling rates, and produce less of the virgin material that is the major driver of emissions. This contrast is particularly notable in the case of plastics and petrochemicals, where the fracking boom of the last decade has driven a massive buildout of new plastics infrastructure even as communities around the world recognize that we need to reduce, not increase, our production and use of disposable plastics.

Even for aluminum, which is already heavily recycled, increasing the recycling of scrap metal could avoid 200 million tons of GHG emissions per year.[36] Replacing virgin steel with increased use of scrap metal or direct reduced iron also has high potential to reduce emissions from steel production — potential that should be tapped, given that CCS technology for steel remains immature and economically unproven, according to industry analysis.[37]

Applying CCS to industrial sources requires massive infrastructure buildout. Even assuming carbon can be captured effectively and economically from an industrial process, that does not assure it can be safely sequestered. The geographic distribution of CO_2 storage sites is a limiting factor for CCS deployment in industry.[38] The overwhelming majority of industrial facilities including those in high-emitting industries like cement, steel, and aluminum, were sited to ensure access to critical

FIGURE 4

Map of CO_2-Emitting Facilities Compared to Viable Geological Storage Sites



Elizabeth Abramson, Regional Carbon Capture and Transport Opportunities for Storage in Louisiana. Presentation to "Developing CCUS Projects in Louisiana and the Gulf Coast" (USDOE/USEA/GCCSI) November 17, 2020. *https://www.globalccsinstitute.com/wp-content/uploads/2020/11/PPT-LA_Day-1-and-Day-2.pdf* at slide 42.

resources like steam, electricity, water, and end markets, not carbon storage.

Accordingly, only a small fraction of existing or proposed facilities in these sectors are located in areas suitable for CO_2 storage. Storing carbon captured from such facilities would demand a vast network of new pipelines, some running hundreds of miles, and carrying hazardous CO_2 through populated areas.

Transporting carbon to storage sites and injecting it underground involves further risks and costs. As discussed more fully below, this reality means that the growing risks of carbon capture will be borne disproportionately by the few communities already living near concentrations of both heavy industry and potential storage or injection sites.

CCS Perpetuates Fossil Fuel Systems and Impacts

By design, CCS enables an underlying emissions-generating activity to continue — by capturing some of the CO_2 it would otherwise emit. The promise of CCS is being used to rationalize — and subsidize — continued investment in fossil fuel infrastructure that would lock in emissions of CO_2 and other pollutants for decades to come.

Even in its idealized form, CCS only prevents a fraction of emissions from the underlying source. At every stage of their lifecycle, including extraction, refining, transport, use, and disposal, fossil fuels release a wide array of pollutants, many of which pose known or suspected hazards to humans and the environment. For example, a study released in February 2021 by Harvard University and University College London researchers found that fine particulate matter (PM2.5) from burning fossil fuels is responsible for millions of deaths worldwide. In 2018, approximately one in five deaths overall, or 8.7 million premature deaths, were linked to PM2.5 pollution from fossil fuels.[39]

CCS does nothing to address these hazards.[40] Indeed, by requiring greater use of fossil fuels to power the CCS process itself, CCS may actually exacerbate them. In the energy sector, there is compelling evidence that the negative climate, environmental, and health impacts of adding carbon capture to fossil fuels are substantially greater than simply replacing fossil fuels altogether with clean alternatives.[41] As discussed more fully above, the deployment of industrial CCS raises similar concerns.

Using captured carbon to produce still more fossil fuels accelerates the climate crisis. At present, carbon capture is not economically viable without enhanced oil recovery or the production of combustible fuels, making the technology inseparable from the fossil economy. Enhanced oil recovery (EOR) is a technique through which CO_2 — either from natural sources or captured carbon — is injected into underground oil reservoirs to boost oil and gas production from old wells. In essence, CO_2 waste products from a fossil fuel-burning activity are used to generate more fossil fuels, propping up the unsustainable fossil fuel energy system.

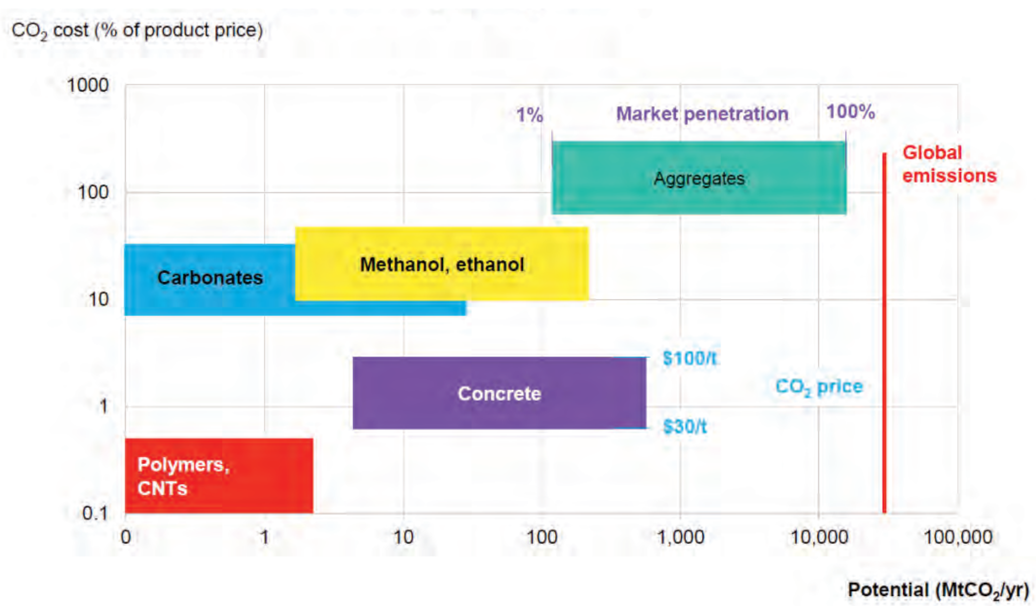
More than 80 percent of all CCS capacity deployed to date has been used for EOR.[42] And the majority of CCS projects in active development also incorporate EOR. The US Department of Energy estimates this could result in up to 48 billion additional barrels of oil used in the US alone by 2030.[43] This is disastrous from a climate mitigation perspective, since it will result in more oil extracted and more carbon emissions from the oil burned. The emissions impact from burning oil produced with CO_2 + EOR is currently excluded from lifecycle analyses touting the technology.[44] While the resulting CO_2 emissions may be invisible to carbon accountants, their presence in the atmosphere and their impact on the climate remains real and significant.

Proponents of CCUS argue that "[t]he most efficient strategy to reduce the concentration of CO_2 in the atmosphere is to convert it to useful chemicals and fuels."[45] But such proposals confront a fundamental challenge: global emissions of CO_2 are orders of magnitude greater than global demand for CO_2 in products. In 2018, the world emitted more than 37 billion tons of CO_2 and other GHGs from fossil fuel combustion for energy and industry.[46] By contrast, it used just 230 million tons of CO_2 for commercial purposes — equal to just 0.5 percent of total annual emissions. Two uses alone — EOR and fertilizer production — account for more than 85 percent of all CO_2 consumed globally.[47] All other commercial and industrial uses combined account for just 20 million tons of CO_2 each year, a mere drop in the bucket.

The touted uses of CO_2 are also unviable. Using captured carbon to produce combustible fuels, including via EOR, defeats any climate mitigation purpose, as the fuels release the carbon back into the atmosphere. Transforming CO_2 into chemicals requires massive

FIGURE 5

CO_2 Utilization Markets and Sensitivity to CO_2 Prices



BNEF Executive Factbook 2021 at 56: https://assets.bbhub.io/professional/sites/24/BNEF-2021-Executive-Factbook.pdf amounts of energy, which is why only a handful of commercialized chemicals use CO_2 in significant quantities.[48] Technologies for embedding captured carbon in plastics, for example, are currently confined to laboratory environments, and neither technologically nor economically proven at scale.[49] Just as importantly, using captured carbon to increase production of plastics — which are themselves made from fossil fuels — would compound the plastics crisis while doing little to address the climate crisis.[50] Proposals to store captured carbon in concrete are no more promising. Storing 1 pound of CO_2 requires 100 times its weight in concrete when embedded in cement mix and over 1,000 times its weight when embedded in standard concrete blocks.[51] Embedding coal combustion wastes or industrial slag in concrete does not eliminate smokestack emissions and increases risks of toxic leaching from the treated materials.[52] Just as using captured carbon to produce more oil increases emissions, embedding industrial wastes into new products does nothing to curb emissions from the activity that generated the waste.

CCS subsidies end up in oil industry pockets. The tax credit for CCS projects (under Section 45Q of the US Internal Revenue Code, which Congress extended in December 2020) is the main federal policy support for CCS. Its biggest beneficiaries are oil companies that claim the credit for injecting carbon into underground oil deposits to produce more oil, through EOR.[53] The tax credit thus functions as a fossil fuel subsidy.[54]

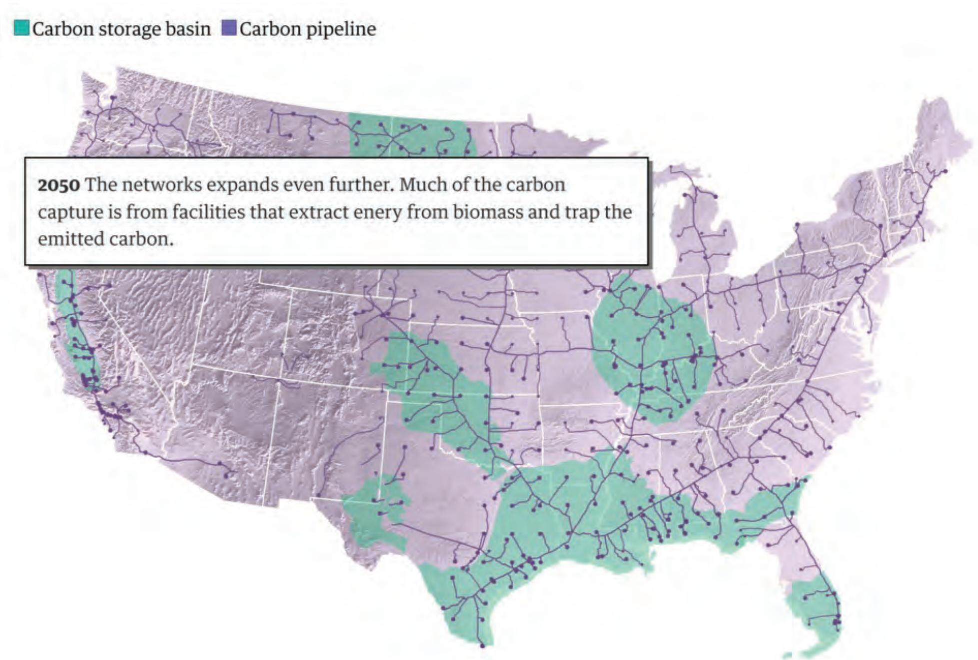
Moreover, the lack of adequate monitoring of CCS activities means claimed credits may be based on little more than hot air, not on stored carbon.[55] For example, an investigation by the US Treasury's Inspector General for Tax Administration found that fossil fuel companies improperly claimed nearly $900 million in tax credits under Section 45Q.[56]

The push for carbon capture and storage primarily benefits the fossil fuel industry. The most vocal and active proponents of CCS are oil and gas, petrochemical, and utility companies. They tout the necessity and promise of carbon capture to protect a business model that is contributing to climate catastrophe.[57]

In addition to investing directly in carbon capture ventures, companies in the fossil fuel industry promote

FIGURE 6

Map of Proposed US CO_2 Pipeline Network



Oliver Milman, Alvin Chang & Rashida Kamal, The race to Zero: can America reach net-zero emissions by 2050. The Guardian (March 15, 2021). https://www.theguardian.com/us-news/2021/mar/15/race-to-zero-america-emissions-climate-crisis

CCS advocacy, research, and policy through an array of corporate consortia, industry-government working groups, and funding partnerships with universities. For example, the Global CCS Institute, an international think tank dedicated to accelerating CCS deployment, includes various coal, oil and gas, and energy and utility companies as members, and a handful of national and sub-national governments.[58] Corporate polluters benefit from promoting CCS, while the environmental and community impacts of scaling up the CCS industry are too often ignored.

CCS Poses a Growing and Poorly Understood Threat to Communities & the Environment

Scaling up the technology and infrastructure required to capture, compress, transport, and store CO_2 entails significant risks.[59] Whether paired with fossil fuel power plants or industrial manufacturing, CCS technology demands massive infrastructure buildout. In terms of scale, it is estimated the CCS industry and associated infrastructure would need to be two to four times larger by 2050 than the current global oil industry.[60] As the IPCC has noted, extensive deployment of CCS "will require a large network of pipelines."[61] To date, the heavy environmental footprint and safety and health hazards[62] associated with CCS infrastructure have been largely overlooked.[63]

The transportation of compressed CO_2 raises a host of health and safety concerns. Especially when moved over long distances and/or through heavily populated areas, piping CO_2 poses risks similar to those associated with fossil fuel pipelines, from land disturbance and water contamination to the danger of explosions and other accidents. These risks are rarely disclosed or discussed in public discussion of CCS.

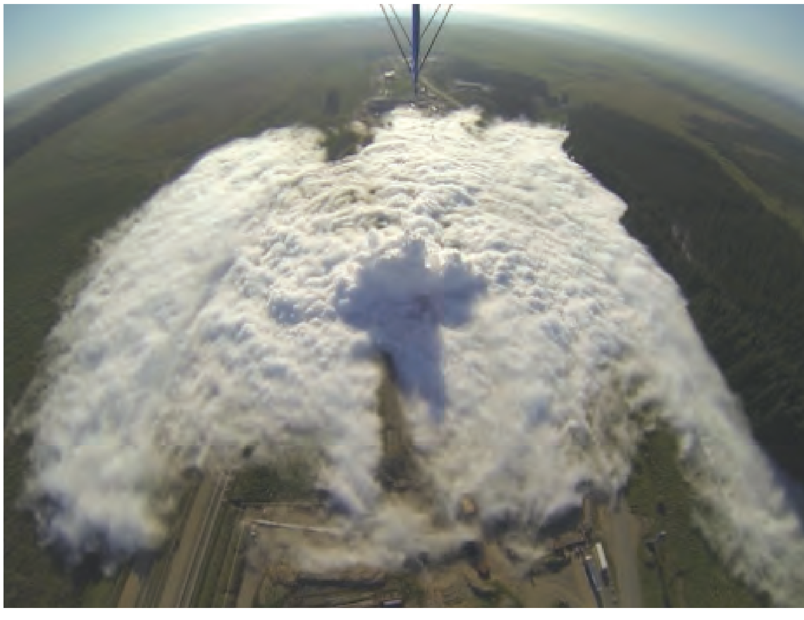
Effective transport through pipelines requires that CO_2 be shipped at very high pressure and extremely low temperatures, demanding pipelines capable of withstanding those conditions. The presence of moisture or contaminants can make this condensed CO_2 corrosive to the steel in those pipelines, increasing the risk of leaks, ruptures, and potentially catastrophic running fractures.

Because of the intense pressures involved, explosive decompression of a CO_2 pipeline releases more gas, more quickly, than an equivalent explosion in a gas pipeline.[64] Video recordings of pipeline failure tests under controlled conditions demonstrate that even a modest rupture can spread freezing CO_2 over a wide area within seconds.[65] The emergence of a running pipeline rupture could extend impacts the entire length of a pipeline segment.[66]

As a paper published by the Institution of Chemical Engineers Symposium cautions: "The combination of the massive amount of CO_2 released in a relatively short period of time, the resulting dense cloud followed by solid discharge and its slow sublimation will pose a major challenge to safety practitioners when dealing with the hazards associated with the failure of pressurized CO_2 pipelines."[67]

The IPCC recognizes that "carbon dioxide leaking from a pipeline forms a potential physiological hazard for humans and animals."[68] These risks take several forms.

The explosive rupture of a pipeline and its associated shockwave pose immediate physical risks to nearby people and property. In areas closest to the pipeline, a release of CO_2 can quickly drop temperatures to minus 60°C, coating the surrounding area with super-cold dry ice.[69] At high concentrations, CO_2 is a toxic gas and an



CO_2 cloud from a rupture test performed at DNV GL Spadeadam, Photo: DNV GL

Photo Credit: Mississippi Emergency Management Agency

asphyxiant capable of causing “rapid ‘circulatory insufficiency’, coma and death.”[70] And potential contaminants in CO_2 streams, such as hydrogen sulfide (H_2S) can dramatically compound these risks.[71]

Accidents are inevitable as CO_2 pipelines are increasingly built in populated areas. In February 2020, a 24-inch high-pressure pipeline containing carbon dioxide and sulfur dioxide ruptured in Yazoo County, Mississippi. According to the Mississippi Emergency Management Agency, more than 300 residents were evacuated and[46] dozens were hospitalized.[72] The pipeline owner, Denbury Enterprises, operates hundreds of miles of CO_2 pipelines in the Gulf Coast and Rocky Mountain regions. At least two Denbury pipelines run through the heavily polluted petrochemical corridor known as Cancer Alley,[73] predominately populated by communities of color.

These safety hazards and environmental risks fall disproportionately on marginalized communities. Fossil fuel and petrochemical infrastructure, and the threats to health and public safety that infrastructure creates, already overburden Black, Brown, and Indigenous communities. The deployment of CCS threatens to significantly increase these risks, particularly in the regions being most heavily targeted for new CCS buildouts.

Both the Gulf Coast of Texas and Cancer Alley in southern Louisiana have been widely touted as potential epicenters for industrial CCS development due to existing concentrations of oil, gas, and petrochemical infrastructure, along with oil fields and salt domes that are the most viable injection and storage sites.[74] CCS proposals in other regions also focus on areas where energy and industrial infrastructure are concentrated, which are typically in or adjacent to poor neighborhoods and communities of color. The expansion of CCS would add a significant new source of pollution and safety risks in Black, Brown, and Indigenous communities already suffering the disproportionate and deadly impacts of environmental racism.

Conclusion

CCS and CCUS are not only unnecessary, ineffective, uneconomic, and unsafe; the technologies are also exceptionally risky, prop up the fossil fuel industry and carbon-intensive industrial activities, and distract from the urgent task of transitioning away from fossil fuels at a time when the US and the world must dramatically accelerate that transition. These technologies, and the dangerous myth they perpetuate of climate-safe fossil fuels, have no place in US climate policies and financing. Such policies should focus instead on phasing out fossil fuels and implementing proven climate mitigation strategies on an urgent, comprehensive basis, reflecting their fundamental importance for this and all future generations.

Endnotes

1. Carbon Capture, Utilization & Storage, U.S. Department of Energy (last visited Feb. 9, 2021).
2. For a recent scientific review of the climate and environmental impacts of CCS/CCUS in coal and gas-fired power plants, see M. Z. Jacobson, Evaluation of Coal and Natural Gas with Carbon Capture as Proposed Solutions to Global Warming, Air Pollution, and Energy Security in M.Z. Jacobson, 100% Clean, Renewable Energy and Storage for Everything (2020).
3. S. Garcia Freites & C. Jones, Tyndall Centre, A Review of the Role of Fossil Fuel-Based Carbon Capture and Storage in the Energy System (2021), at 12.
4. J. Smyth, Petra Nova carbon capture project stalls with cheap oil, Energy & Policy Inst. (Aug. 6, 2020); N. Groom, Problems plagued U.S. CO2 capture project before shutdown: document, Reuters (Aug. 6, 2020); see also nrg, Petra Nova: Carbon capture and the future of coal power (last visited May 18, 2021).
5. N. Groom, Power plant linked to idled U.S. carbon capture project will shut indefinitely - NRG, Reuters (Jan. 29, 2021).
6. IPCC, Summary for Policymakers in IPCC, Global Warming of 1.5°C: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (2018) [hereinafter IPCC SR1.5], at 14, Section C.1.1., Figure SPM 3b (Pathway 1); see also IPCC SR1.5, at Ch. 2.3.3 and Table 2.SM.12.
7. Id., Ch. 2, Section 2.4.2.3.
8. Id., Ch. 4, Table 4.13.
9. Id., Ch. 5, Section 5.4.1.2.
10. CAN Position: Carbon Capture, Storage, and Utilization, Climate Action Network Int'l (2021), at 6.
11. Achieving the Paris Climate Goals in the COVID-19 era, F20 (2020).
12. Projected Costs of Generating Electricity, 2020 Edition, International Energy Agency & Nuclear Energy Agency (2020).
13. Scale Up of Solar and Wind Puts Existing Coal and Gas at Risk, Bloomberg New Energy Finance (Apr. 28, 2020).
14. A. Colthorpe, BloombergNEF: 'Already cheaper to install new-build battery storage than peaking plants', Energy Storage News (Apr. 30, 2020, 10:16 AM).
15. S. Ray, Renewables account for most new U.S. electricity generating capacity in 2021, U.S. Energy Information Administration (Jan. 11, 2021).
16. J. Anderson, Miscalculated levelized cost of electricity data has overvalued power plants: study, S&P Global/Platts (Mar. 15, 2020) (reporting on Dorr & Seba, infra note 17).
17. Dorr & T. Seba, RethinkX, The Great Stranding: How Inaccurate Mainstream LCOE Estimates are Creating a Trillion-Dollar Bubble in Conventional Energy Assets, (2021), at 7.
18. Butler, Institute for Energy Economics and Financial Analysis, Carbon Capture and Storage Is About Reputation, Not Economics (2020).
19. Dorr & Seba, supra note 17, at 7, 23.
20. P. Psarras et al., Cost analysis of carbon capture and sequestration from U.S. natural gas fired power plants, 54 Envtl. Sci. Tech. 6272, 6273 (2020).
21. Id. at 6274.
22. Id. at 6277.
23. US EPA, Draft Inventory of US Greenhous Gas Emissions and Sinks: 1990-2019, at 2.14-2.15, Table 2-5 (published for public review and comment, 86 Fed. Reg. 9339 (Feb. 12, 2021)).
24. H. Pilorgé et al., Cost Analysis of Carbon Capture and Sequestration of Process Emissions from the U.S. Industrial Sector, 54(12) Envtl. Sci. Tech. 7524-7532 (2020).
25. Id.
26. Id. at Supporting Information, S8.
27. Id.
28. Id. at Supporting Information, S2.
29. World Econ. Forum, Aluminum for Climate: Exploring Pathways to Decarbonize the Aluminum Industry (2020), at 10, 13.
30. Int'l Aluminum Inst., Aluminum Sector Greenhouse Gas Pathways to 2050 (Mar. 2021), at 10 & Figure 10.
31. S. Julio Friedmann et al., Low-Carbon Heat Solutions for Heavy Industry: Sources, Options, and Costs Today, Columbia Univ. Ctr. on Global Energy Policy (2019), at 10.
32. Id. at 23.
33. D. Quick, Concentrated solar viable for industrial uses after exceeding 1,000°C, New Atlas (Nov. 21, 2019).
34. M. Barnard, Cement's CO2 Emissions are Solved Technically, But Not Economically, CleanTechnica (Nov. 26, 2019).
35. Int'l Energy Agency, Aluminum: Tracking report - October 2020 (2020).
36. Int'l Aluminum Inst., supra note 30, at 16.
37. C. Hoffman et al., Decarbonization Challenge for Steel, McKinsey and Company (June 3, 2020).
38. Friedmann et al., supra note 31, at 12.
39. K. Vohra et al., Global mortality from outdoor fine particulate pollution generated by fossil fuel combustion: Results from GEOS-Chem, 195 Envtl. Research 110754 (2021).
40. See, e.g., Jacobson, supra note 2, at 3.1.2.
41. T. Kubota, Stanford study casts doubt on carbon capture, Stanford News, (Oct. 25, 2019); M. Jacobson, The health and climate impacts of carbon capture and direct air capture, 12 Energy & Envtl. Sci. 3567 (2019).
42. Freites, supra note 3, at 3.
43. Dept. of Energy-Nat'l Energy Tech. Lab., Carbon Dioxide Enhanced Oil Recovery: Untapped Domestic Energy Supply and Long Term Carbon Storage Solution (2010), at 20.
44. Carbon dioxide capture, transportation and geological storage — Carbon dioxide storage using enhanced oil recovery (CO2-EOR), ISO 27916:2019.
45. S. Samanta & R. Srivastava, Catalytic conversion of CO2 to chemicals and fuels: the collective thermocatalytic/photocatalytic/electrocatalytic approach with graphitic carbon nitride, 1(6) Materials Advances 1506, 1508 (2020).
46. Z. Hausfather, Analysis: Fossil Fuel Emissions in 2018 Increasing at Fastest Rate for Seven Years, Carbon Brief (Dec. 5, 2018, 6:00 PM).
47. K. Novak Mavar, N. Gaurina-Medimurec, L. Hrnčević, Significance of Enhanced Oil Recovery in Carbon Dioxide Emission Reduction, 13(4) Sustainability 1, 3 (Table 1) (2021) (showing that 91% of all CO2 used commercially is used for enhanced oil and gas recovery (including enhanced coalbed methane), and fertilizer production).
48. Nat'l Acads. of Scis., Eng'g, and Med., Gaseous Carbon Waste Streams Utilization: Status and Research Needs (2019), at 63-64.
49. G. Chui, Fuels, Plastics, and Feedstocks from CO2? They're Working On It, SLAC Nat'l Acceleratory Lab. (Sept. 9, 2019) ("We concluded that renewable energy prices

would have to fall below 4 cents per kilowatt hour, and systems would need to convert incoming electricity to chemical products with at least 60% efficiency, to make the approach economically competitive with today's methods.").

50. Ctr. for Int'l Envtl. Law (CIEL), Plastics and Climate: The Hidden Costs of a Plastic Planet (2019), at 2-5.
51. CO2 Mineralization—Applications, Carbon Cure (last visited June 21, 2021).
52. See, e.g., M. Huang et al., Leaching Behavior of Heavy Metals from Cement Pastes Using a Modified Toxicity Characteristic Leaching Procedure (TCLP), 96 Bulletin Envtl. Contamination & Toxicology 354 (2016) (reporting standard testing protocols reported lower levels of toxic metal leaching from cement produced using industrial slags than were evident in a modified testing procedure more suited to cement rotary kiln processing products).
53. N. Kusnetz, Exxon Touts Carbon Capture as a Climate Fix, but Uses it to Maximize Profit and Keep Oil Flowing, InsideClimate News (Sept. 27, 2020).
54. J. Redman, Expanding Subsidies for CO2-Enhanced Oil Recovery: A Net Loss for Communities, Taxpayers, and the Climate, Oil Change Int'l (Oct. 24, 2017).
55. Letter from J. Russel George, Inspector General for Tax Administration, U.S. Envtl. Protection Agency, to Senator Robert Menendez (Apr. 15, 2020).
56. Press Release, Senator Robert Menendez, Menendez Releases Inspector General Investigation Finding Fossil Fuel Companies Improperly Claimed Nearly $1B in Clean Air Tax Credits (Apr. 30, 2020).
57. CIEL, Fuel to the Fire (2019), at 19-22.
58. See Global CCS Institute Members, Global CCS Institute (last visited Apr. 16, 2021).
59. J. Sekera & A. Lichtenberger, Assessing Carbon Capture: Public Policy, Science, and Societal Need, 5(14) Biophys. Econ. Sust. 11-12, 18-20 (2020).
60. N. Mac Dowell et al., The role of CO2 capture and utilization in mitigating climate change, 7 Nature Climate Change 243 (2017).
61. IPCC Special Report on Carbon Dioxide Capture and Storage, Chapter 4: Transport of CO2 (2005), at 181.
62. J. Fogarty & M. McCally, Health and Safety Risks of Carbon Capture and Storage, 303(1) JAMA 67 (2010).
63. Sekera & Lichtenberger, supra note 59.
64. H. Mahgerefteh, G. Denton & Y. Rykov, Pressurised CO2 pipeline rupture, Inst. of Chem. Eng'rs Symposium Series (2008), at 869-879; E. Aursand et al., Fracture propagation control in CO2 pipelines: Validation of a coupled fluid-structure model, SINTEF Energy Research (2016), at 1, ("Compared to natural-gas pipelines, the pressure level at the opening fracture flaps is sustained at a much higher level and at a much longer distance behind the moving fracture tip. This may be one important reason why the existing engineering methods do not work for dense-phase CO2.").
65. Dense phase CO2 8" NB pipe rupture, DNV GL (last visited Apr. 16, 2021).
66. S.T. Munkejord, Understanding the forces at play when boiling CO2 drives a running pipeline fracture, #SINTEFblog (June 14, 2016). See also a video demonstration at the same link.
67. Mahgerefteh et al., supra note 64, at 869.
68. IPCC Special Report on Carbon Dioxide Capture and Storage Chapter 4, supra note 61, at 188.
69. See, e.g., Mahgerefteh, supra note 64, manuscript at 6.
70. P. W. Parfomak & P. Folger, Congressional Research Service, Carbon Dioxide (CO2) Pipelines for Carbon Sequestration: Emerging Policy Issues (2007), at 15.
71. X. Liu, A. Godbole, C. Lu, G. Michal & P. Venton, Study of the consequences of CO2 released from high pressure pipelines, 116 Atmospheric Env't 51-64 (2015), manuscript at 26 ("If the CO2 stream contains H2S, the H2S may present a greater hazard than the CO2 itself.").
72. Pipeline Ruptures in Yazoo County, Dozens Rushed to the Hospital, Miss. Emergency Mgmt. Agency (Feb. 23, 2020).
73. Gulf Coast CO2 Pipelines, Denbury (last visited June 21, 2021).
74. D. Dismukes et al., Integrated Carbon Capture and Storage in the Louisiana Chemical Corridor (2019).

CIEL
CENTER for INTERNATIONAL ENVIRONMENTAL LAW

1101 15th Street NW, #1100, Washington, DC 20005
15 rue des Savoises, 1205 Geneva, Switzerland
www.ciel.org

Confronting the Myth of Carbon-Free Fossil Fuels: Why Carbon Capture Is Not a Climate Solution was prepared by Dana Drugmand and Carroll Muffett of the Center for International Environmental Law (CIEL), with editorial assistance from Nikki Reisch, Steven Feit, and Cate Bonacini.

Cite as: Conley *et al.*, *Science* 10.1126/science.aaf2348 (2016).

Methane emissions from the 2015 Aliso Canyon blowout in Los Angeles, CA

S. Conley,[1,2]*† G. Franco,[3] I. Faloona,[2] D. R. Blake,[4] J. Peischl,[5,6] T. B. Ryerson[6]†

[1]Scientific Aviation, Boulder, CO, USA. [2]Department of Land, Air, and Water Resources, University of California–Davis, Davis, CA, USA. [3]Research and Development Division, California Energy Commission, Sacramento, CA, USA.[4]Department of Chemistry, University of California–Irvine, Irvine, CA, USA. [5]Cooperative Institute for Research in Environmental Sciences, University of Colorado–Boulder, Boulder, CO, USA. [6]Earth System Research Laboratory, National Oceanic and Atmospheric Administration, Boulder, CO, USA.

***Corresponding author. E-mail: sconley@scientificaviation.com**

†These authors contributed equally to this work.

Single-point failures of the natural gas infrastructure can hamper deliberate methane emission control strategies designed to mitigate climate change. The 23 October 2015 blowout of a well connected to the Aliso Canyon underground storage facility in California resulted in a massive release of natural gas. Analysis of methane (CH_4) and ethane (C_2H_6) data from dozens of plume transects from 13 research aircraft flights between 7 Nov 2015 and 13 Feb 2016 shows atmospheric leak rates of up to 60 metric tonnes of CH_4 and 4.5 metric tonnes of C_2H_6 per hour. At its peak this blowout effectively doubled the CH_4 emission rate of the entire Los Angeles Basin, and in total released 97,100 metric tonnes of methane to the atmosphere.

Underground storage of large volumes of processed natural gas is used to accommodate variability in energy demand on diurnal to seasonal time scales. Underground storage facilities constitute strategic gas reserves in many countries worldwide, with a volume equal to 10% of global annual consumption (*1*). Roughly 86% of stockpiled natural gas in the U.S. is stored at high pressure in depleted subsurface oil reservoirs (*2*). The Aliso Canyon storage facility, a depleted subsurface oil reservoir in the San Fernando Valley 40 km northwest of Los Angeles, CA, has a total capacity of 4.79×10^9 m^3 at standard temperature and pressure [168 billion standard cubic feet (SCF)], of which only 86 billion SCF (the "working capacity") is routinely accessed for commercial use (*2*). It is the fourth largest facility of its kind in the U.S., accounting for 2.1% of the total U.S. natural gas storage in 2014 (*2*). Processed natural gas is composed primarily of methane (CH_4), a powerful greenhouse gas, and ethane (C_2H_6), both of which can lead to background tropospheric ozone production; at sufficiently high concentrations, natural gas leaks pose an explosion hazard and if inhaled can induce nausea, headaches, and impaired coordination. Exposure to odorants added to natural gas, typically sulfur-containing compounds such as tetrahydrothiophene ($(CH_2)_4S$) and 2-methylpropane-2-thiol (*t*-butyl mercaptan; $(CH_3)_3CSH$) can cause short-term loss of the sense of smell, headaches, and respiratory tract irritation. Major natural gas leaks therefore can have adverse impacts on climate, air quality, and human health.

On 23 October 2015 a major natural gas leak of indeterminate size was reported in the Aliso Canyon area and was later identified as originating from SS-25, one of 115 wells connected to the subsurface storage reservoir. The SS-25 well began oil production in 1954 and was converted to a gas storage well in 1973 (*3*). Seven unsuccessful attempts to shut in the leak have been reported. A relief well intercepted the leaking pipe at a depth of ~8500 feet, below the subsurface breach; heavy fluid injection (a "bottom kill") temporarily halted the leak on 11 February, and cement injection sealed the well on 18 February 2016 (*4*).

We deployed a chemically-instrumented Mooney aircraft in 13 flights from 7 November 2015 to 13 February 2016. We measured CH_4 and C_2H_6 to quantify the atmospheric leak rate and to assess air quality downwind of the leaking well (*5*). Ground-based whole-air sampling (WAS) into stainless-steel canisters on 23 Dec 2015 followed by laboratory analysis provided chemical speciation of the leaking hydrocarbon mixture. We used the continuous airborne data and the ground-based WAS canister data to fingerprint the plume chemical composition, quantify the atmospheric leak rate, and document trends in the leak rate over time.

The airborne chemical data show the continuing transport on northerly winds of exceptionally high concentrations of CH_4 and C_2H_6 into the densely populated San Fernando Valley a few kilometers south of the leaking well (Fig. 1). The plume C_2H_6-to-CH_4 enhancement ratio (ER) derived from linear-least-squares regression fits to the continuous airborne data on 23 Dec 2015 is identical, within total uncertainties propagated by quadrature addition of errors (*6*), to the plume ER derived from WAS canister data taken at the surface on the same day (Fig. 2A).

The hydrocarbon composition of WAS canister samples taken at surface locations in the San Fernando Valley (Fig. 1) on 23 Dec 2015 (*5*) is consistent with a leak of pipeline-quality processed natural gas with a hydrocarbon composition of ~95% CH_4, ~4% C_2H_6, and ~0.3% C_3H_8 (propane) (table S1). Plume enhancements of natural gas liquids (ethane through butanes) and condensates (pentanes and higher hydrocarbons that are liquid at ambient temperature and pressure) were detected (table S1) and are likely responsible for reports of oily deposits on surfaces in affected residential areas downwind. Trace enhancements of benzene, toluene, ethylbenzene, and xylene isomers (the so-called BTEX compounds) were also detected at ratios of 0.001% or lower relative to CH_4 (table S1).

Benzene is a known human carcinogen (*7*); thus population exposure to benzene from the Aliso Canyon leak has received particular attention. Composition data from the WAS canisters indicates a benzene-to-CH_4 enhancement ratio of $(5.2 \pm 0.1)\times10^{-6}$ (uncertainties throughout are ±1 standard error of the mean), broadly consistent with an ER of $\sim7\times10^{-6}$ derived from highly concentrated samples collected ~10 feet downwind of the SS-25 well site and posted online (*8*). Together these samples suggest minimal variation over time in the benzene composition of the leaking gas. Publicly available benzene data reported in near-daily 12-hour air samples (*9*) were often below the 1 nanomole/mole (part-per-billion; ppb) detection limit of the contract laboratories used for the analyses, but also show a relatively constant ER over time. We note that plume benzene enhancements can be estimated from the abundant CH_4 data by multiplying plume CH_4 enhancements by the benzene-to-CH_4 ER determined using the research-grade WAS canister samples.

Sulfur-containing odorants were not measured, but concentrations above the odor threshold are estimated similarly (Fig. 1) from observed CH_4 enhancements by assuming an industry-standard value of ~5 parts per million of total odorant in processed natural gas (*10*).

Continuous airborne CH_4 and C_2H_6 data were taken on each flight between 11 AM and 3:30 PM local time with a resolution of 30 m along track during repeated crosswind transects at multiple altitudes from 60 to 1400 m above ground. These data define the horizontal and vertical extent of the leaking natural gas plume on each flight (Fig. 1 and fig. S1). These flights provided highly spatially resolved data from which an atmospheric mass flux can be accurately calculated (*11*) within well-defined uncertainties (*12*). Plumes from nearby landfills have low concentrations of CH_4, are clearly identified by lack of co-emitted C_2H_6, and were eliminated from further analysis. Background levels of CH_4 and C_2H_6 were measured during aircraft transects on multiple flights immediately upwind, confirming the SS-25 well as the dominant source of enhanced natural gas to the region. Operational restrictions on aircraft flight patterns were imposed by the elevated terrain at the leak site, the highly controlled airspace of the San Fernando Valley, and proximity to approach corridors of the nearby Van Nuys airport (Fig. 1). These restrictions were overcome by performing crosswind transects at multiple altitudes immediately downwind of the leak site which afforded accurate reconstruction of a vertical concentration profile, even before the plume completely mixed through the full vertical extent of the atmospheric boundary layer (*5*).

The chemical data show that the airborne sampling captured the full vertical extent of the lofted plumes on each flight day (fig. S1). Atmospheric mass fluxes calculated from the chemical data during each downwind transect (*5*) suggest an average leak rate of 53 ± 6 tonnes of CH_4 and 3.9 ± 0.5 tonnes of C_2H_6 per hour for the first six weeks of the leak, and decreasing thereafter (Fig. 2B and table S2). The decreasing trend beginning around the first week of December 2015 (Fig. 2B and table S2) is consistent with decreasing reservoir pressure following withdrawal of gas, in a deliberate effort to slow the leak rate, via the other storage wells connected to the subsurface reservoir (*13*). The absence of a decrease in the leak rate after the first week of January 2016 is consistent with cessation of withdrawals to maintain a minimum working pressure in the reservoir, which throughout the leak duration supplied natural gas to customers in the greater Los Angeles Basin.

These data demonstrate the blowout of a single well in Aliso Canyon temporarily created the largest known anthropogenic point source of CH_4 in the U.S. (*14*), effectively doubling the leak rate of all other sources in the Los Angeles Basin combined (*15, 16*). Further, at its peak this leak rate exceeded that of the next largest point source in the U.S. – an underground coal mine in Alabama - by over a factor of 2 (*14*) and was a factor of 10 larger than the CH_4 leak rate reported from the Total *Elgin* rig blowout in the North Sea in 2012 (*17*). The Aliso Canyon CH_4 leak rates were comparable to total CH_4 emission rates of entire oil and gas production regions in the U.S. (*e.g.*, Barnett shale, 76 tonnes per hour (*18*); Haynesville shale, 80 tonnes per hour (*19*); Fayetteville shale, 39 tonnes per hour (*19*); northeastern Marcellus shale, 15 tonnes per hour (*19*)).

Our aircraft flights following the "bottom kill" confirmed cessation of flow from the SS-25 well on 11 February 2016 and revealed a residual leak rate of < 1 ton per hour of CH_4 (Fig. 2B and table S2), consistent with nonzero leak rates observed from other natural gas, oil, and petrochemical facilities nationwide (*16*, *18–24*). These data show the Aliso Canyon natural gas leak duration of 112 days released a total of 97,100 tonnes (5.0 billion SCF) of CH_4 (Fig. 2C) and 7,300 tonnes of C_2H_6 to the atmosphere, equal to 24% of the CH_4 and 56% of the C_2H_6 emitted each year from all other sources in the Los Angeles Basin combined (*16*).

This CH_4 release is the second-largest of its kind recorded in the U.S., exceeded only by the 6 billion SCF of natural gas released in the collapse of an underground storage facility in Moss Bluff, TX in 2004, and greatly surpassing the 0.1 billion SCF of natural gas leaked from an underground storage facility near Hutchinson, KS in 2001 (*25*). Aliso Canyon will have by far the largest climate impact, however, as an explosion and subsequent fire during the Moss Bluff release combusted most of the leaked CH_4, immediately forming CO_2. The total release from Aliso Canyon will substantially impact the State of California greenhouse gas (GHG) emission targets for the year (*26*) and is equivalent to the annual energy sector CH_4 emissions from medium-sized EU nations (*27*). The radiative forcing from this amount of CH_4, integrated over the next 100 years, is equal to that from the annual GHG emissions from 572,000 passenger cars in the U.S. (*28*). The volume of CH_4 released represents only 3% of the total capacity of the Aliso Canyon storage facility, raising the possibility of substantial additional emissions if the leaking SS-25 well had not been sealed, or the remaining natural gas not completely withdrawn through other wells, before the reservoir had been completely exhausted to the atmosphere.

We note that the agreement reached at the 21st Conference of the Parties (COP21) to the Framework Convention on Climate Change (*29*) includes specific requirements for the Parties to account for anthropogenic GHG emissions with accuracy and completeness. In the post-COP21 world, rapid evaluation of episodic releases of GHGs like the Aliso Canyon blowout will be an essential contribution to meeting these requirements.

Our analysis quantifies a massive CH_4 release using a rapid, direct, and repeatable method with known accuracy. As such, results from this method serve as reference values for less direct and timely estimates using retrievals of surface (*30, 31*), airborne (*32*), and/or satellite remote sensing observations (*33*). For example, our airborne method offers an *a priori* estimate of the Aliso Canyon leak rates for inverse modeling methods that analyze continuous in situ CH_4 monitoring data from fixed ground sites (*15, 34*). This incident highlights the utility of rapid-response airborne chemical sampling method in providing an independent, time-critical, accurate, spatially and temporally resolved leak rate, as well as plume location and plume composition. Such information helps document human exposure, formulate optimal well control intervention strategies, quantify the efficacy of deliberate control measures, and assess the climate and air quality impacts of major unanticipated chemical releases to the atmosphere (*35, 36*).

REFERENCES AND NOTES

1. S. Cornot-Gandolphe, *Underground Gas Storage in the World 2013: Executive Summary* (Centre International d'Information sur le Gaz Naturel et tous Hydrocarbures Gazeux, Rueil-Malmaison, France, 2015).
2. www.eia.gov/cfapps/ngqs/ngqs.cfm?f_report=RP7.
3. State of California Department of Conservation, Division of Oil and Gas, *Report on Proposed Change of Well Designation* (1991); ftp://ftp.consrv.ca.gov/pub/oil/Standard_Sesnon_25_API_037-00776_Well_File/03700776_DATA_03-19-2008.pdf.
4. SoCalGas, press release (18 February 2016); www.alisoupdates.com/1443738511730/press-release-doggr-confirms-en.pdf.
5. Materials and methods are available as supplementary materials on *Science* Online.
6. P. R. Bevington, D. K. Robinson, *Data Reduction and Error Analysis in the Physical Sciences* (McGraw-Hill, ed. 3, 2003).
7. http://cfpub.epa.gov/ncea/iris2/chemicalLanding.cfm?substance_nmbr=276.
8. srvwww.aqmd.gov/home/regulations/compliance/aliso-canyon-update/gas-sample-near-leaking-well/laboratory-results.
9. www.socalgas.com/newsroom/aliso-canyon-updates/aliso-canyon-air-sample-results.
10. www.pge.com/pipeline/operations/sulfur/sulfur_info_values/index.page.
11. W. H. White, J. A. Anderson, D. L. Blumenthal, R. B. Husar, N. V. Gillani, J. D. Husar, W. E. Wilson Jr., Formation and transport of secondary air pollutants: Ozone and aerosols in the St. Louis urban plume. *Science* **194**, 187–189 (1976). Medline doi:10.1126/science.959846
12. T. B. Ryerson, M. Trainer, J. S. Holloway, D. D. Parrish, L. G. Huey, D. T. Sueper, G. J. Frost, S. G. Donnelly, S. Schauffler, E. L. Atlas, W. C. Kuster, P. D. Goldan, G. Hubler, J. F. Meagher, F. C. Fehsenfeld, Observations of ozone formation in power plant plumes and implications for ozone control strategies. *Science* **292**, 719–723 (2001). Medline doi:10.1126/science.1058113
13. SoCalGas, press release (11 February 2016); www.alisoupdates.com/1443738468372/SoCalGas-Temporarily-Controls-Flow-of-Gas-021116-2.pdf.
14. http://ghgdata.epa.gov/ghgp/service/html/2014?id=1010328&et=undefined.
15. S. Jeong, C. Zhao, A. E. Andrews, L. Bianco, J. M. Wilczak, M. L. Fischer, Seasonal variation of CH_4 emissions from central California. *J. Geophys. Res.* **117**, D11306 (2012). doi:10.1029/2011JD016896
16. J. Peischl, T. B. Ryerson, J. Brioude, K. C. Aikin, A. E. Andrews, E. Atlas, D. Blake, B. C. Daube, J. A. de Gouw, E. Dlugokencky, G. J. Frost, D. R. Gentner, J. B. Gilman, A. H. Goldstein, R. A. Harley, J. S. Holloway, J. Kofler, W. C. Kuster, P. M. Lang, P. C. Novelli, G. W. Santoni, M. Trainer, S. C. Wofsy, D. D. Parrish, Quantifying sources of methane using light alkanes in the Los Angeles basin, California. *J. Geophys. Res., D, Atmospheres* **118**, 4974–4990 (2013). doi:10.1002/jgrd.50413
17. Total, press release (11 March 2013); http://www.elgin.total.com/elgin/pressrelease.aspx.
18. A. Karion, C. Sweeney, E. A. Kort, P. B. Shepson, A. Brewer, M. Cambaliza, S. A. Conley, K. Davis, A. Deng, M. Hardesty, S. C. Herndon, T. Lauvaux, T. Lavoie, D. Lyon, T. Newberger, G. Pétron, C. Rella, M. Smith, S. Wolter, T. I. Yacovitch, P. Tans, Aircraft-based estimate of total methane emissions from the Barnett shale region. *Environ. Sci. Technol.* **49**, 8124–8131 (2015). Medline doi:10.1021/acs.est.5b00217
19. J. Peischl, T. B. Ryerson, K. C. Aikin, J. A. de Gouw, J. B. Gilman, J. S. Holloway, B. M. Lerner, R. Nadkarni, J. A. Neuman, J. B. Nowak, M. Trainer, C. Warneke, D. D. Parrish, Quantifying atmospheric methane emissions from the Haynesville, Fayetteville, and northeastern Marcellus shale gas production regions. *J. Geophys. Res.* **120**, 2119–2139 (2015).
20. A. R. Brandt, G. A. Heath, E. A. Kort, F. O'Sullivan, G. Pétron, S. M. Jordaan, P. Tans, J. Wilcox, A. M. Gopstein, D. Arent, S. Wofsy, N. J. Brown, R. Bradley, G. D. Stucky, D. Eardley, R. Harriss, Methane leaks from North American natural gas systems. *Science* **343**, 733–735 (2014). Medline doi:10.1126/science.1247045
21. A. Karion, C. Sweeney, G. Pétron, G. Frost, R. Michael Hardesty, J. Kofler, B. R. Miller, T. Newberger, S. Wolter, R. Banta, A. Brewer, E. Dlugokencky, P. Lang, S.

A. Montzka, R. Schnell, P. Tans, M. Trainer, R. Zamora, S. Conley, Methane emissions estimate from airborne measurements over a western United States natural gas field. *Geophys. Res. Lett.* **40**, 4393–4397 (2013). doi:10.1002/grl.50811

22. E. A. Kort, C. Frankenberg, K. R. Costigan, R. Lindenmaier, M. K. Dubey, D. Wunch, Four corners: The largest US methane anomaly viewed from space. *Geophys. Res. Lett.* **41**, 6898–6903 (2014). doi:10.1002/2014GL061503
23. G. Pétron, A. Karion, C. Sweeney, B. R. Miller, S. A. Montzka, G. J. Frost, M. Trainer, P. Tans, A. Andrews, J. Kofler, D. Helmig, D. Guenther, E. Dlugokencky, P. Lang, T. Newberger, S. Wolter, B. Hall, P. Novelli, A. Brewer, S. Conley, M. Hardesty, R. Banta, A. White, D. Noone, D. Wolfe, R. Schnell, A new look at methane and nonmethane hydrocarbon emissions from oil and natural gas operations in the Colorado Denver-Julesburg Basin. *J. Geophys. Res.* **119**, 6836–6852 (2014).
24. T. B. Ryerson, M. Trainer, W. M. Angevine, C. A. Brock, R. W. Dissly, F. C. Fehsenfeld, G. J. Frost, P. D. Goldman, J. S. Holloway, G. Hübler, R. O. Jakoubek, W. C. Kuster, J. A. Neuman, D. K. Nicks Jr., D. D. Parrish, J. M. Roberts, D. T. Sueper, Effect of petrochemical industrial emissions of reactive alkenes and NO_x on tropospheric ozone formation in Houston, Texas. *J. Geophys. Res.* **108**, 4249 (2003). doi:10.1029/2002JD003070
25. B. Miyazaki, in *Underground Gas Storage: Worldwide Experiences and Future Development in the UK and Europe,* D. J. Evans, R. A. Chadwick, Eds. (The Geological Society, vol. 313, London, 2009), pp. 163–172.
26. www.arb.ca.gov/cc/ab32/ab32.htm.
27. http://edgar.jrc.ec.europa.eu/datasets_grid_list42FT2010.php?v=42FT2010&edgar_compound=CH4.
28. U.S. EPA, *Greenhouse Gas Emissions from a Typical Passenger Vehicle* (2014).
29. http://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf.
30. R. A. Washenfelder, P. O. Wennberg, G. C. Toon, Tropospheric methane retrieved from ground-based near-IR solar absorption spectra. *Geophys. Res. Lett.* **30**, 2226 (2003). doi:10.1029/2003GL017969
31. K. W. Wong, D. Fu, T. J. Pongetti, S. Newman, E. A. Kort, R. Duren, Y.-K. Hsu, C. E. Miller, Y. L. Yung, S. P. Sander, Mapping CH_4: CO_2 ratios in Los Angeles with CLARS-FTS from Mount Wilson, California. *Atmos. Chem. Phys.* **15**, 241–252 (2015). doi:10.5194/acp-15-241-2015
32. R. O. Green, M. L. Eastwood, C. M. Sarture, T. G. Chrien, M. Aronsson, B. J. Chippendale, J. A. Faust, B. E. Pavri, C. J. Chovit, M. Solis, M. R. Olah, O. Williams, Imaging spectroscopy and the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS). *Remote Sens. Environ.* **65**, 227–248 (1998). doi:10.1016/S0034-4257(98)00064-9
33. A. Butz, S. Guerlet, O. Hasekamp, D. Schepers, A. Galli, I. Aben, C. Frankenberg, J.-M. Hartmann, H. Tran, A. Kuze, G. Keppel-Aleks, G. Toon, D. Wunch, P. Wennberg, N. Deutscher, D. Griffith, R. Macatangay, J. Messerschmidt, J. Notholt, T. Warneke, Toward accurate CO_2 and CH_4 observations from GOSAT. *Geophys. Res. Lett.* **38**, L14812 (2011). doi:10.1029/2011GL047888
34. S. M. Miller, S. C. Wofsy, A. M. Michalak, E. A. Kort, A. E. Andrews, S. C. Biraud, E. J. Dlugokencky, J. Eluszkiewicz, M. L. Fischer, G. Janssens-Maenhout, B. R. Miller, J. B. Miller, S. A. Montzka, T. Nehrkorn, C. Sweeney, Anthropogenic emissions of methane in the United States. *Proc. Natl. Acad. Sci. U.S.A.* **110**, 20018–20022 (2013). Medline doi:10.1073/pnas.1314392110
35. M. K. McNutt, R. Camilli, T. J. Crone, G. D. Guthrie, P. A. Hsieh, T. B. Ryerson, O. Savas, F. Shaffer, Review of flow rate estimates of the Deepwater Horizon oil spill. *Proc. Natl. Acad. Sci. U.S.A.* **109**, 20260–20267 (2012). Medline doi:10.1073/pnas.1112139108
36. T. B. Ryerson, R. Camilli, J. D. Kessler, E. B. Kujawinski, C. M. Reddy, D. L. Valentine, E. Atlas, D. R. Blake, J. de Gouw, S. Meinardi, D. D. Parrish, J. Peischl, J. S. Seewald, C. Warneke, Chemical data quantify Deepwater Horizon hydrocarbon flow rate and environmental distribution. *Proc. Natl. Acad. Sci. U.S.A.* **109**, 20246–20253 (2012). Medline doi:10.1073/pnas.1110564109
37. J. J. Colman, A. L. Swanson, S. Meinardi, B. C. Sive, D. R. Blake, F. S. Rowland, Description of the analysis of a wide range of volatile organic compounds in whole air samples collected during PEM-tropics A and B. *Anal. Chem.* **73**, 3723–3731 (2001). Medline doi:10.1021/ac010027g
38. S. A. Conley, I. C. Faloona, D. H. Lenschow, A. Karion, C. Sweeney, A low-cost system for measuring horizontal winds from single-engine aircraft. *J. Atmos. Ocean. Technol.* **31**, 1312–1320 (2014). doi:10.1175/JTECH-D-13-00143.1
39. H. Chen, J. Winderlich, C. Gerbig, A. Hoefer, C. W. Rella, E. R. Crosson, A. D. Van Pelt, J. Steinbach, O. Kolle, V. Beck, B. C. Daube, E. W. Gottlieb, V. Y. Chow, G. W. Santoni, S. C. Wofsy, High-accuracy continuous airborne measurements of greenhouse gases (CO_2 and CH_4) using the cavity ring-down spectroscopy (CRDS) technique. *Atmos. Meas. Tech.* **3**, 375–386 (2010). doi:10.5194/amt-3-375-2010
40. J. Peischl, T. B. Ryerson, J. S. Holloway, M. Trainer, A. E. Andrews, E. L. Atlas, D. R. Blake, B. C. Daube, E. J. Dlugokencky, M. L. Fischer, A. H. Goldstein, A. Guha, T. Karl, J. Kofler, E. Kosciuch, P. K. Misztal, A. E. Perring, I. B. Pollack, G. W. Santoni, J. P. Schwarz, J. R. Spackman, S. C. Wofsy, D. D. Parrish, Airborne observations of methane emissions from rice cultivation in the Sacramento Valley of California. *J. Geophys. Res. D Atmos.* **117**, D00V25 (2012). doi:10.1029/2012JD017994
41. M. L. Smith, E. A. Kort, A. Karion, C. Sweeney, S. C. Herndon, T. I. Yacovitch, Airborne ethane observations in the Barnett Shale: Quantification of ethane flux and attribution of methane emissions. *Environ. Sci. Technol.* **49**, 8158–8166 (2015). Medline doi:10.1021/acs.est.5b00219
42. T. I. Yacovitch, S. C. Herndon, J. R. Roscioli, C. Floerchinger, R. M. McGovern, M. Agnese, G. Pétron, J. Kofler, C. Sweeney, A. Karion, S. A. Conley, E. A. Kort, L. Nähle, M. Fischer, L. Hildebrandt, J. Koeth, J. B. McManus, D. D. Nelson, M. S. Zahniser, C. E. Kolb, Demonstration of an ethane spectrometer for methane source identification. *Environ. Sci. Technol.* **48**, 8028–8034 (2014). Medline doi:10.1021/es501475q
43. T. B. Ryerson, M. P. Buhr, G. J. Frost, P. D. Goldan, J. S. Holloway, G. Hübler, B. T. Jobson, W. C. Kuster, S. A. McKeen, D. D. Parrish, J. M. Roberts, D. T. Sueper, M. Trainer, J. Williams, F. C. Fehsenfeld, Emissions lifetimes and ozone formation in power plant plumes. *J. Geophys. Res.* **103**, 22569–22583 (1998). doi:10.1029/98JD01620
44. M. Trainer, B. A. Ridley, M. P. Buhr, G. Kok, J. Walega, G. Hübler, D. D. Parrish, F. C. Fehsenfeld, Regional ozone and urban plumes in the southeastern United States: Birmingham, a case study. *J. Geophys. Res.* **100**, 18823–18834 (1995). doi:10.1029/95JD01641

ACKNOWLEDGMENTS

The first two Scientific Aviation flights were funded by the California Energy Commission via University of California-Davis project #201401201. Subsequent flights were funded by the Southern California Gas Company, the operator of the Aliso Canyon storage facility. I.F. was supported in part by the California Agricultural Experiment Station, Hatch project CA-D-LAW-2229-H. J.P. and T.R. were supported in part by the NOAA Climate Program Office and the NOAA Atmospheric Chemistry, Carbon Cycle, and Climate (AC4) program. We acknowledge the contributions of M. Trainer for scientific input and K. Aikin and S. Wolter for time-critical technical support. The views expressed here are those of the authors, and do not constitute endorsement by their funding agencies. Data used in this report are posted at esrl.noaa.gov/csd/scientificaviation.

SUPPLEMENTARY MATERIALS

www.sciencemag.org/cgi/content/full/science.aaf2348/DC1
Materials and Methods
Figs. S1 and S2
Tables S1 and S2
References (*37*–*44*)

11 January 2016; accepted 17 February 2016
Published online 25 February 2016
10.1126/science.aaf2348

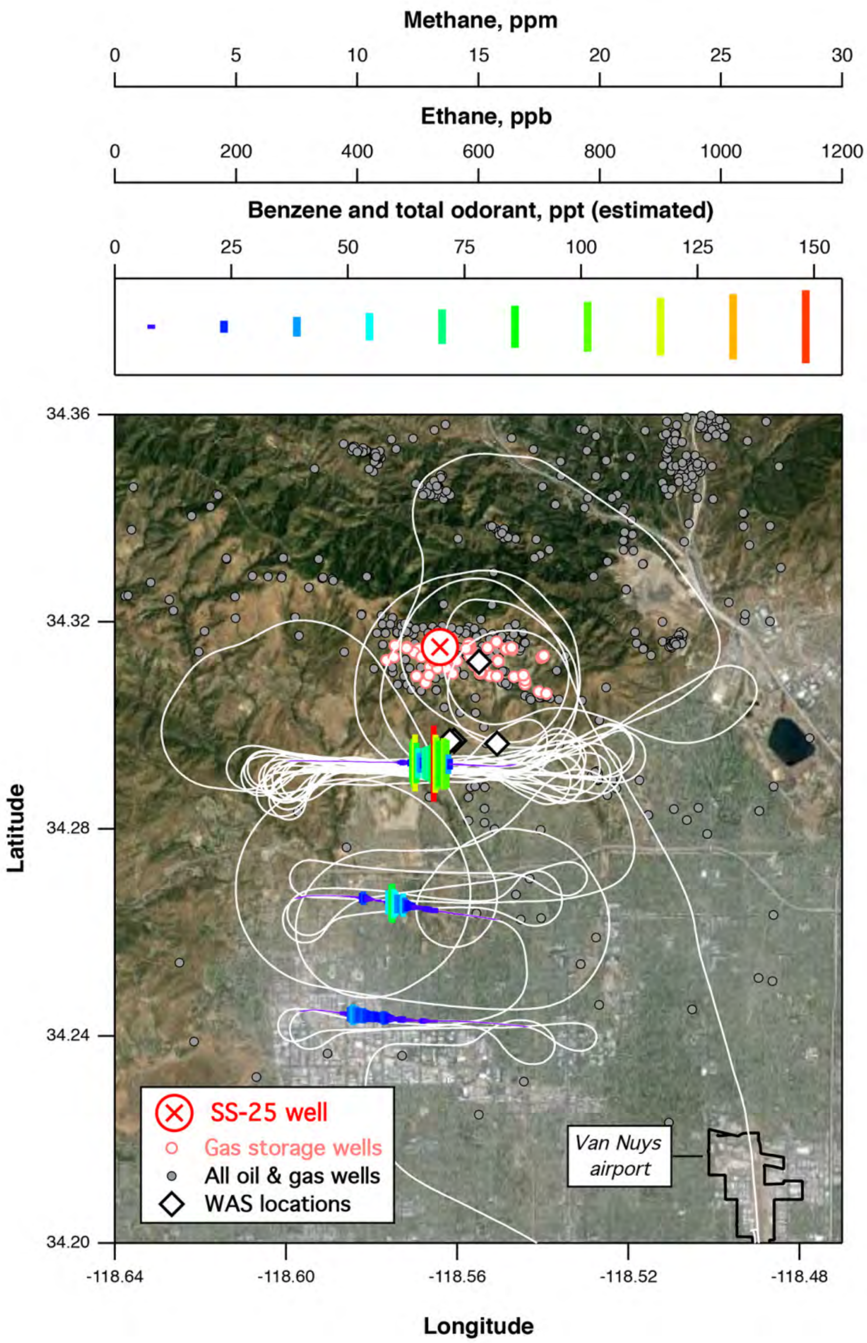


Fig. 1. Aliso Canyon gas plume transport into populated areas. Airborne chemical data from multiple flights demonstrate transport into the San Fernando Valley; data from 10 November 2015 are shown. Plume enhancements above the local background (colored markers) are plotted along the flight track (white line) and can be scaled using the legends at top to yield measured CH_4, measured C_2H_6, estimated benzene based on the WAS benzene-to-CH_4 ER, and estimated total odorant assuming 5 ppm in the leaking gas.

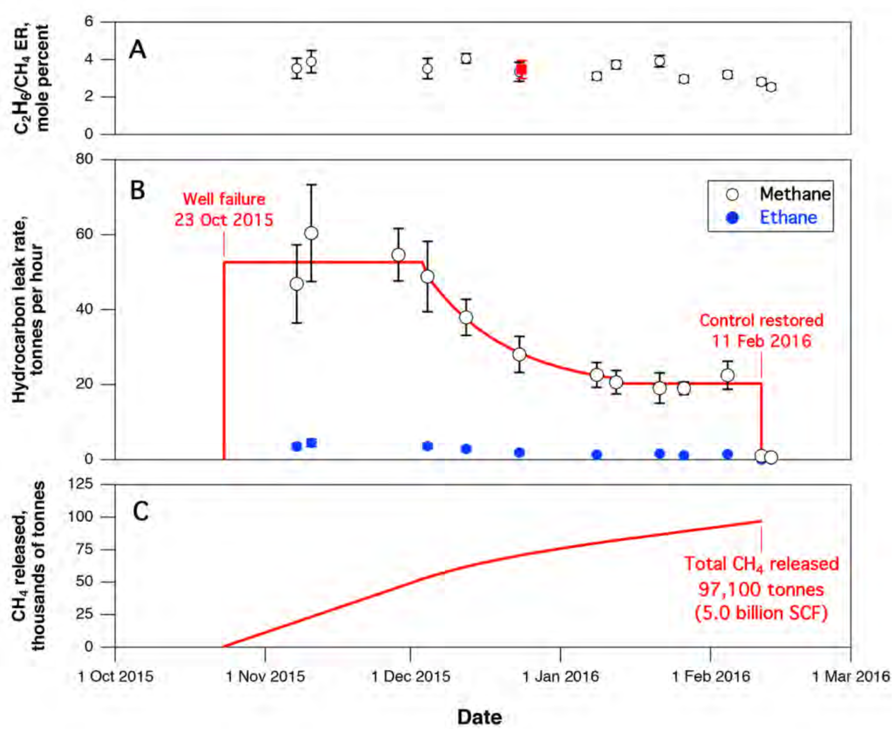


Fig. 2. Time series of the Aliso Canyon natural gas leak. (**A**) Plume C_2H_6-to-CH_4 enhancement ratios from airborne measurements (black circles) and ground-based WAS measurements (red square). (**B**) CH_4 (black) and C_2H_6 (blue) leak rates from airborne measurements. Red line is a fit to the airborne CH_4 data assuming an average leak rate from blowout to day 43, an exponential decrease between days 43 and 80, and an average leak rate thereafter to day 112 when control was restored. (**C**) Total amount of CH_4 released calculated from the fit in 2B. Error bars indicate ±1 standard error of the mean.

frontiers in Energy Research

ORIGINAL RESEARCH
published: 15 May 2018
doi: 10.3389/fenrg.2018.00040

Bearing the Cost of Stored Carbon Leakage

Adriano Vinca[1,2]*, *Johannes Emmerling*[1,3] *and Massimo Tavoni*[1,3,4]

[1] Fondazione Eni Enrico Mattei , Milan, Italy, [2] International Institute for Applied System Analysis, Laxenburg, Austria, [3] Centro-Euro Mediterraneo per i Cambiamenti Climatici, Milan, Italy, [4] Politecnico di Milano, Milan, Italy

Carbon capture and sequestration (CCS) is considered a key technology for stabilizing climate change. However, leakage of CO_2 from stored carbon can potentially undermine the value of carbon storage as a mitigation option. Thus, monitoring and verifiability of CO_2 storage should be encouraged through policy provisions such as accounting and pricing of leaked emissions. Here we assess different institutional and economic mechanisms for accounting for carbon leakage. Using an integrated assessment model we quantify the impacts on the climate, the economy and the mitigation strategies. Results show that carbon leakage can reduce the share of fossil based CCS by up to 35%, if it is controlled and correctly priced. Biomass based CCS is less affected. Accounting for leakage leads to an increase of climate policy costs of up to 0.4 percentage points due to increased emissions.

Keywords: carbon leakage, CCS, CO_2 geological storage, integrated assessment model, climate mitigation

OPEN ACCESS

Edited by:
Sonia Yeh,
Chalmers University of Technology,
Sweden

Reviewed by:
Phil Renforth,
Cardiff University, United Kingdom
Tobias Proell,
Universität für Bodenkultur Wien,
Austria
David Daniels,
United States Energy Information Administration, United States
Jennifer Wilcox,
Colorado School of Mines,
United States

Correspondence:
Adriano Vinca
vinca@iiasa.ac.at

Specialty section:
This article was submitted to Energy Systems and Policy, a section of the journal Frontiers in Energy Research

Received: *09 February 2018*
Accepted: *24 April 2018*
Published: *15 May 2018*

Citation:
Vinca A, Emmerling J and Tavoni M (2018) Bearing the Cost of Stored Carbon Leakage. Front. Energy Res. 6:40. doi: 10.3389/fenrg.2018.00040

HIGHLIGHTS

- Carbon leakage from CCS can lead to up to 25 $GtCO_2$ of additional emissions throughout the twenty-first century for a leakage rate of 0.1% per year.
- CCS deployment is lowered, by as much as 30% (Fossil) and 10% (BECCS), when leakage is taken into account.
- Carbon prices increase by around 5 per cent. Overall policy costs increase by about 0.2–0.4 percentage points.
- If not taken into consideration nor priced, leakage contributes to an additional 0.01–0.02 degrees of temperature increase.
- China, Latin America, the U.S., and Canada have the highest expected leakage.

1. INTRODUCTION

The increasing awareness of possibly irreversible damages of global warming has pushed both public opinion and governments toward the support of increasingly stringent climate mitigation measures. However, the path toward climate change policies is correlated to both technological and economic challenges (IPCC, 2014). Among typical mitigation strategies, Carbon Capture and Storage (CCS) and Carbon Dioxide Removal (CDR) represent valuable alternatives to renewable energy sources. According to existing studies IPCC (2014), the CCS potential will have an important role in reducing the carbon intensity of electricity. CCS might thus represent a considerable share of emission reduction in the energy sector (Metz et al., 2005; Finkenrath, 2011; NAS, 2015; GCCSI, 2016).

CCS and CDR can also help reduce the costs of mitigation. Nonetheless, their development has not been as fast as expected in the last decades (Davidson et al., 2017). This low deployment can be associated with the absence of adequate incentives, lack of public acceptance, and to technological uncertainties associated with CCS (IEA, 2016; Lipponen et al., 2017). Among these barriers, carbon leakage from stored CO_2 could counteract the usefulness of carbon sequestration to help limiting global temperature increase (van der Zwaan and Smekens, 2009). In this paper, we analyze the impact of CO_2 leakage on the propsects of CCS in the power sector and the economic costs of mitigation[1].

We evaluate different policy provisions to help take leakage into account. Several problems can arise with leakage. Estimating its size is difficult and costly, since monitoring techniques have focused on small scale case studies so far (Romanak et al., 2012; Dethlefsen et al., 2013). A second source of uncertainty is related to the economic liability of leaked emissions (Wilson et al., 2003; Imbus et al., 2013). Finally, leakage might depend on the stringency of the climate policy. To address these questions, we use an integrated assessment model to examine three main dimensions: climate targets, leakage rates and policy provisions to counteract it. We consider the 2 and 1.5°C temperature increase targets by 2100, a range of possible leakage rates consistent with the literature, and different cases of pricing and liability of carbon leakage in the atmosphere. On this last point, we analyze whether leaked CO_2 is (a) not monitored nor taken into account in the carbon budget, (b) taken into account for the chosen carbon budget, but not priced at the carbon price, e.g., due to institutional or technological constraints, or (c) taken into account in the carbon budget and priced at the carbon price. These three cases allow us to disentangle the importance of monitoring and pricing leaked emissions.

2. BACKGROUND INFORMATION

2.1. CO_2 Transportation and Storage

Carbon dioxide, once removed from the exhaust gases of a power plant, can be re-used for industry purposes or stored (GCCSI, 2011). Capture, transportation, and storage or use each require the construction and maintenance of additional infrastructure, along with associated costs (Metz et al., 2005; GCCSI, 2011; Benson et al., 2012). After storage, transporting CO_2 to storage or use sites is the next important cost component. Although transportation through pipelines of dense supercritical CO_2 appears to be the most convenient technology for inland transport, other options, including shipping, are conceivable for particular cases (e.g., remote offshore distances) (Cole et al., 2011; ZEP, 2011). The costs for pipeline transportation comprise both capital costs (e.g., pipeline construction, pipe coating, protection systems) and operations costs (e.g., surveillance, maintenance, expert supervision) (McCoy and Rubin, 2008).

[1]Note that we therefore do not consider direct air capture (DAC) or other CDR options, which face additional technical and other uncertainties.

When it comes to the options for carbon storage, here we focus on geological storage, which comprises several different storage options under ground. Among the different storage options, only a few are considered reliable for large scale injections: underground saline aquifers, depleted or expiring oil and gas fields, and coal beds. Deep saline aquifers are geological formations of porous rocks, permeable and saturated with water, that allow the withdrawal of non-potable water (IEAGHG, 2008). Also oil and gas fields where extraction is declining are interesting options for CO_2 storage. Enhanced oil recovery (EOR) consist of injecting CO_2 in declining oil fields to boost oil extraction due to fluid pressure. Being an economically convenient technique, it has already been used in the U.S. for many decades. However, traditional EOR was not intended to maximize carbon storage, and the amount of CO_2 trapped has always been relatively low (Godec et al., 2011; IEA, 2015). Depleted oil or gas fields can be reliable storage sites, as they have naturally stored natural gas for thousands of years and have been geologically fully characterized. Coal seams that are uneconomic to mine may still contain methane trapped in coal pores, which may be released via Enhanced Coal Bed Methane (ECBM) recovery (IEA-ETSAP, 2010). Similar to EOR, ECBM consists of injecting CO_2 into the the coal bed, some of which displaces the CH_4 and remains sequestered in its place. Other potential CO_2 storage options, such as CO_2 mineralization or deep ocean storage, although considered important potential future storage options by some sources (Sanna et al., 2014; Romanov et al., 2015), are excluded from the current study due to their high current and uncertain future costs, public acceptance issues, and uncertain impacts on ecosystems (IEA, 2008).

Since estimating global or regional available storage capacity requires extensive investigation of vast geological areas and the use of advanced measurement processes, the uncertainty on available capacity is still high. Dooley (2013) considers a theoretical global capacity of 35,300 $GtCO_2$, which is reduced to an effective and then practical potential of 13,500 and 3,900 $GtCO_2$, respectively. In the IEAGHG (2011, 2016) reports, an average global availability of 11,152 $GtCO_2$ is estimated, which is an order of magnitude that is accepted also by other authors (Hendriks et al., 2004; Koelbl et al., 2014).

With regard to the geological storage costs, the variability in the literature is even higher, since many studies describe specific sites, which can have different properties one from another, such as the storage type, regional geology, and pre-built infrastructure. For example, Rubin et al. (2015) estimates a cost range of between 1 and 18 $\$/tCO_2$. Similar values are reported in IEAGHG (2011) and ZEP (2011)[2]. Concerning ECBM and EOR storage options, the estimated costs range from negative to high positive values, depending on whether the process is used to boost gas or oil extraction, or to optimize CO_2 storage (Gale, 2004; Koelbl et al., 2013, 2014).

2.2. Carbon Leakage

With the term leakage, or seepage, we refer to undesired CO_2 losses to the atmosphere due to infrastructure or

[2]Every cost in this study is expressed in 2005 US Dollars.

storage malfunctions. Leakage could occur during CO_2 transportation, underground injection, or after storage. Leakage from transportation is due to pipeline losses, but can be considered unlikely due to pipeline monitoring systems that measure pressure losses (GCCSI, 2014). The injection process can also lead to unwanted CO_2 leakage: injection requires a wellbore, a conduit where upward flows are possible. Finally, undesired loss of CO_2 from storage sites can occur due to imperfect storage sealing. Pipeline and injection losses are referred to as instantaneous leakage, as they take place at the same time period of capture and before the CO_2 is stored. On the contrary, seepage from storage sites is delayed in time, meaning that CO_2 can also leak from under ground several years after being captured. In this case, leakage is related to the cumulative quantity of CO_2 that has been stored in the past. This aspect is critical as one of the main issues related to CCS deployment is the long term suitability of storage options (Metz et al., 2005; van der Zwaan and Gerlagh, 2009b). Moreover, there is still high uncertainty about the true reliability of storage sites. As the long term response of storage sites could hinder CCS effectiveness as a mitigation option, we focus our attention on storage leakage.

The damages that leakage might cause can be distinguished between local and global (Wilson et al., 2003). From the local point of view, meaning a few kilometers around the storage site, concentrated CO_2 leakage could be harmful for people and livestock. Another problem caused by CO_2 losses is ground water contamination. Seepage could reach groundwater aquifers, rather than reaching directly the atmosphere surface (Bielicki et al., 2015; Deng et al., 2017). This would lower the aquifer water pH and could lead to the release of harmful metals, an effect known as acidification (Little and Jackson, 2010). Alternatively, acidification might also occur during the injection in saline aquifers, degrading the well cements (Celia et al., 2015). These local issues might raise discussions on storage management and public acceptance, however they have less consequences at a global level. By contrary, this article focuses on CO_2 leakage into the atmosphere as a global issue that contributes to global warming. In particular, the prospect of leakage could hinder the mitigation potential of fossil fuel CCS, hampering its future deployment. Consequently, it would lead to an increase in climate policy costs (van der Zwaan and Smekens, 2009). For this reason it is important to understand the magnitude of leakage, which is captured typically through the leakage rate, that is, the rate at which CO_2 leakage occurs at a specific storage site per year in terms of the stored carbon.

Bielicki et al. (2015) summarizes results on percentage of stored emissions from the storage sites, with different levels of permeability and compares the results with the U.S. Department of Energy aim of not more than 1% leaked CO_2 in total (Bielicki et al., 2016). Assuming a pessimistic estimate of rock permeability equal to $10^{-10}\mathrm{m}^2$, 10% of stored volumes are expected to leak within 30 years, with permeability of $10^{-12}\mathrm{m}^2$, the leaked emissions decrease to about 0.1% during the same period. However, an evaluation of leaked quantities over larger time horizons like 100 or 1,000 years, which are the time frames usually considered by institutions like the DOE or IPCC, is still missing. According to Bielicki et al. (2015) only the case with $10^{-12}\mathrm{m}^2$ permeability would conform to the storage permanence goal of 1% leakage. These permeability assumptions have been tested in the GCAM model by Deng et al. (2017), obtaining leakage over the twenty-first century of between ~0.003 and ~0.2%[3]. Another finding is that with a low injection rate, leakages are higher at the beginning, while in the long term this might change. The behavior of leakage rates could therefore depend also on time: in particular, the percentage of CO_2 lost with respect to the total stored amount could exponentially decay or show an S-shaped behavior. These complex paths try to replicate some important geological and fluid-dynamic aspects of CO_2 leakage. For example, the exponentially decaying curve stands for a storage site where CO_2 leaks at first easily, then increasingly more scarcely due to the fact that only the best trapped CO_2 remains in the storage site. An S-shaped curve would represent the CO_2 leaking through multiple layers of media (van der Zwaan and Gerlagh, 2009a,b). However, as in van der Zwaan and Smekens (2009), leakage rate could be also reasonably well approximated as a constant percentage of the cumulative stored quantity within each storage site. Summing up, according to the IPCC (Metz et al., 2005), storage sites are probably reliable and safe, meaning they release very low or practically zero leakages. van der Zwaan and Smekens (2009) suggest a maximum acceptable value for the leakage rate below 0.5% per year, while for Bielicki et al. (2015) lower leakage rates are conceivable. In this study we therefore consider the maximum leakage rate of 0.1% per year, which implies leakage of 9.5% over a century, while a more reasonable leakage rate that we test is 0.01%/*year*, which leads to a theoretical leakage of 1% of injected CO_2 over 100 years[4].

As leakage remains uncertain, it is of vital importance to ensure effective and reliable monitoring systems that consistently measure CO_2 flows. In recent years, several studies have addressed the issue of monitoring leakage flows to the atmosphere or affecting underground aquifers (Benson and Hepple, 2005; Dethlefsen et al., 2013). Monitoring seepage implies scanning a large area of land in proximity of storage sites, and there is not a consolidated or standardized approach yet, rather a number of research and demonstration projects (Jones et al., 2009; Etheridge et al., 2011; Romanak et al., 2012). Moreover, to guarantee an effective control on storage sites, the responsibilities and consequences of seepage must be clearly outlined, covered through appropriate regulation and, if applicable, covered under carbon pricing schemes (Imbus et al., 2013). Problems can arise when private companies or public institutions responsible for the injected CO_2 do not monitor adequately, leading to undetected leakage. Considering the long term outlook, some regulations envisage a transition in responsibilities from private operators to governments after a certain number of years (e.g., 50 years) or in case of company closures. Furthermore, assuming leakage occurs and is correctly detected and measured, someone has to pay for local damages

[3]Note that these values are modeled leakage rates over the century and thus depend on the timing and deployment of CCS and carbon storage.

[4]These values per century are theoretical, meaning the amount of gas that would leak if it was all stored on the first year. The real leakage per century will depend on the intertemporal storage profile of the model, see **Figure 2**.

and for the cost of global externality it is generating. In the case of a carbon pricing scheme, the latter cost is set by the carbon price. Also in this case, dodging responsibility by private or public authority would inhibit the economic benefits of CCS or CDR.

Not all countries have appropriate or specific regulation to address the safety and liability issue. Liu et al. (2016) provides a review of existing regulations in some developed countries and compares them with general Chinese environmental regulation. As an example, EU regulation establishes the payment for emissions credits in the Emissions Trading System (ETS) system for the storage operator (EU, 2009). Other useful measures are insulation of the perforation of the well, re-injection in more safe sites and insurance plans, also for companies that go bankrupt (Lackner and Brennan, 2009; Imbus et al., 2013). In conclusion, we have seen how important it is to assign responsibilities for monitoring and compensate leakage damages. Therefore, we included these aspects in this exercise, developing some scenarios that mimic successful or failed monitoring, pricing, and management of stored emissions.

3. METHODOLOGY

We use an integrated assessment model (IAM) to simulate the impact of leakage on the set of mitigation strategies. IAMs are tools which are routinely used to evaluate global climate policies. Currently, many integrated assessment models use aggregated storage cost and availability curves, notably the ones from Hendriks et al. (2004). For this exercise, we disaggregated the storage according to different types of storage including their respective potential and costs. Moreover, transportation costs also vary according to the storage site considered. Finally, we added leakage from the different storage sites and assessed a set of scenarios capturing different climate policies, leakage rates, and options to consider leaked carbon emissions. We use the WITCH (World Induced Technical Change Hybrid) integrated assessment model in this study.

WITCH is a global integrated assessment model with two main distinguishing features: a regional game-theoretic setup, and an endogenous treatment of technological innovation for energy conservation and decarbonization (Emmerling et al., 2016). A top-down inter-temporal Ramsey-type optimal growth model is hard linked with a representation of the energy sector described in a bottom-up fashion, hence the hybrid denomination. The regional and intertemporal dimensions of the model make it possible to differentiate and assess the optimal response to several climate and energy policies across regions and over time. The non-cooperative nature of international relationships is explicitly accounted for via an iterative algorithm which yields the open-loop Nash equilibrium between the simultaneous activity of a set of representative regions. Regional strategic actions interrelate through greenhouse gas (GHG) emissions, dependence on exhaustible natural resources, trade of fossil fuels and carbon permits, and technological research and development (R&D) spillovers. R&D investments are directed toward either energy efficiency improvements or development of carbon-free breakthrough technologies. Such innovation accumulates over time and spills across countries in the form of knowledge stocks and flows. R&D investments, along with investments in energy technologies and the final goods sector, are endogenously determined in the intertemporal optimization. Within the energy sector, for new renewable energy sources (wind and solar), battery development, and advanced bio-fuels, learning is also taken into account through one or two factor learning curves, which determine future capital costs. The competition for land use between agriculture, forestry, and bioenergy, which are the main land-based production sectors, is described through a soft link with a land use and forestry model (GLOBIOM, Global Biosphere Management Model). A climate model (MAGICC) is used to compute climate variables from GHG emission levels, and an air pollution model (FASST) is linked to compute air pollutant concentrations.

Concerning CCS in the model, we consider four coal technology options (including the possibility of retrofitting existing plants), one gas and one biomass technology with carbon capture. The model includes seven types of storage (saline aquifers, EOR sites, depleted oil and gas fields, all either onshore or offshore, and onshore ECBM sites), each characterized by a maximum available capacity, a storage cost and an average distance from power plants. Apart from storage costs for the different types, all values are regionally differentiated. Finally, we account for an average specific transport cost dependent on the distance calibrated as $c'_{tr} = 0.006667\$/tCO_2\ km$ (Rubin et al., 2015). The total cost of captured CO_2 transport and storage $C_{t\&s}[\$/year]$ is therefore evaluated according to the following equation, where the dimensions are time (t), regions (n), and type of storage (k_{st}):

$$C_{t\&s}(t,n) = \sum_{k_{st}} Q_{st}(k_{st},n,t) \cdot \left(c'_{tr} \cdot l_{tr}(n,k_{st}) + c_{st}(k_{st}) \right) \tag{1}$$

Here, Q_{st} $[GtCO_2/year]$ represents the yearly quantity of CO_2 captured by CCS plants, l_{tr} [km] represents the average distance, and c_{st} $[\$/tCO_2]$ the storage cost. We consider an annual leakage rate λ_{lk} of between 0.0%/$year$ and up to 0.1%/$year$ and include leaked emissions in the model. The cumulative amount of CO_2 stored CUM_{st} $[GtCO_2]$ is therefore calculated based on annual stored values, considering that the model is run at a time step of 5 years, and including possible leakage every time period:

$$\begin{aligned} CUM_{st}(k_{st},n,t+1) \;=\; & CUM_{st}(k_{st},n,t) \cdot (1-\lambda_{lk}(k_{st},n,t))^5 \\ & + 5 \cdot Q_{st}(k_{st},n,t) \end{aligned} \tag{2}$$

Here, λ_{lk} stands for the leakage rate, or the percentage of CO_2 stored in the previous year that is lost due to leakage and emitted in the atmosphere. This set of equations allow us to represent the transport and storage chain as a single cost function, differentiated across regions. The cost function for each storage type follows a step increase in function of the cumulative stored quantity, where each step means a switch from a cheap but replete storage type to the immediate next, more expensive site. Finally, annual leaked emissions Q_{leak} are computed as follows:

$$Q_{leak}(n,t) = \sum_{k_{st}} \lambda_{lk}(k_{st},n,t) \cdot CUM_{st}(k_{st},n,t) \tag{3}$$

It should be noted that Q_{leak} in period t is accounted for based on CUM_{st} in t, which is not including the emission captured in the same period, but only until $t-1$. This is to represent delay in leakage.

4. SCENARIO DESIGN

Based on this model implementation of storage, transportation, and leakage of CO_2, we explore a set of 31 scenarios to capture the following dimensions: leakage rates, climate targets, and policy provisions. We implement different leakage rates (LR) starting from zero leakage, 0.01%, 0.05%, and up to 0.1% per year.

Secondly, we consider different stringency of climate policies, represented by carbon budgets covering total CO_2 emissions from fossil fuels and industrial processes from 2010 to 2100. In addition to the business as usual (BAU) case without a future climate policy, we consider cases of 550, 1,000, and 1,600 $GtCO_2$ corresponding to roughly 1.5, 2.0, and 2.5°C of global warming in 2100, according to the definition in the IPCC AR5 report (Edenhofer et al., 2014; Vuuren et al., 2017)[5]. When running these scenarios, the model sets a constraint on emitted CO_2 equal to the budget and solves finding the cost optimal solution for attaining the target.

Finally, we differentiate the economic and policy treatment of carbon leakage emissions. In particular, we consider whether or not (a) leaked emissions are priced (through a carbon tax or the price of emission permits) or not, and (b) the leaked emissions are included in the carbon budget of the policy maker. Four cases are possible based on these distinctions: In the first case (NN), leakage is not taken into account in the policy target nor priced, e.g., due to technical, institutional, or political barriers. This case allows us to assess the climatic impact of leakage if it is not taken into account for climate targets, nor in emission pricing schemes. The other limiting case, where pricing and monitoring are effective (YY), constitutes the first best case where the actual climate target is attained, and leakage is treated the same way as other carbon emissions and priced at the marginal cost of abatement. The two remaining cases represent different institutional, economic, and technological situations: In the YN case, leakage is anticipated for the climate policy goal, while due to monitoring or institutional constraints, the source cannot be taxed or held accountable. Hence, in this case, other mitigation options are required to counteract leakage emissions. Hypothetically, in the fourth situation (NY), on the other hand, pricing leakage emissions is possible and implemented, but the climate policy does not take leakage into account a situation which is not realistic and hence we do not consider it here.

[5]The IPCC AR5 Scenarios Database documents the long-term scenarios as reviewed in the Fifth Assessment Report (AR5) of Working Group III of the Intergovernmental Panel on Climate Change (IPCC) (Edenhofer et al., 2014).

TABLE 1 | Scenarios considered (31 in total).

(A) THREE CASES REPRESENTING LEAKAGE MONITORING AND LIABILITY

		liability: No	liability: Yes
monitoring	No	**NN** leakage not accounted in carbon budget, nor priced	[Not realistic]
monitoring	Yes	**YN** leakage accounted in carbon budget, but not priced	**YY** leakage accounted in carbon budget and correctly priced

(B) BAU AND THREE CARBON BUDGETS [GtCO$_2$ BY 2100] / **(C) FOUR LEAKAGE RATES**

Climate target	Leakage rate (%/year)
BAU	0.00%
1,600	0.01%
1,000	0.05%
550	0.10%

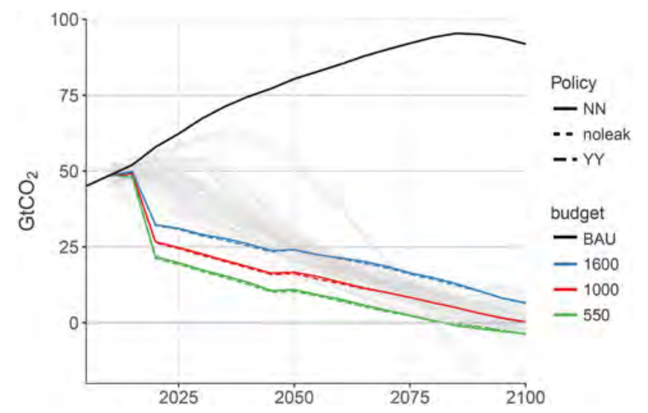


FIGURE 1 | Global greenhouse gas emissions ($GtCO_{2eq}$) across scenarios. For target different from BAU, leakage is set to 0 or 0.1%/*year*. In gray are plotted the scenarios form the AR5 Scenario Database in line with the 2°C.

As summarized in **Table 1**, we consider three different policy prescriptions (NN, YN, YY) for three different carbon budgets (1600, 1000, 550 $GtCO_2$) and three leakage rates (0.01, 0.05, 0.1 %/*year*, total: 27 scenarios), in addition to the four scenarios without leakage (BAU, 1,600, 1,000, 550).

5. RESULTS

The different sets of scenarios show different patterns in terms of emissions, CCS deployment, and economic costs. Firstly, looking at overall greenhouse gas emissions, **Figure 1** shows the no leakage and high leakage scenarios and compares them to the scenarios of the AR5 database that are consistent with the two degree target (Edenhofer et al., 2014). Overall, emissions

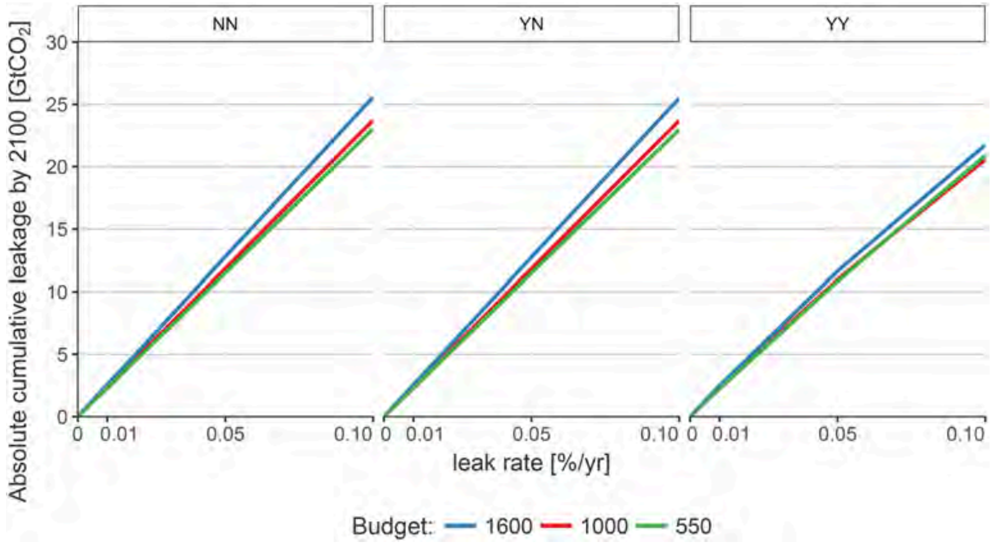


FIGURE 2 | Cumulative leaked emissions in the different scenarios [$GtCO_2$]. Captured emissions are around 700–750 $GtCO_2$ for NN and YN scenarios and 650–700 $GtCO_2$ for the YY scenario.

are only mildly affected by carbon leakage at the global scale, and the mitigation pathways are dominated by the stringency of the carbon budgets. In particular in the 550 scenarios, total emissions become negative toward the end of the century. The difference between cases where leakage (set as 0.1%/*year* of stored CO_2) is well accounted for (YY) and when it is not (NN) is small compared to total emissions, though still visible.

Looking closer at the leaked emissions, one can see that leakage can contribute to emissions as shown in **Figure 2**. The amount of leakage over this century in the NN and YN scenarios ranges from 2.5 GtCO_2 (for a leakage rate of 0.01%/*year*) to around 25 $GtCO_2$ for a leakage rate of 0.1%/*year*. Moreover, while it is quite similar for the different climate targets, it shows the highest values always for the 1,600 $GtCO_2$ scenario, where fossil-based CCS is widely deployed. Comparing the leakage to the amount of captured emissions for the NN and YN scenarios (around 700–750 $GtCO_2$), we get around 0.5% of leakage until 2100 for the low leakage rate, and 3% for the high leakage rate cases. These values are virtually unchanged in the YN and NN scenarios, where leakage is not priced and hence does not affect CCS deployment. However, in the YY scenario, when the effect and cost of leakage are fully accounted for, the model responds with a reduction in leakage, linked to a reduction in CCS technology adoption and captured emissions. For the highest leakage rate of 0.1%, captured emissions are lowered by about 5–10 $GtCO_2$ across the different climate targets. The percentage of leaked emission on the total captured between 2015 and 2100 is however similar to the previous scenarios. If compared to Deng et al. (2017), our results show higher percentage of emission leaking over the century given similar leakage rates. This is due to their assumption that most of leaked emissions do not reach the surface, but are priced and thus have a negative impact on CCS deployment.

Leaked emissions have an impact on the climate, in terms of CO_2 concentrations and global temperature increase, shown in **Figure 3**. In absolute terms, variations in global mean temperature increase in 2100 are relatively small, of the order of magnitude of 0.01°C when leaked emissions are not monitored. For the YN and YY scenarios where leakage is accounted in the carbon budget target, the results show a small temperature decrease with increasing leakage rate. This can be explained due to different timing of emissions, notably due to the early shift to zero carbon technologies replacing CCS. While overall the temperature effect is relatively small, it still implies further exacerbation of global warming when leakage is not accounted in the budget, which might be relevant for the most stringent scenarios.

Figure 4 shows that the reduction in CCS (in terms of capacity reduction by 2100) is linked to the leakage rate, and to whether it is priced and accounted for in the carbon budget: only in the case where the costs of leaked emissions are accounted for in the economy through carbon pricing (YY) is CCS substantially reduced. Therefore, in the scenarios where countries do not pay for their leaked emission, CCS is not affected, both in the case where seepage is considered in the carbon budget or not (YN and NN scenarios). This result can be explaind since leakage can not be directly linked to the storage owners and the capturing power plant. The CCS reduction is particularly high for fossil fuel based CCS where the reduction reaches between 10 and up to 35 per cent of the capacity without leakage. Bio-energy with carbon capture and storage (BECCS), on the other hand, shows reductions lower than 10%. That is, for biomass CCS, leakage seems to provide a less important barrier, even with a leakage

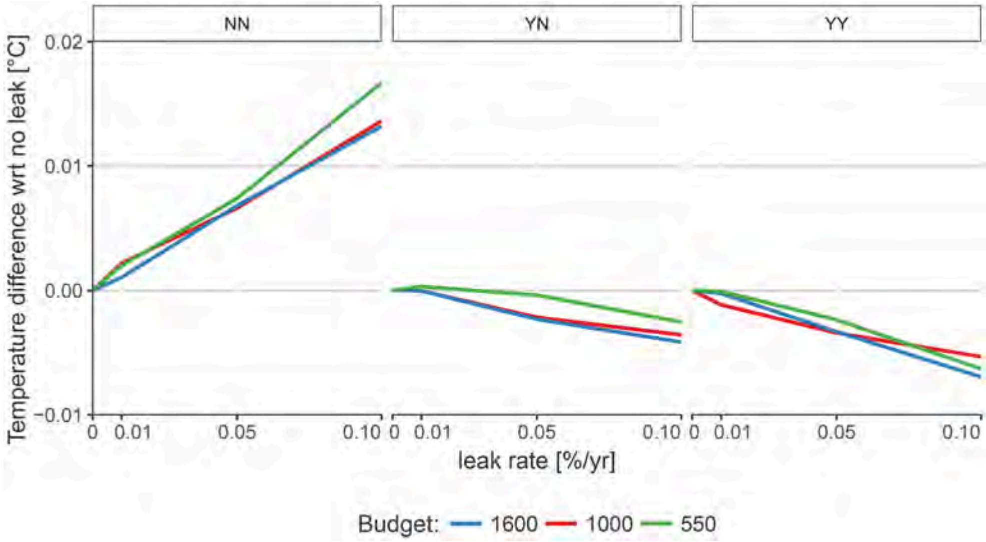


FIGURE 3 | Global mean temperature increase compared to no leakage case [°C].

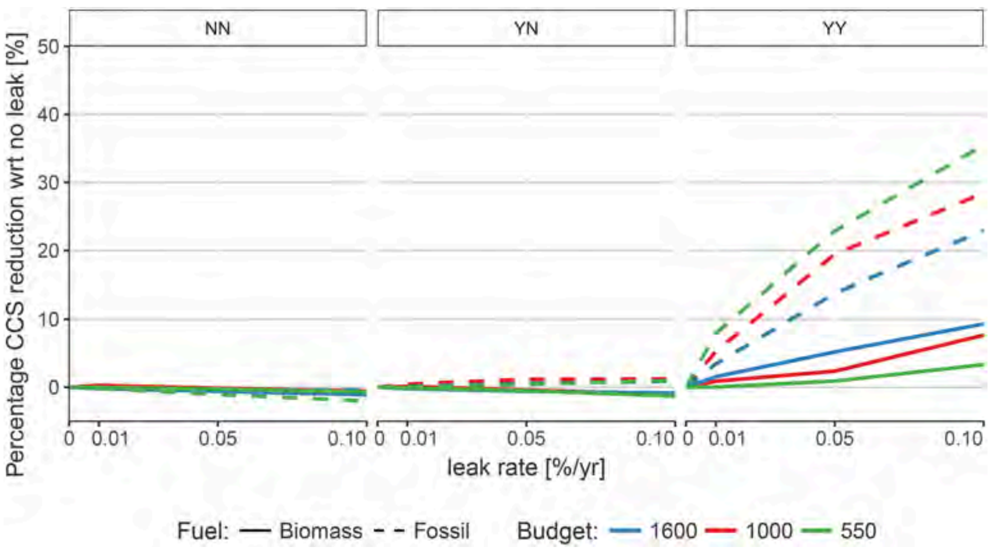


FIGURE 4 | Capacity reduction in CCS compared to no leakage case [%]. The reference values of total installed capacity by 2100 in case of zero leakage are: 61 *TW* (biomass) and 52 *TW* (fossil) for the 1,600 scenario, 63 *TW* (bio) and 37 *TW* (fossil) for 1,000 $GtCO_2$ and 75 *TW* (bio) and 25 *TW* (fossil) in the 550 $GtCO_2$ case.

rate of 0.1% per year, especially in the most stringent 1.5°C scenario. Moreover, it is interesting to note that the ordering across stringency of the climate targets is reversed for fossil fuel and biomass based CCS: The more stringent the scenario considered, the lower the impact on BECCS and the higher the reduction of fossil based CCS. This result is in line with the intermediary role of fossil fuel based CCS found e.g., in Rogelj et al. (2015), van der Zwaan and Smekens (2009) and Deng et al. (2017), even if these two latter studies did not consider stringent scenario such as the 1.5°C (550 $GtCO_2$).

In terms of economic costs of carbon leakage, we first look at the implied carbon price required to meet the different climate targets. **Figure 5** shows the increase in carbon price with respect to the no leakage cases, noticeable for scenarios where leakage is included in the carbon budget. The standard carbon prices in the three scenarios in the year 2020 to implement the carbon budgets of 1,600, 1,000, and 550 $GtCO_2$ are 79, 164, and 318 $\$/tCO_{2eq}$ respectively, and grow at a rate of 5% per year[6]. Comparing to these default scenarios the leakage cases, first note that the NN scenario does not show any change in the carbon price as leakage increases, since it is not considered for the policy

[6]Note that therefore the relative difference in carbon prices shown in **Figure 5** are constant over time and across regions.

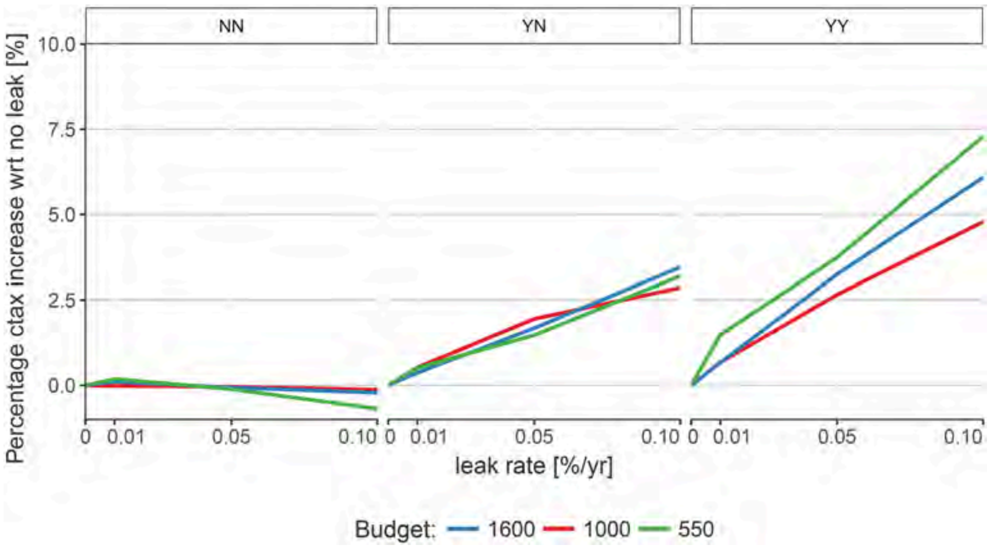


FIGURE 5 | Relative increase of the carbon price compared to no leakage case [%]. The carbon prices in 2,020 for 1,600, 1,000, and 550 $GtCO_2$ (no leakage case) are 79, 164, and 318 $\$/tCO_{2eq}$ respectively.

FIGURE 6 | Cumulative leaked emissions by 2100 in the scenario 550, NN and leakage rate of 0.1 $\%/year$ [$GtCO_2$].

design. When seepage affects the carbon budget available for each climate policy, it becomes necessary to mitigate this effect using other technological strategies more expensive than CCS. This results in an increase of carbon price in the YN and YY scenarios, which ranges from 2.5 to 7.5%. When leakage is not priced (YN), it still leads to a higher carbon price due to the reduced global carbon budget, albeit to a lesser extent, resulting from higher mitigation effort based on the most cost-effective mitigation options available. When it is also priced, the cost-effective potential of CCS is significantly reduced, resulting in higher use of more expensive mitigation options such as energy efficiency improvements or renewable energy sources. Across carbon budgets, it should be noted that, although the relative variation in the carbon tax is similar, in absolute value it differs significantly.

The previous results showed how uncontrolled seepage would affect global climate and how, even well monitored leakage might be binding for CCS development and would lead, globally, to a more expensive energy system. Now we focus on the regionally differentiated modeling results, focusing here on the most stringent scenario (550) and using the 0.1% leakage rate, while for smaller rates the results scale down almost linearly as shown before.

As shown in **Figure 6**, the cumulative leaked emissions are not evenly distributed across regions: China, the United States, Canada/Japan (cajaz), and Latin America (laca) countries are expected to extensively use CCS power plants, and therefore are projected to leak more than 2 $GtCO_2$, with China reaching 5 $GtCO_2$ by 2100 (see **Table 2** for the description of the regions).

Given the relatively high carbon price required to achieve the stringent climate policy targets, leakage can imply substantial additional costs of emissions, according to the carbon price in place. In the aforementioned regions with high projected leakage potential, this amounts to values between 75 and 200 billion USD over the century, with exception of 550 billion for China, see the left panel in **Figure 7** (all values reported there refer to NPV cumulative values from 2015 to 2100, discounted at a 5% discount rate). In the scenario 550, NN with high leakage, the (discounted) yearly value of leaked emissions in 2100 reaches up to 12 billion USD in China and about 7 billion USD in Latin America. Globally, the yearly leakage in 2100 of 0.78 $GtCO_2$ amounts to a discounted value of 54 billion USD. Given the relatively small carbon budget consistent with the 1.5 degree scenario, the additional 25 $GtCO_2$ of leaked carbon emissions associated with the high leakage rate (0.1%/*year*) scenario represent a significant cost, with particular economic implications for some regions. Moreover, we can compare which regions have to bear the additional costs if, while initially not being priced, now leaked emissions are accordingly priced and the climate target is the same, i.e., moving from scenario YN to YY. The right part of **Figure 7** shows the additional cost of leakage emissions when they are priced at the global carbon price (YY) compared to the case where they are not (YN): almost all regions show a negative difference, meaning that they reduce expenses when leakage is well regulated. In Canada/Japan (cajaz), including the leakage costs in the economy does not lead to a large CCS reduction. Therefore, the higher carbon price in the YY scenario results in higher costs for the country. This occurs mainly because the use of BECCS late in the century seems essential for these countries. In countries where CCS is only marginally profitable, its optimal deployment is reduced facing leakage, and hence the required carbon price is slightly higher, while leakage is significantly reduced. Since the latter effect dominates, those countries gain in terms of the value of carbon.

TABLE 2 | Regions of the WITCH model.

WITCH region	Description
usa	United States of America
oldeuro	Western Europe (EU15+EFTA)
neweuro	Eastern Europe (EU12+European EITs excluding FSU countries)
kosau	South Korea, South Africa, Australia
cajaz	Canada, Japan, New Zealand
te	Non-EU Eastern European countries, including Russia
mena	Middle East and North Africa
ssa	Sub Saharan Africa
sasia	South Asia (except India)
china	China, including Taiwan
easia	South East Asia, including Indonesia
laca	Latin America, Mexico and Caribbean
india	India

These are the value of losses that would not be payed by companies or countries in absence of regulation. But they can also be seen as a waste of money for a country which is investing in climate mitigation policies, and the cost of re-abating leaked emission. Moreover, other costs, like local or climate change damages are not accounted in this estimation, therefore the real economic loss might be even higher. Note that in both cases the carbon price increases with leakage rate, as more expensive low carbon technologies are installed to compensate seepage. However the YY scenario represents a perfect regulation system where CCS owners pay for the leaked emissions, so that use of CCS is reduced and the carbon price increases further. This behavior is considered more convenient than continuing using CCS and paying for leakage. The difference in total leakage costs can be considered as the regional gain or loss if leakage is well regulated or not. Moreover, we also compare the GDP of all scenarios to

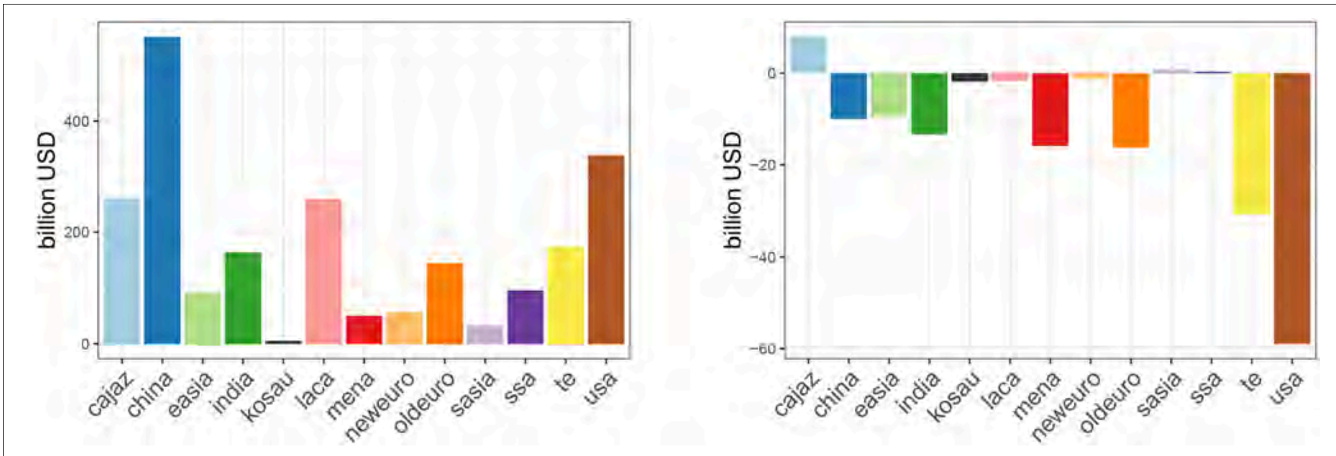


FIGURE 7 | Total value of leaked emission by 2100 in scenario 550 with leakage rate of 0.1%/*year* (NN, **left**), and difference when priced (between YY and YN, **right**).

TABLE 3 | Policy Cost with respect to BAU for different leakage rates and pricing policies [% of GDP].

Leakage rate	0	0.01%/year		0.05%/year		0.1%/year	
CB\policy		YN	YY	YN	YY	YN	YY
1,600	3.38	3.39	3.40	3.42	3.47	3.46	3.54
1,000	5.64	5.66	5.68	5.72	5.75	5.77	5.86
550	8.52	8.53	8.55	8.56	8.68	8.64	8.86

analyze the changes in policy costs with respect to the BAU scenario. **Table 3** reports the policy cost for the aforementioned scenarios. We confirm the above mentioned trend of policy cost[7] increasing with leakage rate and from zero leakage case to YY setting. Overall, policy costs increase in the range of 0.1–0.2% in the YN case due to the higher mitigation effort needed. If moreover leakage is priced, they increase by a further 0.1-0.2 percentage points. For instance, in the stringent 550, YY scenario and for a leakage rate of 0.1%, the costs of staying below 1.5° increase from 8.5% to almost 8.9% due to leakage.

6. CONCLUSION

The purpose of this work is to expand the assessment of leakage impact on CCS deployment and climate policies. We consider different institutional and economic settings reproducing issues in monitoring and paying for possible leakage. Furthermore, we perform analysis over leakage rates, and over three different climate scenarios, including the 1.5 and 2°C temperature increase target by 2100, particularly relevant after the Paris agreement in 2015. The results show that carbon leakage can lead to up to 25 $GtCO_2$ of additional emissions throughout the twenty-first century for a leakage rate of 0.1% per year, which represents about 3% of total captured emissions. Considering a more optimistic leakage rate (0.01%), only 0.5% of injected emissions would leak by 2100. If accounted for in the carbon budget and priced, CCS deployment is expected to be lowered by up to 35% (fossil) and 10% (BECCS) for high leakage rates. This means that CCS remains an important technology for mitigation in the power sector, notably coal and gas based in less stringent scenarios, and biomass fueled for the 1.5°C scenario. Due to more early-on abatement, considering leakage leads to slightly lower global warming in the long run. If not taken into consideration nor priced, on the other hand, it leads to an around 0.01–0.02 degrees higher global mean temperature. Overall, policy costs increase by about 0.2–0.4 percentage points (of GDP loss) due to considered leakage. In terms of regional distribution, China, Latin America, the U.S., and Canada have the highest leakage amount to be expected by 2100. The associated economic value of this quantity ranges across regions from 70 to more than 200 billion USD. Finally, we demonstrated how appropriate monitoring and accounting of leakage imply a reduction in use of CCS and also economic saving for most countries.

[7] measured as NPV of GDP differences in global GDP discounted at a 5% rate.

AUTHOR CONTRIBUTIONS

AV contributed to developing the idea, methodology, model design and execution, writing and revising the manuscript; JE contributed to developing the idea and methodology, supervised model design and execution, writing and revising the manuscript; MT have supervised the work, providing suggestions on the research scope and revisions.

REFERENCES

Benson, S., and Hepple, R. (2005). "Detection and options for remediation of leakage from underground CO_2 storage projects," in *Greenhouse Gas Control Technologies* (Vancouver, BC).

Benson, S. M. K., Bennaceur, P., Cook, J., Davison, H., de Coninck, K., Farhat, A., et al. (2012). "Chapter 13-carbon capture and storage," in *Global Energy Assessment-Toward a Sustainable Future* (Cambridge, UK; New York, NY: Cambridge University Press; Laxenburg: International Institute for Applied Systems Analysis), 993–1068.

Bielicki, J. M., Peters, C. A., Fitts, J. P., and Wilson, E. J. (2015). An examination of geologic carbon sequestration policies in the context of leakage potential. *Int. J. Greenhouse Gas Control* 37, 61–75. doi: 10.1016/j.ijggc.2015.02.023

Bielicki, J. M., Pollak, M. F., Deng, H., Wilson, E. J., Fitts, J. P., and Peters, C. A. (2016). The leakage risk monetization model for geologic CO_2 storage. *Environ. Sci. Technol.* 50, 4923–4931. doi: 10.1021/acs.est.5b05329

Celia, M. A., Bachu, S., Nordbotten, J. M., and Bandilla, K. W. (2015). Status of CO_2 storage in deep saline aquifers with emphasis on modeling approaches and practical simulations. *Water Resour. Res.* 51, 6846–6892. doi: 10.1002/2015WR017609

Cole, I. S., Corrigan, P., Sim, S., and Birbilis, N. (2011). Corrosion of pipelines used for CO_2 transport in CCS: is it a real problem? *Int. J. Greenhouse Gas Control* 5, 749–756. doi: 10.1016/j.ijggc.2011.05.010

Davidson, C. L., Dahowski, R. T., McJeon, H. C., Clarke, L. E., Iyer, G. C., and Muratori, M. (2017). The value of CCS under current policy scenarios: NDCs and beyond. *Energy Procedia* 114, 7521–7527. doi: 10.1016/j.egypro.2017.03.1885

Deng, H., Bielicki, J. M., Oppenheimer, M., Fitts, J. P., and Peters, C. A. (2017). Leakage risks of geologic CO_2 storage and the impacts on the global energy system and climate change mitigation. *Clim. Change* 144, 151–163. doi: 10.1007/s10584-017-2035-8

Dethlefsen, F., Köber, R., Schäfer, D., Hagrey, S. A. A., Hornbruch, G., Ebert, M., et al. (2013). Monitoring approaches for detecting and evaluating CO_2 and formation water leakages into near-surface aquifers. *Energy Procedia* 37(Suppl. C), 4886–4893. doi: 10.1016/j.egypro.2013.06.399

Dooley, J. J. (2013). Estimating the supply and demand for deep geologic CO_2 storage capacity over the course of the 21st century: a meta-analysis of the literature. *Energy Procedia* 37, 5141–5150. doi: 10.1016/j.egypro.2013.06.429

Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., et al. (2014). *Climate Change 2014: Mitigation of Climate Change: Contribution of Working Group iii to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK; New York, NY: Cambridge University Press..

Emmerling, J., Drouet, L., Reis, L. A., Bevione, M., Berger, L., Bosetti, V., et al. (2016). "The WITCH 2016 Model-Documentation and Implementation of the Shared Socioeconomic Pathways," in *Working Paper 2016.42*. Milan: Fondazione Eni Enrico Mattei.

Etheridge, D., Luhar, A., Loh, Z., Leuning, R., Spencer, D., Steele, P., et al. (2011). Atmospheric monitoring of the CO_2crc Otway project and lessons for large scale CO_2 storage projects. *Energy Procedia* 4, 3666–3675. doi: 10.1016/j.egypro.2011.02.298

EU, C. (2009). *Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006*. Technical report, European Union.

Finkenrath, M. (2011). "Cost and performance of carbon dioxide capture from power generation," in *IEA Energy Papers 2011/5*. Paris: International Energy Agency.

Gale, J. J. (2004). Using coal seams for CO_2 sequestration. *Geol. Belgica* 7, 99–103. Available online at: https://popups.uliege.be:443/1374-8505/index.php?id=239

GCCSI (2011). *Accelerating the Uptake of CCS: Industrial use of Captured Carbon Dioxide*. Technical report, Global Carbon Capture and Storage Institute.

GCCSI (2014). *What Happens When CO_2 is Stored Underground? q&a From the IEAGHG Weyburn-Midale CO_2 Monitoring and Storage Project*. Technical report, Global CCS Institute (Docklands, VIC).

GCCSI (2016). *The Global Status of CCS 2016: Summary Report*. Technical report, Global Carbon Capture and Storage Institute.

Godec, M., Kuuskraa, V., Van Leeuwen, T., Stephen Melzer, L., and Wildgust, N. (2011). CO_2 storage in depleted oil fields: the worldwide potential for carbon dioxide enhanced oil recovery. *Energy Procedia* 4, 2162–2169. doi: 10.1016/j.egypro.2011.02.102

Hendriks, C., Graus, W., and van Bergen, F. (2004). *Global Carbon Dioxide Storage Potential and Costs*. Technical report, Ecofys.

IEA (2008). *CO_2 Capture and Storage: A Key Carbon Abatement Option*. Technical report, International Energy Agency (Paris).

IEA (2015). *Insight Publications: Storing CO_2 Through Enhanced Oil Recovery*. Technical report, International Energy Agency (Paris).

IEA (2016). *20 Years of Carbon Capture and Storage-Accelerating Future Deployment*. Technical report, International Energy Agency (Paris).

IEA-ETSAP (2010). *CO_2 Capture and Storage*. Technical report, IEA Energy Technology Systems Analysis (Paris).

IEAGHG (2008). *Aquifer Storage: Development Issues*. Camberra: IEA Greenhouse Gas R&D Programme. Available online at: http://www.globalccsinstitute.com/publications/aquifer-storage-development-issues

IEAGHG (2011). *Potential for Biomass and Carbon Dioxide Capture and Storage*. Technical report, IEA Greenhouse Gas R&D Programme (Cheltenham). Camberra. Available online at: http://www.globalccsinstitute.com/publications/aquifer-storage-development-issues

IEAGHG (2016). Can CO_2 capture and storage unlock 'unburneable carbon'? Technical report, IEA Greenhouse Gas R&D Programme, (Cheltenham).

Imbus, S. W., Dodds, K., Otto, C. J., Trautz, R. C., Christopher, C. A., Agarwal, A., et al. (2013). CO_2 storage contingencies initiative: detection, intervention and remediation of unexpected CO_2 migration. *Energy Procedia* 37(Suppl. C), 7802–7814. doi: 10.1016/j.egypro.2013.06.343

IPCC (2014). *CLIMATE CHANGE 2014 Mitigation of Climate Change*. Technical report, Intergovernmental Panel on Climate Change.

Jones, D. G., Barlow, T., Beaubien, S. E., Ciotoli, G., Lister, T. R., Lombardi, S., et al. (2009). New and established techniques for surface gas monitoring at onshore CO2 storage sites. *Energy Procedia* 1, 2127–2134. doi: 10.1016/j.egypro.2009.01.277

Koelbl, B. S., van den Broek, M., van Ruijven, B., Faaij, A. P. C., and van Vuuren, D. P. (2014). Uncertainty in the deployment of Carbon Capture and Storage (CCS): a sensitivity analysis to techno-economic parameter uncertainty. *Int. J. Greenhouse Gas Control* 27, 81–102. doi: 10.1016/j.ijggc.2014.04.024

Koelbl, B. S., van den Broek, M., van Ruijven, B., van Vuuren, D. P., and Faaij, A. P. C. (2013). A sensitivity analysis of the global deployment of CCS to the cost of storage and storage capacity estimates. *Energy Procedia* 37, 7537–7544. doi: 10.1016/j.egypro.2013.06.697

Lackner, K. S., and Brennan, S. (2009). Envisioning carbon capture and storage: expanded possibilities due to air capture, leakage insurance, and C-14 monitoring. *Clim. Change* 96, 357–378. doi: 10.1007/s10584-009-9632-0

Lipponen, J., McCulloch, S., Keeling, S., Stanley, T., Berghout, N., and Berly, T. (2017). The politics of large-scale CCS deployment. *Energy Procedia* 114, 7581–7595. doi: 10.1016/j.egypro.2017.03.1890

Little, M. G., and Jackson, R. B. (2010). Potential impacts of leakage from deep CO_2 geosequestration on overlying freshwater aquifers. *Environ. Sci. Technol.* 44, 9225–9232. doi: 10.1021/es102235w

Liu, L.-C., Li, Q., Zhang, J.-T., and Cao, D. (2016). Toward a framework of environmental risk management for CO_2 geological storage in china: gaps and suggestions for future regulations. *Mitigat. Adapt. Strateg. Global Change* 21, 191–207. doi: 10.1007/s11027-014-9589-9

McCoy, S. T., and Rubin, E. S. (2008). An engineering-economic model of pipeline transport of CO2 with application to carbon capture and storage. *Int. J. Greenhouse Gas Control* 2, 219–229. doi: 10.1016/S1750-5836(07)00119-3

Metz, B., Davidson, O., de Coninck, H., Loos, M., and Meyer, L. (2005). *IPCC-Carbon Dioxide Capture and Storage (SRCCS)*. Technical report, Intergovernmental Panel on Climate Change.

NAS (2015). *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration*. Technical report, National Research Council (U.S.), National Academies Press.

Rogelj, J., Luderer, G., Pietzcker, R. C., Kriegler, E., Schaeffer, M., Krey, V., et al. (2015). Energy system transformations for limiting end-of-century warming to below 1.5c. *Nat. Clim. Change* 5, 519–527. doi: 10.1038/nclimate2572

Romanak, K. D., Bennett, P. C., Yang, C., and Hovorka, S. D. (2012). Process-based approach to CO_2 leakage detection by vadose zone gas monitoring at geologic CO_2 storage sites. *Geophys. Res. Lett.* 39:L15405. doi: 10.1029/2012GL052426

Romanov, V., Soong, Y., Carney, C., Rush, G. E., Nielsen, B., and O'Connor, W. (2015). Mineralization of carbon dioxide: a literature review. *ChemBioEng Rev.* 2, 231–256. doi: 10.1002/cben.201500002

Rubin, E. S., Davison, J. E., and Herzog, H. J. (2015). The cost of CO_2 capture and storage. *Int. J. Greenhouse Gas Control* 40, 378–400. doi: 10.1016/j.ijggc.2015.05.018

Sanna, A., Uibu, M., Caramanna, G., Kuusik, R., and Maroto-Valer, M. (2014). A review of mineral carbonation technologies to sequester CO_2. *Chem. Soc. Rev.* 43, 8049–8080. doi: 10.1039/C4CS00035H

van der Zwaan, B., and Gerlagh, R. (2009a). Economics of geological CO_2 storage and leakage. *Clim. Change* 93, 285–309. doi: 10.1007/s10584-009-9558-6

van der Zwaan, B., and Gerlagh, R. (2009b). Effectiveness of CCS with time-dependent CO_2 leakage. *Energy Procedia* 1, 4977–4984. doi: 10.1016/j.egypro.2009.05.002

van der Zwaan, B., and Smekens, K. (2009). CO_2 capture and storage with leakage in an energy-climate model. *Environ. Model. Assess.* 14, 135–148. doi: 10.1007/s10666-007-9125-3

Vuuren, D. P. v., Hof, A., Gernaat, D., and de Boer, H. S. (2017). *Limiting Global Temperature Change to 1.5°C*. PBL Netherlands Environmental Assessment Agency Report.

Wilson, E. J., Johnson, T. L., and Keith, D. W. (2003). Regulating the ultimate sink: managing the risks of geologic CO_2 storage. *Environ. Sci. Technol.* 37, 3476–3483. doi: 10.1021/es021038+

ZEP (2011). *The Costs of CO_2 Capture, Transport and Storage*. Technical report, European Technology Platform for Zero Emission Fossil Fuel Power Plants (Brussels).

Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Gas injection may have triggered earthquakes in the Cogdell oil field, Texas

Wei Gan[a,b] **and Cliff Frohlich**[b,1]

[a]School of Earth Sciences and Resources, China University of Geosciences, Beijing 10083, China; and [b]Institute for Geophysics, Jackson School of Geosciences, University of Texas at Austin, Austin, TX 78758-4445

Edited by Donald W. Forsyth, Brown University, Providence, RI, and approved October 4, 2013 (received for review June 13, 2013)

Between 1957 and 1982, water flooding was conducted to improve petroleum production in the Cogdell oil field north of Snyder, TX, and a contemporary analysis concluded this induced earthquakes that occurred between 1975 and 1982. The National Earthquake Information Center detected no further activity between 1983 and 2005, but between 2006 and 2011 reported 18 earthquakes having magnitudes 3 and greater. To investigate these earthquakes, we analyzed data recorded by six temporary seismograph stations deployed by the USArray program, and identified 93 well-recorded earthquakes occurring between March 2009 and December 2010. Relocation with a double-difference method shows that most earthquakes occurred within several northeast–southwest-trending linear clusters, with trends corresponding to nodal planes of regional focal mechanisms, possibly indicating the presence of previously unidentified faults. We have evaluated data concerning injection and extraction of oil, water, and gas in the Cogdell field. Water injection cannot explain the 2006–2011 earthquakes, especially as net volumes (injection minus extraction) are significantly less than in the 1957–1982 period. However, since 2004 significant volumes of gases including supercritical CO_2 have been injected into the Cogdell field. The timing of gas injection suggests it may have contributed to triggering the recent seismic activity. If so, this represents an instance where gas injection has triggered earthquakes having magnitudes 3 and larger. Further modeling studies may help evaluate recent assertions suggesting significant risks accompany large-scale carbon capture and storage as a strategy for managing climate change.

triggered seismicity | fluid injection | carbon sequestration

Induced seismicity related to underground injection of liquids has been widely reported (1–10) but there are very few reports of gas injection triggering earthquakes large enough to be felt or cause damage at the surface. Thus, the injection-induced earthquakes of concern are not the tiny events accompanying hydrofracturing that have magnitudes of 1.5 or smaller; rather, they are the larger-magnitude earthquakes sometimes caused by injection for water flooding, enhanced production, or waste disposal.

For liquid injection, it is plausible that triggered earthquakes occur when fluids reach suitably oriented preexisting faults, reducing the normal stress and hence the friction, and releasing regional tectonic shear stresses. The same mechanism should allow gas injection to trigger earthquakes. Recently Zoback and Gorelick (11) argued that there is a "high probability that earthquakes will be triggered" by the large-scale injection of CO_2 as a strategy to reduce greenhouse gases; however, they offered no examples of CO_2-injection-triggered earthquakes. Also, we are unaware of any reports of gas-injection-triggered earthquakes having magnitudes exceeding 3 (M3).

The present investigation concerns seismic activity and injection in petroleum fields in Scurry and Kent Counties, Texas (Figs. 1 and 2). The northern field straddling the Scurry–Kent county line is the Cogdell field. The larger field in Scurry County west of Snyder is called the Kelly–Snyder field, or sometimes the Scurry Area Canyon Reef Operators Committee unit. These fields produce from the Horseshoe Atoll, which accumulated in the Late Paleozoic and is one of the largest subsurface limestone reef mounds in the world (12, 13).

The Cogdell field underwent water flooding for secondary recovery between 1956 and 1982 and the earliest earthquakes detected there occurred in November 1974; the largest was an M4.6 on June 16, 1978 (14). Davis and Pennington (1) found that Cogdell seismic activity was correlated with the net liquid injection rate, with the first earthquakes occurring almost 20 y after injection commenced (Fig. S1). They modeled fluid pressures in the field and concluded that the earthquakes occurred at the boundaries of relatively low-pressure areas surrounded by higher-pressure regions. Although they suggested the earthquakes occurred on preexisting faults, there are no faults on regional tectonic maps and available locations of aftershocks did not occur along lineations or elongated clusters (Fig. 3).

There is a history of gas injection as well as water injection in the Kelly–Snyder and Cogdell fields. Northern sections of the Kelly–Snyder field have been undergoing CO_2 injection to enhance recovery since 1971 (17). In 2008 some Kelly–Snyder wells were used for a monitoring and modeling case study to learn about carbon capture use and geologic storage applications (18). Finally, in the Cogdell field, injection of CO_2 to enhance recovery began in 2001 and has been ongoing with nearly constant injection volumes since 2004.

For gas injection at wells in the Cogdell and Kelly–Snyder fields, the database available for this study reports monthly gas volumes at surface pressures and temperatures (STP 1 bar and 15 °C), and does not specify whether the gas injected is CO_2 or methane. At the depth of injection in Cogdell (~2.1 km) the pressure and temperature are ~200 bars and ~75 °C; under these conditions CO_2 is a supercritical fluid ($SCCO_2$) with a volume

Significance

Between 2006 and 2011 a series of earthquakes occurred in the Cogdell oil field near Snyder, TX. A previous series of earthquakes occurring 1975–1982 was attributed to the injection of water into wells to enhance oil production. We evaluated injection and extraction of oil, water, and gas in the Cogdell field. Water injection cannot explain the 2006–2011 earthquakes. However, since 2004 significant volumes of gas including CO_2 have been injected into Cogdell wells. If this triggered the 2006–2011 seismicity, this represents an instance where gas injection has triggered earthquakes having magnitudes 3 and larger. Understanding when gas injection triggers earthquakes will help evaluate risks associated with large-scale carbon capture and storage as a strategy for managing climate change.

Author contributions: C.F. designed research; W.G. evaluated seismic records; W.G. and C.F. analyzed results; and W.G. and C.F. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

[1]To whom correspondence should be addressed. E-mail: cliff@ig.utexas.edu.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1311316110/-/DCSupplemental.

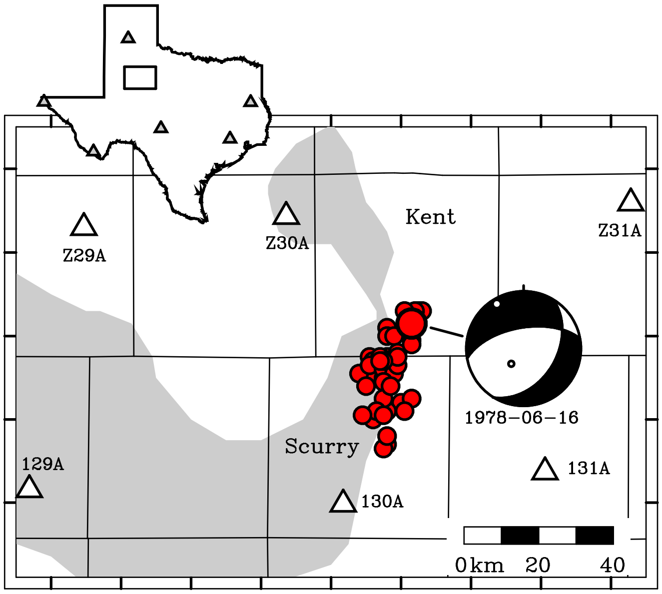


Fig. 1. Map showing location of study area, with earthquakes (red circles) reported by the NEIC 1977–2012, and USArray Transportable Array stations (white triangles) operating March 2009–December 2010 (Table S1). Gray shaded area indicates extent of Horseshoe Atoll. (*Inset*) Rectangle in Texas shows map boundaries; gray triangles in inset are seismograph stations operating in 2005 before passage of USArray. Light lines are county boundaries; labels indicate Scurry and Kent Counties.

~1/339th of that at STP; for methane the volume is ~1/180th of that at STP.

In the Cogdell, since 2004 monthly gas injection volumes have exceeded 85 million m^3/mo at STP (Fig. 4). Thus, at the depth of injection this corresponds to 250,000 m^3/mo for CO_2 and 475,000 m^3/mo for methane. In Cogdell and elsewhere, injected $SCCO_2$ and/or methane are often mixed with water, and the mixtures may undergo phase changes as they move away from the site of injection, so the volumes calculated at depth (e.g., left axis on Fig. 4) are only approximate.

The National Earthquake Information Center (NEIC) reports no Cogdell earthquakes between 1983 and 2005, but since 2006 they list 38 events that appear to be from a different population than earlier seismic activity (Fig. S3). The 2006–2011 epicenters include 18 with magnitudes M3 and greater and one on September 11, 2011, with moment magnitude (M_W) 4.4; if similar events had occurred between 1983 and 2005 most would have been detected and reported by the NEIC (19). Between 2009 and 2011 the EarthScope USArray temporary seismic stations were deployed in Texas; during this period we found 105 epicenters in the Cogdell area in the catalogs from the NEIC, the International Seismological Center (ISC), and the Array Network Facility (ANF), the organization that manages USArray data. Of these, 97 occurred between March 2009 and December 2010 when the six USArray stations surrounding Cogdell were all operational.

The focus of the present investigation is to analyze the characteristics of the recent Cogdell seismicity and to evaluate its relationship with water and gas injection. Although some of the recent earthquakes occurred at distances as great as ~5 km from active injection wells (Fig. 3), induced earthquakes at greater distances have been observed elsewhere (2, 3), especially where injection has been ongoing for many years. The fortuitous presence of the USArray stations between 2009 and 2011 makes it possible to identify much smaller earthquakes and determine their epicenters more accurately than during prior or subsequent times (Fig. 1).

Results

Earthquake Locations and Focal Mechanisms. The relocated epicenters (red circles, Fig. 3) cluster into several discrete groups. Overall they form a much less diffuse pattern than the epicenters reported in the ANF catalog (Fig. S4).

Certain linear features in the groups are approximately consistent with focal mechanism nodal planes. In the north a group of five events (labeled "A" in Fig. 3) forms a lineation trending just north of east, approximately the same as the trend (80° east of north) as the most steeply dipping nodal plane of the June 16, 1978, earthquake (Table S2). About 4 km to the southwest there are two more groups; one with 14 events (group B) forms a tight cluster, whereas the other group of 30 events (group C) lies along a distinct line trending ~45° east of north. Still further south are several more clusters; groups D, E, F, and G all lie along a line trending about 25° east of north. This is nearly identical to the 23° east of north trend of a nodal plane for the August 8, 2010, earthquake which is a member of group F. Finally, two small outlier clusters (H and J) of three and two events, respectively, lie ~2–3 km to the west of the other events.

The linear features in the relocated epicenters, including some approximately coincident with nodal planes, suggest that the seismic activity may occur along preexisting faults. As noted in previous studies (1, 13), the absence of mapped faults is unsurprising considering that the Cogdell and Kelly–Snyder reservoirs are reef buildups rather than fault-bounded traps.

No accurate location is available for the largest historical Cogdell earthquake (June 16, 1978; M4.6) because of near-absence of contemporary nearby regional seismographs. However, the

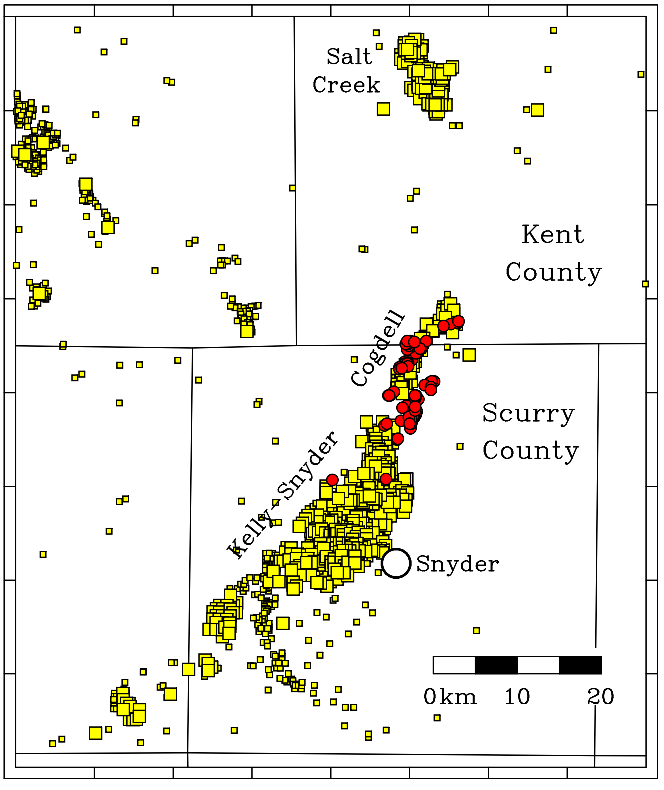


Fig. 2. Map of study area, showing 2009–2011 earthquakes (red circles) located in this study, and wells injecting water (yellow squares). Large squares, wells where monthly injection volumes exceeded 16,000 m^3/mo for one or more months during 2004–2011 period. White circle indicates town of Snyder, TX. Labels "Cogdell," "Kelly–Snyder," and "Salt Creek" are petroleum fields discussed in the text.

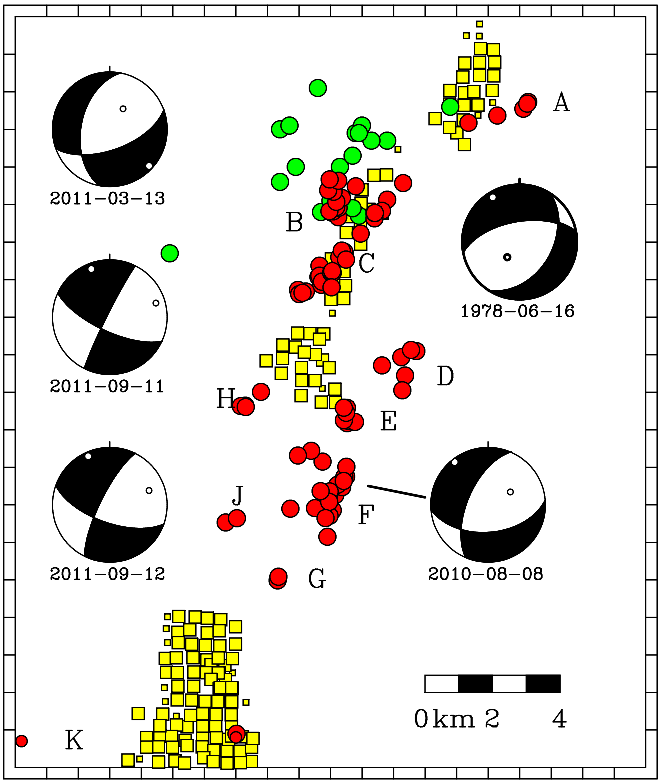


Fig. 3. Map showing 2009–2011 earthquakes relocated in this study (red circles), earthquakes occurring 1979–1980 (green circles) reported by Harding (15), gas injection wells active since 2004 (yellow squares), and focal mechanisms for regional events. Focal mechanisms are from the St. Louis group (16); labels indicate the date of occurrence (Table S2). Only the August 8, 2010, mechanism is for an earthquake relocated in this study. Larger red circles are epicenters occurring between March 2009 and December 2010 relocated using the double-difference method; two smaller red circles at southernmost boundary of plot are single-event locations of outlier events. Labels "A" through "K" indicate clusters discussed in *Results*. The 1979–1980 epicenters were determined from data collected by a temporary local network. For gas injection wells, larger symbols indicate wells where maximum monthly injection rate exceeds 2.8 million m^3/mo at standard conditions (8360 m^3/mo at depth for $SCCO_2$).

epicenters of aftershocks determined by a temporary local network in 1979–80 (green circles in Fig. 3) are mostly within a few kilometers of group B of 2009–2011 epicenters, suggesting that the 1978 epicenter may have been nearby, and that the present seismicity is a renewal of the earlier activity.

Seismicity and Injection/Extraction of Liquids and Gas. For wells in the Cogdell field, the available digital database has continuous monthly reports of oil produced, water extracted, water injected, gas produced, and gas injected extending back to 1990 (Figs. 4 and 5). Before that, and especially before 1982, the data are incomplete; Davis and Pennington (1) retrieved some of this information from records stored on microfiche and reported that the net volume of fluid extracted before 1982 exceeded 300,000,000 m^3 (Fig. S1).

Since 1990, however, volumes of water/oil injection and production have been roughly comparable, generally in the range of 400,000–800,000 m^3/mo (Fig. 5). A brief spike of higher injection volumes did take place in July and August of 2006 and this coincides with the renaissance of earthquake activity (the M2.8 August 8, 2006 event). However, there are no sustained changes in injection or extraction rates occurring before the 2006–2011 seismic activity, and no obvious overall changes in volumes of liquid extraction, injection, or the net during or before the 2006–2011 period when the field again became seismically active.

In contrast, a significant increase in gas injection (Fig. 4) in the Cogdell field took place before the 2006–2011 earthquake activity. $SCCO_2$ injection began in 2001, but rates were negligible until 2002, when sustained injection at rates of ∼40 million m^3/mo at standard conditions (125,000 m^3/mo at depth for $SCCO_2$) began in the cluster of wells near label A in Fig. 3. In 2003 sustained injection at rates of ∼25–50 million m^3/mo (80,000–160,000 m^3/mo at depth for $SCCO_2$) began in the cluster of wells near H in Fig. 3; the rates in August and September of 2006 were anomalous and exceeded 85 million m^3/mo (250,000 m^3/mo at depth for $SCCO_2$). Also in 2006, injection at rates averaging ∼25 million m^3/mo (80,000 m^3/mo at depth for $SCCO_2$) began in the cluster of wells near B and C in Fig. 3. In August–September 2006 this group of wells also experienced a 2-mo spike in injection where rates were 70–82 million m^3/mo (209,000–242,000 m^3/mo at depth for $SCCO_2$). For Cogdell as a whole, the combined effect is that gas injection rates were about 113 million m^3/mo (334,000 m^3/mo at depth for $SCCO_2$) between 2004 and 2012, and there was a temporary increase to more than 225 million m^3/mo (668,000 m^3/mo at depth for $SCCO_2$) in August of 2006, just as the first earthquake in the 2006–2011 sequence was detected.

Gas injection rates also increased for wells in the northern Kelly–Snyder field (wells near K label in Fig. 3), but this occurred somewhat later than in Cogdell. For Kelly–Snyder wells north of the southern boundary of Fig. 3, injected volumes first exceeded 42 million m^3/mo (125,000 m^3/mo at depth for $SCCO_2$) in July 2009, and increased to rates that averaged more than 285 million m^3/mo (840,000 m^3/mo at depth for $SCCO_2$) after July 2010.

Discussion and Summary

Earthquakes Possibly Triggered by Gas Injection. The most significant result of this investigation is that gas injection may have contributed to triggering a sequence of earthquakes occurring since 2006 in and near the Cogdell field in Texas. This sequence followed a 24-y interval when no earthquakes were detected. The post-2006 sequence followed significant increases in gas injection in the Cogdell field (Fig. 4) and many earthquake epicenters were within 2 km of actively injecting wells (groups A–C, E, and

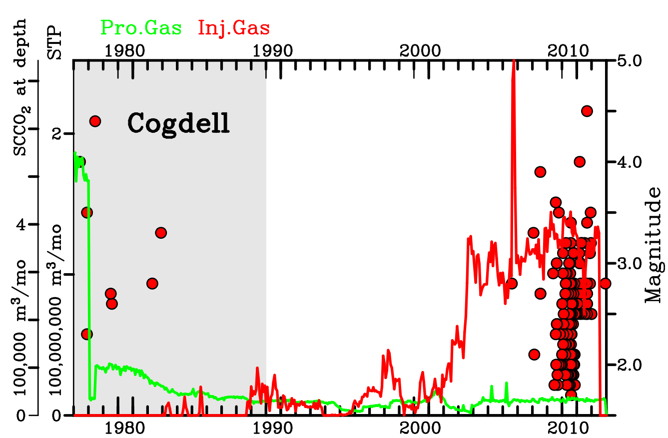


Fig. 4. For the Cogdell field, monthly volumes of natural gas produced (green line), gas injected (red line), and earthquakes detected from 1977 to 2012 (red circles). Volumes on left axes are as reported by RRC for gas at surface at STP, and for CO_2 at 200 bars and 75 °C ($SCCO_2$ at depth). Volumes at depth are highly approximate because the pressure–temperature effect differs for natural gas and CO_2, and because injected gas is often mixed with water and the physical properties of the mixture changes after injection. Gas volume data are from RRC and IHS digital database for the region labeled "Cogdell" in Fig. S2. Gas volume data before 1990 (gray area) are incomplete (see *Materials and Methods*).

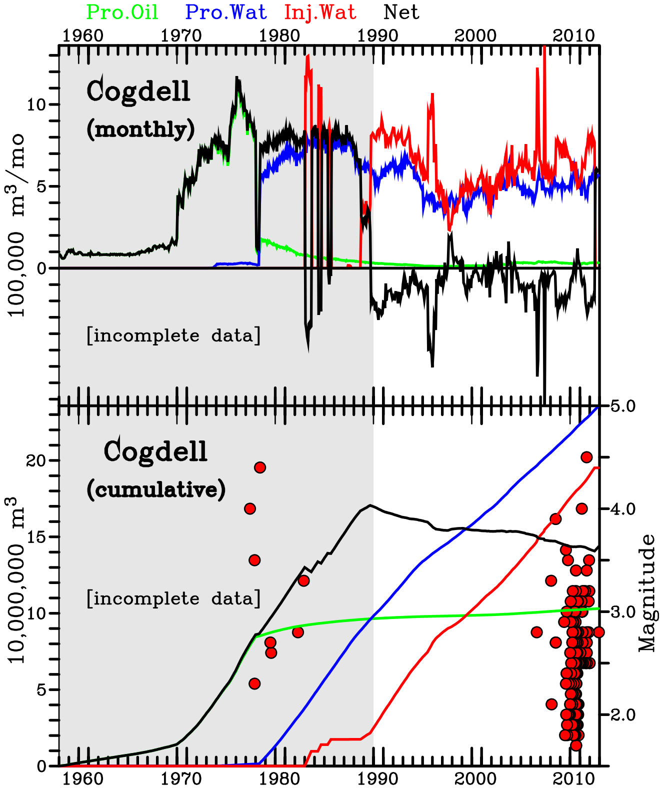


Fig. 5. For the Cogdell field, monthly (*Upper*) and cumulative (*Lower*) volumes of oil produced (green line), water produced (blue line), water injected (red line), and net volume extracted (black line: oil + water produced minus water injected). Red circles and right axis are earthquakes detected from 1977 to 2012. Volume data are from RRC and IHS digital database for the region labeled "Cogdell" in Fig. S2. Data before 1990 (gray area) are incomplete (see *Materials and Methods*).

H in Fig. 3). Between 1990 and 2006 there were no significant changes in rates of injected water except for a 1-y interval beginning in 1995 and 2 mo in 2006 (Fig. 5).

Since 1990 net cumulative volumes (liquid extracted minus injected) have been negative, i.e., the volume of material at depth has increased, and amount to about 20,000,000 m^3 (Figs. 5 and 6). When this volume is adjusted to account for the effect of extracted and injected gas, an additional ~20,000,000 m^3 since 2004 is attributable to injected gas (red line, Fig. 6). Thus, if one attributes the seismicity either to overpressuring reducing friction on faults, or to exceeding the capacity of "effectively sealed compartments," as Keranen et al. (10) recently suggested might contribute to causing a 2011 M5.7 earthquake in Oklahoma, it is plausible that injected gas played a dominant role.

This is an unusual and noteworthy instance where gas injection may have contributed to triggering earthquakes having magnitudes of 3 or larger, as the 2006–2012 sequence included 18 earthquakes with magnitudes exceeding 3, and an M_W4.4 earthquake that occurred September 11, 2011. A recent review of induced seismicity associated with CO_2 storage reported no instances where gas injection triggered seismicity (20). Microseismic monitoring has accompanied $SCCO_2$ injection projects at fields in Australia, Algeria, and Utah (21, 22), but in each case recorded seismic activity had magnitudes of zero or less, even in fields where interferometric synthetic aperture radar measurements showed that surface uplifts of several centimeters accompanied the injection. Two reportedly induced or triggered earthquakes with magnitudes of M7 occurred in 1976 and 1984 in gas fields in Gazli, Soviet Uzbekistan (23); however, these have been associated with massive gas extraction (not injection), and there is controversy about whether they are induced or natural.

Faulting in the Cogdell Region? The recent seismic activity provides strong evidence for the presence of subsurface faults in the Cogdell region. The five currently available focal mechanisms (Fig. 3) include both predominantly normal-faulting and strike slip mechanisms; all five have nearly horizontal tension axes along a north-northwest–south-southeast direction. The observed northeast–southwest-trending linear features in the relocated epicenters, some approximately parallel to the nodal planes, are consistent with the hypothesis that seismicity is releasing tectonic stress along previously existing faults. The observation that some of the 2009–2011 epicenters are near locations reported in 1979–1980 (15) suggests these may be the same faults or part of the same fault system active 1974–1982. Elsewhere in Texas, in Dallas–Fort Worth (8), earthquakes apparently triggered by the injection of water occur along similar northeast–southwest-trending linear features.

Unanswered Questions. If the recent Cogdell earthquakes are triggered, it is still puzzling why there are no earthquakes in similar nearby fields (Fig. 2) such as the Kelly–Snyder field and the Salt Creek field. Like Cogdell, both fields have experienced a combination of years of sustained injection/extraction of water/oil, followed by recent increases in gas injection (Fig. 6 and Figs. S5–S8). Since 1990, when the injection/extraction data are complete, within all three fields liquid injection and extraction rates have been approximately equal, whereas the injection of gas has increased the volume of material at depth (Fig. 6).

This observation, and the fact that no other gas injection sites have reported earthquakes with magnitudes as large as 3, suggests that despite Zoback and Gorelick's (11) concerns, it is possible that in many locations large-volume CO_2 injection may not induce earthquakes. What is different about Cogdell that allows earthquakes

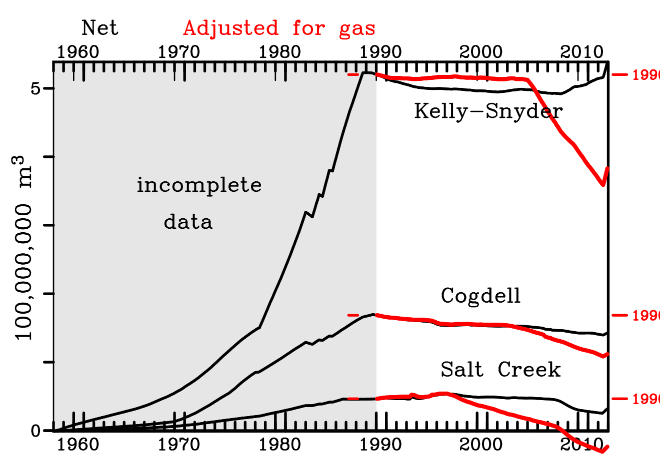


Fig. 6. Comparison of net cumulative volumes extracted for the Cogdell, Salt Creek, and Kelly–Snyder fields. Black line is oil + water produced minus water injected. Red line is volume adjusted for gas produced and injected after 1990 to approximate volume removed at production depth since 1990. Adjusted volumes are determined by assuming gas extracted is methane, and injected gas is CO_2; thus, red line is black line plus (1/180) gas produced minus (1/339) gas injected; at production depths where temperature is ~75 °C and pressure is ~200 bars, volumes of natural gas and CO_2 are ~(1/180) and ~(1/339), respectively, of volumes at surface conditions (see introduction in text). Volume data are from IHS digital database for the three regions (Fig. S2). Data before 1990 (gray area) are incomplete (see *Materials and Methods*). Ticks labeled "1990" on right axis show net volume as of 1990; note that since 1990 effect of gas injection is to decrease cumulative volume extracted, i.e., to increase the volume at depth.

to occur there? Detailed modeling investigations (21, 24) of hydrology and subsurface stress, comparing subsurface conditions in the Cogdell, Kelly–Snyder, and Salt Creek fields, might provide answers to this question. There have been preliminary monitoring and modeling of the consequences of $SCCO_2$ injection in the Kelly–Snyder (SACROC) unit (25, 26). The presence of detectable seismic activity in the Cogdell field and its absence in the apparently similar Kelly–Snyder and Salt Creek fields makes these fields attractive candidates for detailed geomechanical modeling, as has been recently applied to CO_2 injection sites near the coast of Italy (27). It would be informative to apply similar analyses to the Cogdell field, incorporating information about faulting, our reported epicentral locations, and Texas Railroad Commission (RRC) data concerning extraction/injection rates at individual wells.

Utility of USArray Data. As in our previous investigation of triggered seismicity in the Barnett Shale of northeast Texas (9), the present study is an apt example of a positive but unanticipated benefit of the USArray Temporary Array, part of the National Science Foundation-funded EarthScope program. EarthScope was conceived and funded before recent concerns about possible hazards from earthquakes triggered by water injection associated with disposal of hydrofracturing wastes (27) or by $SCCO_2$ injection for carbon sequestration (11, 28, 29). Analysis of USArray data makes it possible to determine accurate epicenters for small events and evaluate their proximity to nearby wells; it is plausible that similar analysis could provide critical information about possibly triggered earthquakes elsewhere.

For studies of this kind, the most serious limitation of USArray data is that it is difficult to assess the focal depths of triggered earthquakes with data collected at 70-km average station spacing. In the present study we arbitrarily fixed the depths at 5 km. To obtain more accurate depths from travel times one needs data from stations situated at intervals of a few kilometers or less. Alternatively, if very accurate information about crustal structure were available, reliable depths might be determined using currently available data by comparing recorded waveforms with synthetics.

Materials and Methods

Information concerning volumes of gas, oil, and water injected and extracted at individual wells is publicly available from the Texas RRC. The RRC regulates activity related to petroleum production and issues permits for drilling wells; by law, petroleum producers must provide the RRC with information concerning well locations, depths, and monthly volumes of injection/extraction of oil, water, and gas. Originally this information was filed as paper records and archived on microfiche. Nowadays most of these data are stored digitally. There has been some effort to convert older data; because this required keypunching there are occasional errors. This study mostly used RRC data as compiled by the company IHS Inc. Generally, before about 1990 the digital information is only partially complete. We wrote computer programs to sum data from individual wells and construct volume/time histories for specific fields and geographic areas. The RRC reports volumes of liquids in units of barrels. Because the volumes of oil and other fluids depend on pressure and on amounts of dissolved gas, subsurface volumes may differ slightly from volumes measured at the surface; however, in this study we use the conversion factor 1 m^3 = 6.29 barrels. The RRC reports volumes of gases in thousands of cubic feet at STP; the conversion factor is 1,000 ft^3 = 35.3 m^3.

This investigation analyzed earthquakes recorded by the six USArray stations surrounding the study area (Fig. 1 and Table S1). These were simultaneously operational from March 2009 to December 2010. During this period, the combined NEIC-ISC-ANF catalogs report 97 earthquakes located in northern Scurry and southern Kent Counties. We downloaded three-component seismograms from the USArray stations for these events from the Incorporated Research Institutions for Seismology Data Management Center.

To obtain more accurate locations for these events, we manually picked primary (P) and secondary (S) phases at all six stations. Then, to ensure we were picking the same feature for each phase and thus improve relative location accuracy, we plotted phases for multiple events together (Fig. S9) and adjusted the time picks. P and S arrival time were thus picked with a precision of 20 ms or better for most phases.

We determined preliminary epicenters for 93 of these events using a standard iterated least-squares program, fixing the focal depths at 5 km because USArray station spacing (~70 km) is too large to allow determining meaningful depths. We then jointly relocated the events to determine station corrections and more accurate trial locations. Finally, we relocated using the double-difference program HYPODD (30), obtaining relative locations for 90 events (Fig. 3 and Table S3). The rms residuals for the resulting locations were all 0.12 s or less, and most were smaller than 0.05 s. For relocations we used the CHELSEA (southwest Oklahoma) crustal model used by the Oklahoma Geological Survey for routine network locations (31).

ACKNOWLEDGMENTS. We thank Sue Hovorka, J. P. Nicot, Tip Meckel, Eric Potter, and one anonymous reviewer for helpful comments that improved this manuscript. We especially thank reviewers Wayne Pennington and Bill Ellsworth, who provided helpful comments on two preliminary versions of this work. We also thank Felix Waldhauser for helping us use his double-difference algorithm to locate earthquakes having fixed focal depths. This research was partially supported by National Natural Science Foundation of China Grant 41174076 and by the US Geological Survey (USGS) Department of the Interior, under USGS Award G13AP00023.

1. Davis SD, Pennington WD (1989) Induced seismic deformation in the Cogdell oil field of west Texas. *Bull Seismol Soc Am* 79(5):1477–1495.
2. Hsieh PA, Bredehoeft JD (1981) A reservoir analysis of the Denver earthquakes: A case of induced seismicity. *J Geophys Res* 86(B2):903–920.
3. Ake J, Mahrer K, O'Connell D, Block L (2005) Deep injection and closely monitored induced seismicity at Paradox Valley, Colorado. *Bull Seismol Soc Am* 95(2):664–683.
4. Nicholson C, Wesson RL (1990) *Earthquake Hazard Associated with Deep Well Injection: A Report to the US Environmental Protection Agency*, US Geological Survey Bulletin (USGS, Washington, DC), Vol 1951.
5. Zoback MD, Harjes H-P (1997) Injection-induced earthquakes and crustal stress at 9 km depth at the KTB deep drilling site, Germany. *J Geophys Res* 102(B8):18477–18491.
6. Horton S (2012) Disposal of hydrofracking waste fluid by injection into subsurface aquifers triggers earthquake swarm in central Arkansas with potential for damaging earthquake. *Seismol Res Lett* 83(2):250–260.
7. Suckale J (2009) Induced seismicity in hydrocarbon fields. *Adv Geophys* 51:55–106.
8. Frohlich C, Hayward C, Stump B, Potter E (2011) The Dallas–Fort Worth earthquake sequence: October 2008 through May 2009. *Bull Seismol Soc Am* 101(1):327–340.
9. Frohlich C (2012) Two-year survey comparing earthquake activity and injection-well locations in the Barnett Shale, Texas. *Proc Natl Acad Sci USA* 109(35):13934–13938.
10. Keranen KM, Savage HM, Abers GA, Cochran ES (2013) Potentially induced earthquakes in Oklahoma, USA: Links between wastewater injection and the 2011 Mw 5.7 earthquake sequence. *Geology* 41(6):699–702.
11. Zoback MD, Gorelick SM (2012) Earthquake triggering and large-scale geologic storage of carbon dioxide. *Proc Natl Acad Sci USA* 109(26):10164–10168.
12. Vest E (1970) Oil fields of Pennsylvanian-Permian horseshoe atoll, west Texas. *Geology of Giant Petroleum Fields—Symposium*, ed Halbouty MT, *Amer Assoc Petrol Geol Memoir* 14:185–203.
13. Halbouty MT (1968) Giant oil and gas fields in the United States. *AAPG Bull* 52(7):1115–1152.
14. Frohlich C (2002) *Texas Earthquakes* (Univ Texas Press, Austin, TX), 275 pp.
15. Harding ST (1981) Induced Cogdell Canyon Reef oil field. *Summaries of Technical Reports,* Vol. IX (US Department of the Interior, Menlo Park, CA), pp 452–455.
16. Herrmann RB, Benz H, Ammon CJ (2011) Monitoring the earthquake source process in North America. *Bull Seismol Soc Am* 101(6):2609–2625.
17. Brummett WM, Emanual AS, Ronquille JD (1976) Reservoir description by simulation at SACROC – a case history. *J Pet Technol* 28(10):1241–1255.
18. Han WS, McPherson BJ, Lichner PC, Wang FP (2010) Evaluation of trapping mechanisms in geologic CO_2 sequestration: Case study of SACROC northern platform, a 35-year CO_2 injection site. *Am J Sci* 310(4):282–324.
19. Ellsworth WL (2013) Injection-induced earthquakes. *Science* 341(6142):1225942.
20. Nicol A, Carne R, Gerstenberger M, Christophersen A (2011) Induced seismicity and its implications for CO_2 storage risk. *Energy Procedia* 4:3699–3706.
21. Rutqvist J (2012) The geomechanics of CO_2 storage in deep sedimentary formations. *Geotech Geol Eng* 30(3):525–551.
22. Zhou R, Huang L, Rutledge J (2010) Microseismic event location for monitoring CO_2 injection using double-difference tomography. *Leading Edge (Tulsa Okla)* 29(2):208–214.
23. Simpson DW, Leith W (1985) The 1976 and 1984 Gazli, USSR earthquakes—Were they induced? *Bull Seismol Soc Am* 75(5):1465–1468.
24. Tsang C-F, Birkholzer J, Rutqvist J (2008) A comparative review of hydrologic issues involved in geologic storage of CO_2 and injection disposal of liquid waste. *Environ Geol* 54(8):1723–1737.
25. Xiao C, Harris ML, Wang F, Grigg R (2011) Field testing and numerical simulation of combined CO_2 enhanced recovery and storage in the SACROC unit. CSUG/SPE 147544 (abstr).
26. Romanak KD, et al. (2012) Sensitivity of groundwater systems to CO_2: Application of a site-specific analysis of carbonate monitoring parameters at the SACROC CO_2-enhanced oil field. *Int J Greenh Gas Control* 6:142–152.

27. Castelletto N, Gambolati G, Teatini P (2013) Geological CO_2 sequestration in multi-component reservoirs: Geomechanical challenges. *J Geophys Res Solid Earth* 118(1):1–12.
28. National Research Council (2013) *Induced Seismicity Potential in Energy Technologies* (National Academies, Washington, DC), 225 pp.
29. Benson SM, Cole DR (2008) CO_2 sequestration in deep sedimentary formations. *Elements* 4(5):325–331.
30. Waldhauser F, Ellsworth WL (2000) A double-difference earthquake location algorithm: Method and application to the northern Hayward Fault, California. *Bull Seismol Soc Am* 90(6):1353–1368.
31. Mitchell BJ, Landisman M (1971) Geophysical measurements in the southern Great Plains. The structure and physical properties of the earth's crust. *AGU Geophys Monogr Ser* 14:77–93.

Clark Butler, IEEFA Guest Contributor
July 2020

Carbon Capture and Storage Is About Reputation, Not Economics

Supermajors Saving Face More Than Reducing Emissions

Executive Summary

The Australian Government proposes to broaden the scope of its Climate Solutions Fund[1] to include the ability to invest in carbon capture, use and storage (CCS or CCUS) projects.

This expansion of scope is essential if CCS projects are to be undertaken as CCS projects:

- are prohibitively expensive compared to other greenhouse gas emissions mitigation options, such as renewable energy and energy storage technologies;
- offer no financial return for investors; and
- have a dubious track-record. Even the Global CCS Institute - a booster organisation for CCS - acknowledges in its 2019 *Global Status of CCS* report that CCS is at best a minor contributor to decarbonisation, addressing up to 9% of greenhouse gas (GHG) emissions by 2050.[2]

There isn't one example of a CCS project anywhere in the world that offers a financial justification for investing in CCS.

In the absence of a carbon price, CCS will never provide a return on investment.

European oil companies—in particular, Equinor, Shell and Total—are investing in CCS, notwithstanding the lack of return, because it is an important part of their decarbonisation narrative and supports their aims to be seen as "responsible" energy companies.

There isn't one example of a CCS project anywhere in the world that offers a financial justification for investing in CCS.

The Australian Labor Party's recent statement that it remains "open to CCS" but insists that CCS must *not* be funded by the Clean Energy Finance Corporation (CEFC) nor the Australian Renewable Energy Agency (ARENA), makes sense. These bodies

[1] Australian Government. Clean Energy Regulator. Climate Solutions Fund.
[2] Global CCS Institute. Global Status of CCS 2019.

are intended to facilitate the increased flow of finance into the commercialisation and deployment of Australian based renewable energy, energy efficiency and low carbon technologies."[3] With CCS, there is no flow of finance into the CCS sector because there is no business case. With a carbon price, this might change: the market could then decide how much to invest in CCS projects.

Despite the Minerals Council of Australia's recent hollow statement about the Paris Agreement in its "Climate Action Plan"[4], decarbonisation of electricity, electrification of mining, and the use of green hydrogen in minerals processing will be the contributions its' members make to combating increasing emissions, rather than the limited benefits afforded by CCS.

There is no flow of finance into the CCS sector because there is no business case.

CCS, Carbon Sinks and a Carbon Price

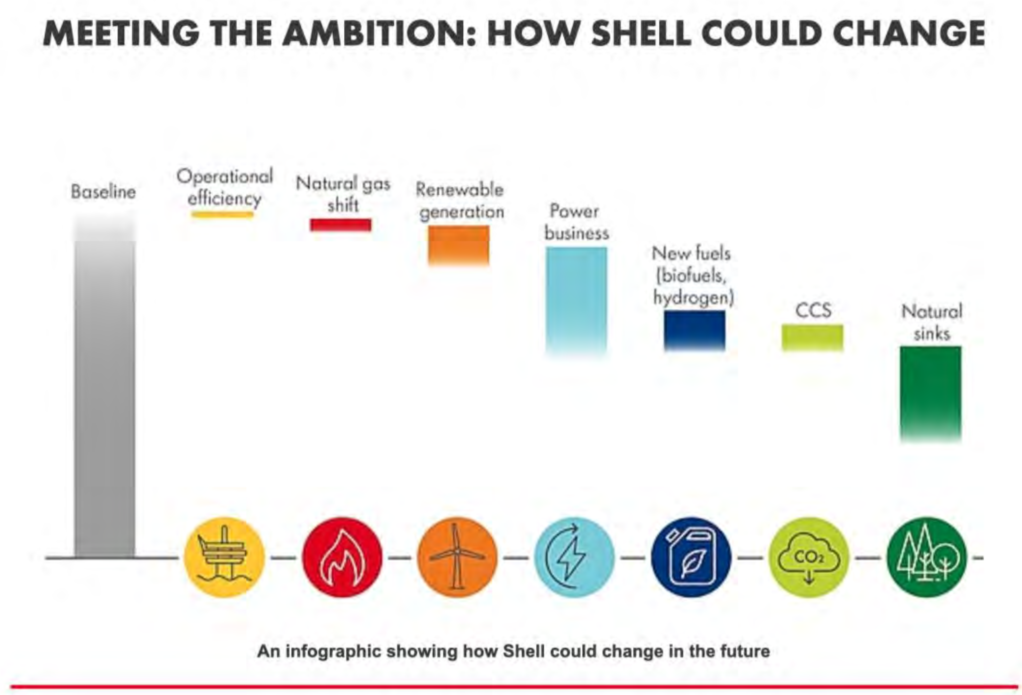
Oil majors Total and Shell have both emphasised the role that CCS, carbon sinks and a carbon price play in their ability to meet their long-term net-zero objectives.

Figure 1 shows directionally how Shell could meet its goal. Although this is not intended to be a precise chart, it is noteworthy the proportion of the reduction attributed to "natural sinks" (i.e., planting trees) and CCS.

Patrick Pouyanné, Chairman and CEO of Total, has stated, "We have the technology to capture and reinject carbon. The real question is how to do it in a way that is economically sustainable. That brings us back to the issue of carbon pricing."[5] In relation to CCS for coal-fired power generation, Pouyanné has said, "… I know that people advocate… for clean coal, but frankly, clean coal means a lot of CCS, and I would like to see where the CCS technologies are."[6]

[3] CEFC. CEFC Investment Policies.
[4] Minerals Council of Australia, Climate Action Plan, 2020.
[5] CNBC. Total gives itself 15 years to make its products 15 percent less carbon intensive. 20 October 2018.
[6] CSIS. A Conversation with Patrick Pouyanné, Chairman and CEO of Total S.A. 17 May 2018.

Figure 1: Shell's Path to Decarbonisation



Source: Shell.

IEEFA supports the idea that a carbon price is essential to achievement of large-scale carbon emission reductions. However, the fact that both companies' CEOs refer to this almost as a precondition to their climate goals invites scepticism about their commitment to unilateral action on CCS. Each company currently spends an immaterial percentage of annual capital expenditure on CCS[7], so it is arguable that CCS is little more than a helpful marketing message to support their boarder decarbonisation ambitions.

It is arguable that CCS is little more than a helpful marketing message.

What is Carbon, Capture and Storage?

Carbon capture, use and storage (CCS or CCUS) encompasses an integrated suite of technologies that can prevent large quantities of carbon dioxide (CO_2) from being released into the atmosphere as a consequence of using fossil fuels.

This technology has been applied in a wide range of industries since 1972 when several natural-gas processing plants in the Val Verde area of Texas began

[7] None of their investments are quantified in annual reports.

employing carbon capture to supply CO_2 for enhanced oil recovery (EOR) operations. Since then, more than 200 million tonnes of CO_2 have been captured and injected deep underground.

The net emissions impact of CCS must include emissions from the energy used in the process (up to 20% more than an operation without CCS) and the emissions from any oil extracted using EOR.

CCS Involves Three Major Steps:

1. **Capture**: The separation of CO_2 from other gases produced at large industrial process facilities such as coal and natural-gas-fired power plants, steel mills, cement plants and refineries.

2. **Transport**: Once separated, the CO_2 is compressed and transported via pipelines, trucks, ships or other methods to a suitable site for geological storage.

3. **Storage**: CO_2 is injected into deep underground rock formations, usually at depths of one kilometre or more, depleted oil or gas fields, deep saline aquifer formations or other forms of underground caverns, though it could apply to any form of storage.

The 'usage' component includes applications of the carbon in industrial processes such as the manufacture of synthetic diesel, biofuels, solvents and polymers.

A Good Idea but…

CCS is an excellent idea: if greenhouse gasses can be prevented from entering the atmosphere, we can continue traditional fossil fuel activities without worrying about the devastating effects of the changing climate.

The Global CCS Institute report quotes Lord Nicholas Stern, Bill Gates and other experts in the fields of climate, engineering and finance all emphasising the crucial role CCS has to play in addressing rising emissions.

There Are Some Key Problems However:

- Storage solutions can and do leak methane;

- The energy cost involved in the process materially reduces its net benefit; and,

- It doesn't make any economic sense, absent a whole-of-economy price on carbon emissions, supported by carbon border taxes (as proposed by the European Union).

What Can Go Wrong… and Does

Transportation and storage are two key areas of concern.

'Captured' carbon must be separated, transformed and, in most cases, transported to the sequestration site. The energy used in this process and the leakages that can occur during transportation and handling can materially reduce the net impact of the CCS process.[8]

Further, the underground storage into which the carbon is injected is not always secure. Wells have weaknesses and gaps. Fracking causes long-term subterranean instability, and seismic activity could dislodge even the most carefully stored carbon. Leaks in the Aliso Canyon natural gas storage facility in 2015 "released 97,100 metric tons of methane to the atmosphere,"[9] doubling the methane emission rate of the entire Los Angeles basin.

The underground storage into which carbon is injected is not always secure.

According to geologists, leaks should not be a practical concern for carbon dioxide (CO_2) storage if the CCS process is carefully implemented. However, further research concludes that the consequences of a minor leakage could reduce the benefit of CCS by up to 35%.[10]

The fossil gas industry has failed to systematically cap, sterilise and monitor abandoned gas wells over the last few decades, so methane leakage is massively underreported and largely ignored (thanks to regulatory capture and constant defunding of EPA departments). Further, the industry resists accepting liability for leakages.

The Economics of CCS Are Wrong

Whilst the technical issues of CCS can probably be addressed with engineering solutions over time, the more significant problem is a financial one.

CCS is an expensive process that generates very little revenue. Aside from limited pricing signals from emissions trading systems, there is no financial reason to invest in CCS. Consequently, there are no commercially viable examples of CCS anywhere in the world.

---

[8] IEEFA. Volkswagen lied about emissions from their vehicles, and the gas industry is also lying about their emissions. March 2020.
[9] Science. Methane emissions from the 2015 Aliso Canyon blowout in Los Angeles, CA. 18 March 2016.
[10] Frontiers in Energy Research. Bearing the Cost of Stored Carbon Leakage. 15 May 2018.

The traditional financial justification for doing CCS is for enhanced oil recovery (EOR). With oil prices currently well below breakeven for oils sands extraction, this does not begin to cover the costs of CCS.

With costs in the order of US$4,200 per kilowatt[11] for a power plant equipped with CCS, even if it works, CCS is a poor investment, multiples of the cost of new renewable energy even when the addition cost of firming is included.

There are no commercially viable examples of CCS anywhere in the world.

It is no surprise that the few operating CCS plants globally are government subsidised.

Playing With Someone Else's Money

Shell

Royal Dutch Shell promotes CCS as a key factor in its new, bold emission reductions strategy: to bring down its net carbon footprint of products by 50% by 2050. As a then new CEO in 2014, Ben van Beurden told the audience in a keynote speech at Columbia University that CCS could remove up to 90% of emissions from power generation. In 2015, Shell promised investment in CCS, coinciding with the opening of the Quest CCS facility in Canada. At every AGM since, van Beurden has returned to CCS as a key part of the solution.

To date, Shell has two CCS projects: Quest in Alberta, Canada, funded by the Albertan and Canadian governments and operated by Shell; and Gorgon in Western Australia, a project in which the project principals (Shell and Chevron) are financially motivated *not* to operate the CCS plant. The Gorgon plant has failed to meet its targets every year, notwithstanding a $60 million subsidy from the Western Australian government.

Shell's actual outlay in CCS over the years remains to be seen. Its overall investment in renewables is well behind its stated targets.[12] Any progress Shell demonstrates in removing carbon from the atmosphere using CCS (1m tonnes per annum at Quest and up to 4m tonnes at Gorgon) should be seen in light of Shell's total emissions of 656 million tonnes per annum (80Mt scope 1 and 2; 576Mt scope 3).[13]

Total SA

Total SA has also promised massive investment in CCS to remove up to 5 million tonnes of CO_2 per annum (8% of Total's scope 1 and 2 GHG emissions and 1% of

---

[11] EIA. PetroNova is one of two carbon capture and sequestration power plants in the world. 31 October 2017.
[12] NS Energy. "Royal Dutch Shell could be set to miss out on its green energy targets". 3 January 2020.
[13] Shell. Shell Sustainability Report 2019.

scope 1/2/3 emissions).[14]

Total SA is an investor in Equinor's Sleipner CO_2 storage as well as, with Shell and Equinor, the larger Nordic project under development, Northern Lights.[15]

Equinor

Equinor, the Norwegian state oil and gas producer, has been investing in CCS since 1996, mainly because Norway has had a carbon price since 1991. Its Sleipner CO2 storage and Snøhvit CO2 storage facilities have cumulatively captured and stored around 22 million tonnes of CO2. Compared to the rest of the fossil fuel industry, this is considerable achievement but this pales into insignificance when one considers that Equinor is responsible for over 330m tonnes of CO2-e emissions every year (scope 1, 2 and 3). With the carbon price, there is a modest economic return on its CCS operations but the impact on emissions is immaterial in the scheme of Equinor's contribution to global warming. By way of comparison, Equinor's scope 3 emissions increased by 26 million tonnes per annum from 2014 to 2018.[16]

Capturing Carbon at Power Stations Proves Fraught

CCS is more problematic in relation to power stations.

Boundary Dam in Saskatchewan, Canada and Petro Nova in Texas are the only power stations to implement a CCS retrofit that were completed in North America this past decade.

Kemper was to be the shining example of 'clean' coal. The cost blew out to US$7.5bn, and the project was abandoned.

Boundary Dam, owned by the Saskatchewan utility, SaskPower, cost C$1.3bn to the retrofit, was years behind schedule, and operated at less than 50% capacity when it finally commenced.[17] Only one power unit has been retrofitted and SaskPower made a decision not to apply the technology to the other units.

Petro Nova cost US$1bn, at approximately $4,200/KW, and captures 33% of emissions from one unit (654MW).[18] The carbon was intended to be supplied for enhanced oil recovery (EOR) but the price has fallen dramatically since the initial modelling was done and the project is a financial failure. It receives a $50/t subsidy

---

14 Total. Integrating Climate into our Strategy. 2019.
15 Northern Lights. About the Project.
16 Equinor. Six ways our oil and gas expertise is energising renewables.
17 Renew Economy. The Fallout from SaskPower's Boundary Dam debacle. 12 November 2015.
18 EIA. Petron ova is one of two carbon capture and sequestration power plants in the world. 31 October 2017.

from the U.S. Government—effectively a carbon price—to keep it running at this minimal level.

Kemper was to be the shining example of 'clean' coal. A massive new coal-fired power station in Mississippi—possibly the largest project ever in the state—promised jobs and cheap, clean electricity. The $2.4bn estimated cost ($4,100/KW) blew out to US$7.5bn and the project was abandoned.[19]

There is no business case for gas CCS other than as a corporate social responsibility initiative, and there is no business case for coal CCS at all.

Conclusion

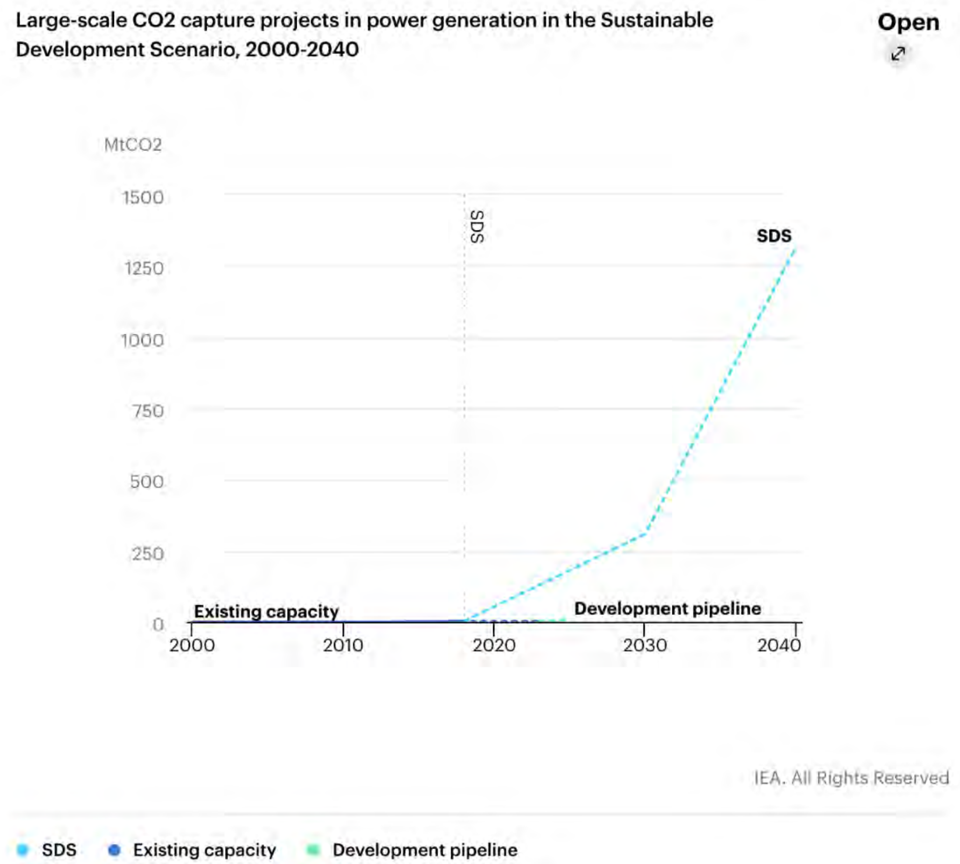
The IEA identifies CCS as mitigating up to 9% of GHG emissions by 2050 but notes:

> *"With only two large-scale CCUS power projects in operation at the end of 2018 and a combined capture capacity of 2.4 million tonnes of CO2 (MtCO2) per year, CCUS in power remains well off track to reach the 2030 Sustainable Development Scenario (SDS) level of 350 MtCO2 per year.*
>
> *As CCUS applied to power is at an early stage of commercialisation, securing investments will require complementary and targeted policy measures such as tax credits or grant funding. Support for innovation needs to target cost reductions and broaden the portfolio of CCUS technologies."*[20]

Figure 2 highlights the IEA's assessment of the huge gap between aspiration and reality in relation to power CCS.

[19] EIA. Petron ova is one of two carbon capture and sequestration power plants in the world. 31 October 2017.
[20] IEA. Tracking Power 2019.

Figure 2: IEA Highlights the Gap Between CCS Ambition and Reality



Source: IEA.

If the Australian Government wishes to encourage the development of CCS in Australia, in both gas and power, a carbon price would be a much better policy than the subsidisation of uneconomic CCS project proposals.

About IEEFA

The Institute for Energy Economics and Financial Analysis (IEEFA) examines issues related to energy markets, trends and policies. The Institute's mission is to accelerate the transition to a diverse, sustainable and profitable energy economy. www.ieefa.org

About the Author

Clark Butler

Clark Butler is an IEEFA guest contributor, and a corporate adviser with a background in the technology and finance sectors. In additional to being a director of and investor in technology and data companies, he is exploring technology and financing solutions to encourage investment in renewable energy solutions. clark.butler@ironbarkgroup.com

Aluminium Sector Greenhouse Gas Pathways to 2050

March 2021

world-aluminium.org

International Aluminium Institute (IAI)

Current IAI membership represents the major producers of bauxite, alumina and aluminium in all significant regions, including China. Since its foundation in 1972, members of IAI have been companies engaged in the production of bauxite, alumina, aluminium, the recycling of aluminium, or fabrication of aluminium, or as joint venture partners in such. The key objectives of IAI are to:

- Increase the market for aluminium by enhancing worldwide awareness of its unique and valuable qualities;
- Provide the global forum for aluminium producers on matters of common concern and liaise with regional and national aluminium associations to achieve efficient and cost-effective cooperation;
- Identify issues of relevance to the production, use and recycling of aluminium and promote appropriate research and other action concerning them;
- Encourage and assist continuous progress in the healthy, safe and environmentally sound production of aluminium;
- Collect statistical and other relevant information and communicate it to the industry and its principal stakeholders; and
- Communicate the views and positions of the aluminium industry to international agencies and other relevant parties.

Through IAI, the aluminium industry aims to promote a wider understanding of its activities and demonstrate both its responsibility in producing the metal and the potential benefits to be realised through their use in sustainable applications and recycling.

Contents

Figures

1. Aluminium: central to a sustainable future

Aluminium products are essential enablers of a low carbon future and the increased use of the metal will lead to reduced economy-wide emissions.

Fleets of lightweight, autonomous, electric vehicles delivering leased mobility services to a growing global population, powered by renewable energy grids; net positive, modular, intelligent buildings, producing more energy than they consume and adapting in real time to the varied needs of their occupants; lightweight and protective packaging solutions, bringing nutritional and pharmaceutical benefits to ten billion people by 2050, minimising wastage and reducing burdens on logistics – all will require the material and energy benefits that aluminium brings…and in increasing quantities.

While aluminium is part of the solution for a sustainable future (because of its unique combination of properties: lightness, strength, durability, electrical and thermal conductivity, formability and recyclability), the industry recognises that it has the potential to be part of the problem if the sector does not plan and act quickly to reduce its greenhouse gas emissions in line with societal climate goals. Increasing demand for aluminium will only be enhanced by transitioning to a low carbon trajectory and such paths will be different for different actors within the aluminium sector around the world and along the value chain.

This is a challenge. Not just an environmental challenge, but an economic, political, social, logistical and technological one, made even more complex by differential access to the solutions that will be required to deliver it (and the fact that many of these solutions are currently on the drawing board while others do not yet exist).

It is, however, a challenge that the aluminium sector is poised to address, in part through the work of the International Aluminium Institute (IAI), which is exploring realistic and credible technological pathways for 2050 sector-wide greenhouse gas emissions reduction. These pathways are in line with the Paris Agreement goal to limit global warming to well below 2°C, preferably to 1.5°C, compared to pre-industrial levels.

With unrivalled industrial and material data and analyses, the IAI has mapped out the three main routes for the aluminium industry to achieve global climate goals (while addressing other sustainability issues). The technology needed in many cases is in the final stages of development and deployment, however, significant investment is required. The greatest need is for policies to support and accelerate that investment.

2. The International Aluminium Institute: a scientific authority & enabler of change

The Greenhouse Gas Pathways Working Group, made up of IAI member companies and regional associations, has worked collaboratively to understand and articulate:

- The emissions benefits delivered by the use and recycling of aluminium products;
- The sector's footprint and sources of emissions;
- How this footprint might change over the next thirty years if no action is taken, given changing demand for aluminium products;
- What the industry as a whole (and individual actors along the value chain) would need to achieve under a below 2-degree warming scenario;
- The range and mix of decarbonisation technologies, including existing, new, under-development and yet-to-be-developed solutions, available to different actors with varying processes and emission profiles;
- Policy (and investment) drivers and barriers to decarbonisation – through production process emissions mitigation and through recycling savings.

All of this is underpinned by the IAI's mature emissions models, built on its member companies' data and analytical expertise.

The pathway choices made by aluminium industry actors will depend on their unique energy endowments, raw material and scrap availability, regional policies, investment options and the availability, speed and cost of technology development and implementation.

There is a need for sector-wide and inter-sectoral partnerships to address the huge challenge of reducing GHG emissions, while satisfying growing demand. Partnerships will be required among and between producers, as well as with the public sector and academia, power generators, semi-fabricators, customers/original equipment manufacturers (OEMs) and end users. Due to its relative homogeneity in terms of processes and products, along with its scale and global scope, the aluminium industry can meet this need, with the IAI uniquely placed to initiate, facilitate and inform such partnerships.

3. What is the aluminium sector's carbon footprint?

The IAI has collected data on industry emissions for more than two decades, recently publishing a 15-year database of sector emissions (IAI, 2020a), which covers all processes cradle-to-gate. That means ALL the emissions that the sector generates in its own facilities (primary and recycling), but also those embedded in the raw materials, ancillary materials and energy that the sector consumes. This is the most comprehensive, detailed and up to date sector-wide dataset that exists for aluminium, but also any material, today.

According to this 2018 data, the sector is responsible for 1.1 billion tonnes of greenhouse gas emissions per annum, around 2% of all global anthropogenic emissions[1]. More than 90% of this footprint is from primary production processes, while primary aluminium currently makes up around 70% of annual metal demand.

	Bauxite mining	Alumina refining	Anode production	Electrolysis	Casting	Recycling*	Semis production	Internal scrap remelting	Total
Electricity (indirect)	0.6	16.9	-	670.6	-	3.1	9.5	2.5	703
Non CO_2 GHGs (direct)	-	32.2	-	35.4	-	-	-	-	68
Process CO_2 (direct)	-	-	6.4	92.6	-	-	-	-	99
Ancillary materials (indirect)	-	14.8	19.3	6.4	-	-	-	-	41
Thermal energy (direct/indirect)	2.6	124.3	6.4	-	6.4	15.6	19.0	8.4	183
Transport (indirect)	-	15.4	-	18.7	-	-	-	-	34
Total (cradle to gate)	3	204	32	824	6	19	29	11	1,127

*Figure 1 2018 total aluminium sector emissions (Mt CO_2e) heat mapped, by process and source (*recycling of pre- and post-consumer scrap), (IAI, 2020a)*

In the IAI's material flow analysis (IAI, 2021a) demand for aluminium is expected to grow by 80% by 2050. This will be met by a combination of recycled and primary aluminium. Aluminium products already have high recycling rates. Yet, even with further improvements in collection, the long lifetimes of durable aluminium products, a growing population and a broader range of applications mean there will not be enough post-consumer scrap to meet this demand alone and primary metal will still need to be produced until at least the second half of the century.

Collection rates of end-of-life products are currently above 70%, having increased by 10% in the past 10 years (IAI, 2020b). However, there are still significant opportunities to increase the collection, sorting and recycling of post-consumer products to reduce (to some extent) the need for primary aluminium.

[1] Expressed as CO_2 equivalents – CO_2e (or 4% of carbon dioxide (CO_2) emissions)

Primary aluminium production is an energy intensive process (IAI, 2020c), requiring huge amounts of electricity to break the strong oxygen bonds of the input chemical - alumina[2]. The reactivity of aluminium is a function of its atomic structure, which is also the source of its valuable physical qualities, such as lightness, strength, durability and conductivity, making it the material of choice for so many applications.

The production of primary aluminium (IAI, 2018) begins with the mining of bauxite ores. Around 5.5 tonnes of bauxite is required on average to produce one tonne of aluminium. The mining process itself is relatively low emitting (compared to other processes in the value chain) representing one quarter of a percent of total sector emissions, mainly from mobile equipment. Transport of bauxite (and all other intermediate products) amounts to around 3% of emissions.

Alumina is extracted from bauxite in the Bayer Process, which requires energy in the form of heat and steam, as well as ancillary materials such as sodium hydroxide, all of which come with a carbon footprint. Alumina production represents just under 20% of all sector emissions.

The smelting of aluminium currently takes the form of a reduction-oxidation reaction between the raw material, alumina, and carbon anodes, in which three electrons are provided to each aluminium ion to reduce it to its metal form, while the carbon atoms of the anodes are oxidised to form carbon dioxide, according to the reaction:

$$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2$$

Thus, direct carbon dioxide emissions from this process are proportional to the production of aluminium. This electro-chemical process (electrolysis) requires electricity, carbon anodes and ancillary products, such as cryolite (sodium aluminium fluoride), as well as thermal energy to cast liquid metal into solid products. Electricity-related emissions dominate the 75% of sectoral emissions that smelting represents. And yet, this is the source with the greatest variation across the industry, depending on the smelter power mix – historically dominated by hydropower, but now increasingly by coal and gas combustion (IAI, 2020d).

Recycling on the other hand, requires much less energy – essentially only that needed to melt the aluminium scrap. It also has no need to reduce aluminium oxide to aluminium metal and so emissions of carbon dioxide from the chemical reaction mentioned above are eliminated.

Thus, the emissions profile of the industry is dominated by primary aluminium production, with a kilogram having a carbon footprint of anywhere between less than 5 and more than 25 kg CO_2e, depending on the source of energy used to generate the electricity.

[2] Alumina is a chemical compound of aluminium and oxygen with the chemical formula Al_2O_3

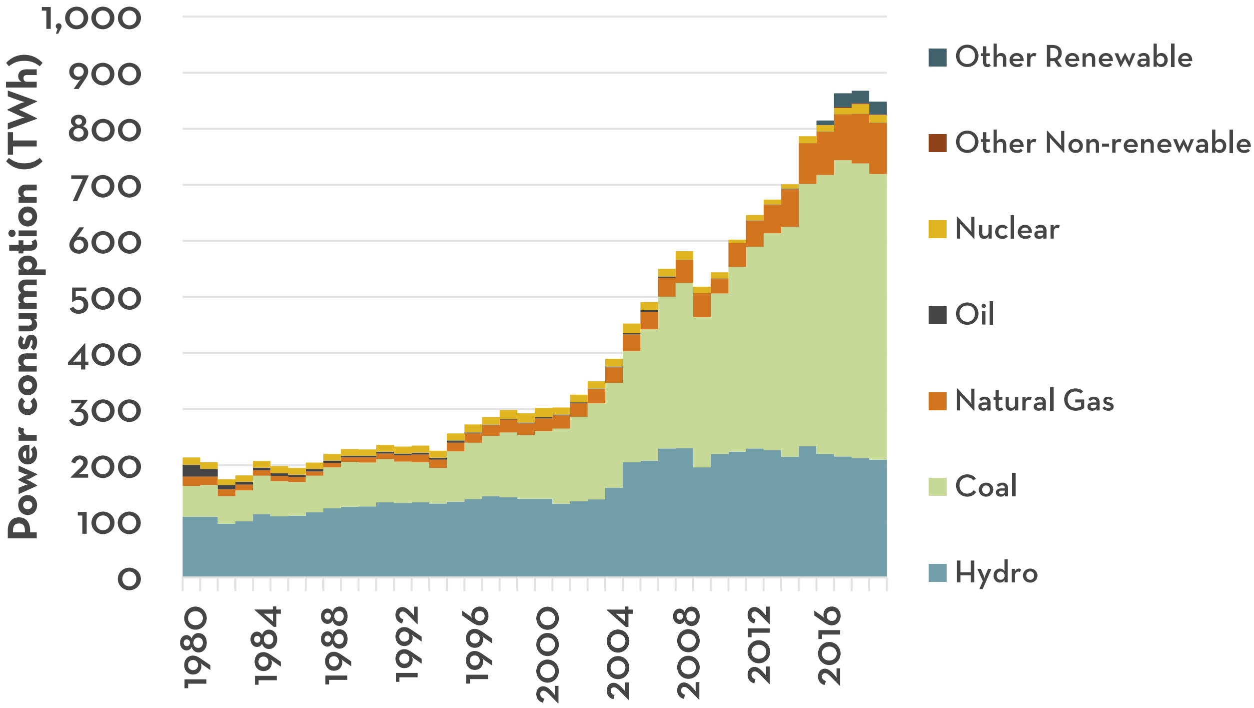


Figure 2 Global primary aluminium smelting power mix, TWh per annum (1980-2019), (IAI, 2020d)

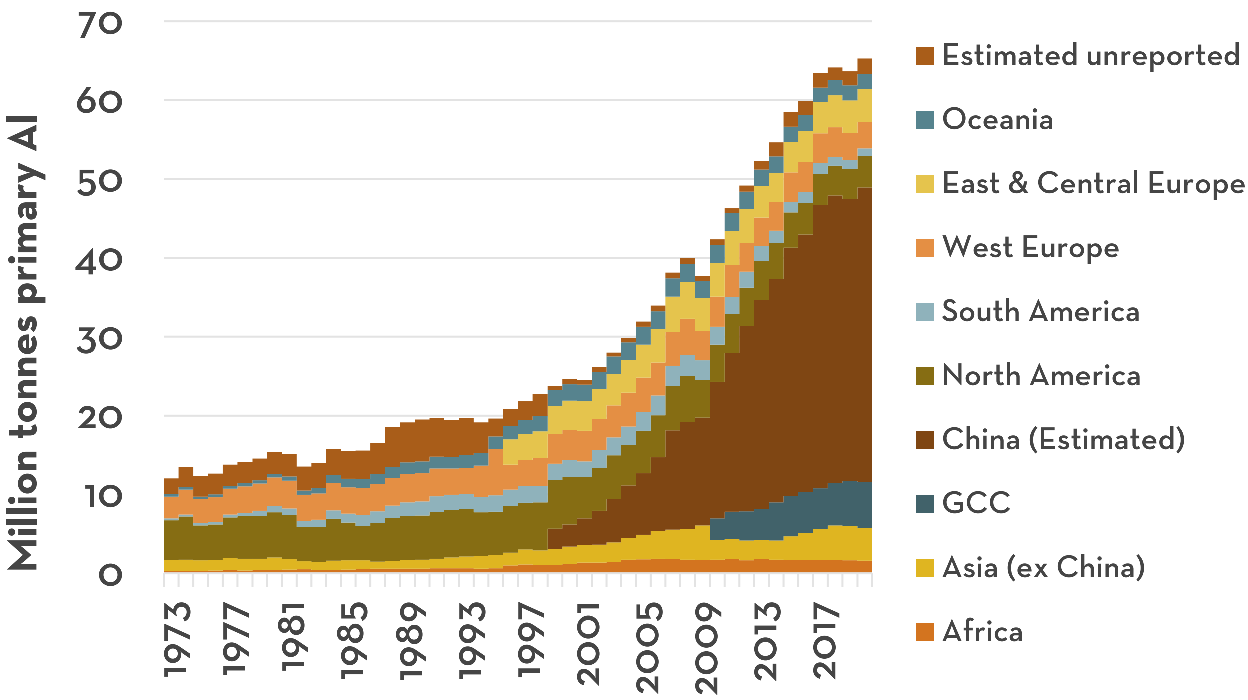


Figure 3 Global primary aluminium production by region, Mt Al per annum (1973-2019), (IAI, 2021b)

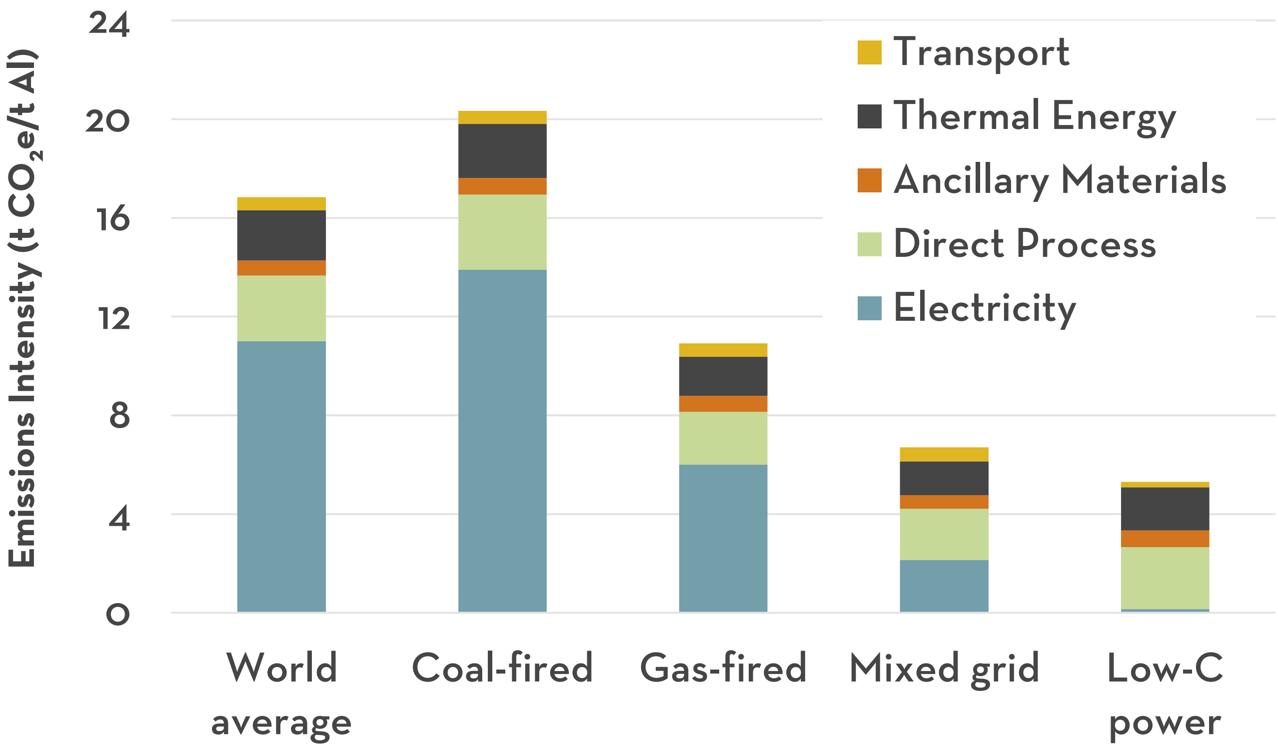


Figure 4 World average 2018 & example power mix cradle-to-gate emissions intensity of PRIMARY aluminium, t CO_2e/t Al

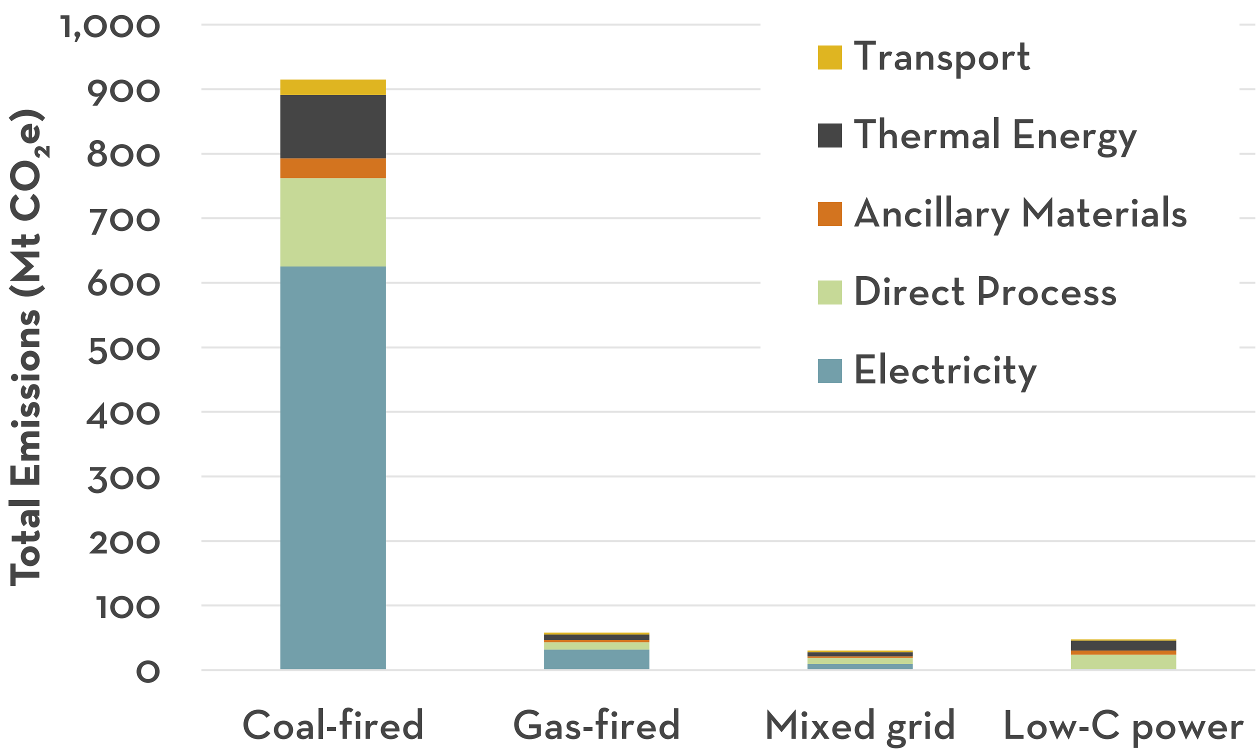


Figure 5 Total 2018 cradle-to-gate emissions from PRIMARY aluminium by power source, Mt CO_2e

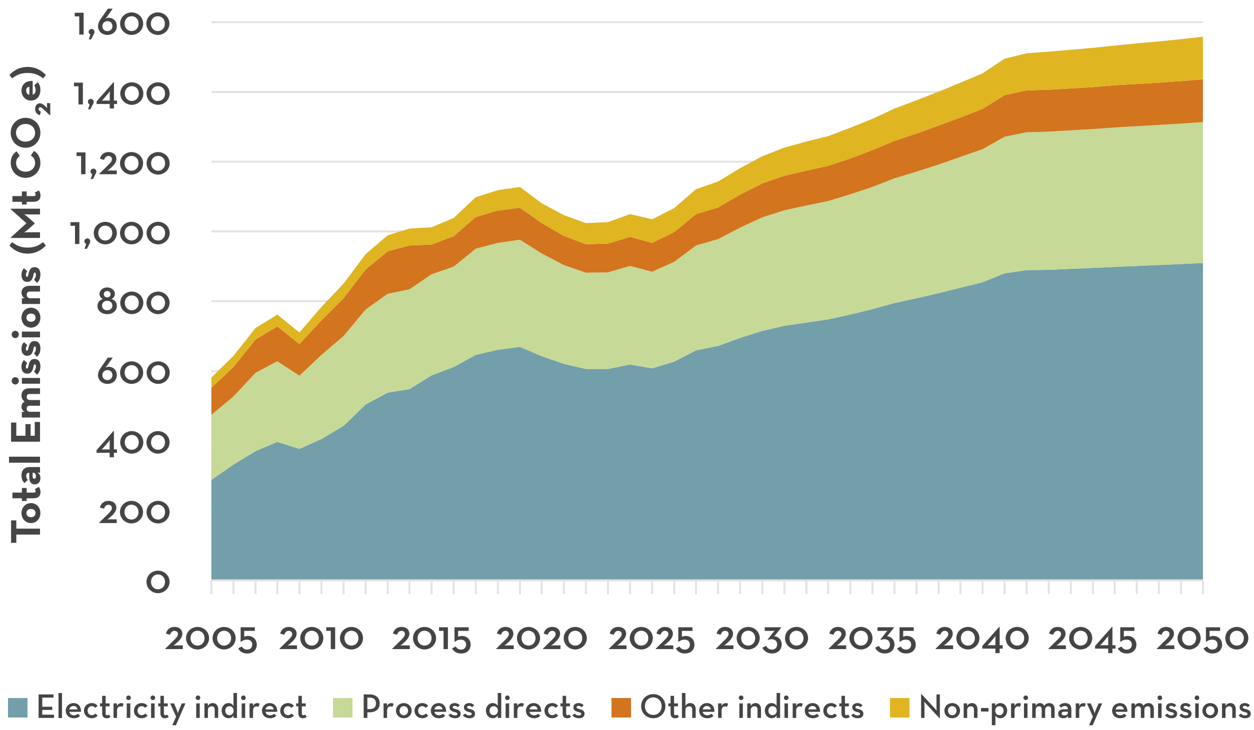


Figure 6 Historic (2005-2018) and forecast (2019-2050) global aluminium sector emissions under the BAU scenario, Mt CO_2e per annum

Driven by the expected growth in demand for aluminium applications, and even with recycling forming a significant proportion of supply (up to 60% by mid-century), Business As Usual emissions for the sector are forecast to reach 1.6 Gt CO_2e by 2050, the majority (1.5 Gt) from primary production.

4. What would a Paris-aligned 2050 aluminium footprint look like?

The *International Energy Agency* (IEA) recognises the contribution of aluminium to a decarbonising world and has therefore given the sector a 2050 allowance for greenhouse gas emissions that is above zero, even as the world would need to be at net zero by the second half of the 21st century.

The IEA has published two below 2°C warming scenarios: the *Beyond 2°C Scenario (B2DS)* (IEA, 2017) and the *Sustainable Development Scenario (SDS)* (IEA, 2020). Under B2DS, the IEA forecasts that by 2050 there should be a reduction in total anthropogenic CO_2 emissions from 34.3 Gt CO_2 (2014) to 4.8 Gt CO_2, whilst the SDS requires a reduction from 35.7 Gt (2019) to 9.4 Gt CO_2 (2050). The IAI decided to work under the B2DS scenario framework due to the availability of regional electricity datasets and the lower overall global CO_2 emissions budget by 2050. Nevertheless, the IAI will continue to work on improving its scenarios based on material flow modelling and updated climate science.

The IEA's B2DS budget for the aluminium sector includes a subset of the industry's direct emissions, with separate regional pathways for the electricity consumed by the industry. The IAI has therefore brought together the IEA scenario for direct CO_2 emissions generated by the aluminium sector and its power consumption and developed B2DS-aligned pathways for the emissions not included in the IEA's dataset. The result is a B2DS-aligned pathway for the entire aluminium sector, which indicates that by 2050:

- Total aluminium sector emissions covering the entire chain (bauxite, alumina and primary aluminium production, pre- and post-consumer aluminium scrap recycling and semi-finished aluminium production processes, cradle-to-gate) would need to be reduced to 250 Mt CO_2e (from a 2018 baseline of 1,100 Mt CO_2e and a projected Business as Usual (BAU) 2050 pathway of 1,600 Mt CO_2e).

- Out of this 250 million tonnes, the emissions from electricity consumed in all processes (but in particular smelting) would account for near zero emissions. Today this source accounts for 700 Mt CO_2e and in 2050 would emit 900 Mt CO_2e under BAU.

- Non-electricity primary aluminium emissions (cradle-to-gate) would need to be reduced from 400 Mt CO_2e today (over 520 Mt in 2050 under BAU) to below 200 Mt CO_2e.

- Fuel combustion emissions from recycling and fabrication processes would need to be reduced by 55% compared to BAU, from over 110 Mt CO_2e to 50 Mt CO_2e.

In 2018, global demand for aluminium was 95 million tonnes per annum; two-thirds of which was met by primary aluminium and one third from recycled scrap.

Rapid population and economic growth over the coming decades means global demand for aluminium is set to increase by up to 80% (to 170 Mt) by 2050 (material flow model "2020 IAI Reference Scenario" (IAI, 2021a) and this will still be met by a mix of both recycled and primary metal.

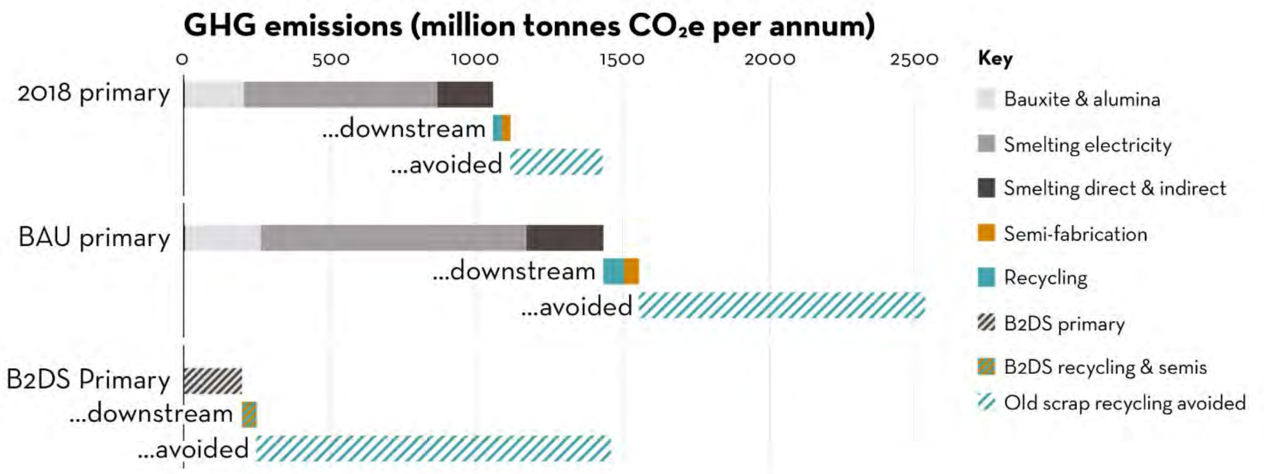


Figure 7 Sector-wide emissions in 2018 and 2050 under BAU and B2DS, Mt CO_2e

The global average emissions intensity of a tonne of aluminium (semi-fabricated) product would therefore need to be around 1.5 t CO_2e/t Al (cradle-to-gate) in 2050 to be B2DS aligned:

(2050 B2DS-aligned sectoral "allowance") / (2050 aluminium semis demand)

(million tonnes CO_2e) / (million tonnes aluminium)

250 / 170

= ***1.5 t CO_2e/t Al semis***

Despite increased projected recycled metal supply, the IAI estimates that between 75 and 90 million tonnes per annum of primary aluminium will still be required in 2050. Assuming a primary aluminium "allowance" of 200Mt (80% of the 2050 budget, compared to 95% today), the average emissions intensity of primary aluminium would need to be 2-3 t CO_2e/t Al (cradle-to-gate) to be B2DS aligned:

(2050 B2DS-aligned primary "allowance") / (2050 aluminium primary demand)

(million tonnes CO_2e) / (million tonnes aluminium)

200 / 80

= ***2.5 t CO_2e/t Al primary***

Broadly these numbers assume a 100% reduction of electricity-related emissions over the next 30 years - a significant challenge for primary producers. This also assumes a 50% reduction in direct (process and thermal energy) emissions and those embedded in raw materials and ancillary processes – a challenge common to all players along the value chain, including the downstream industry.

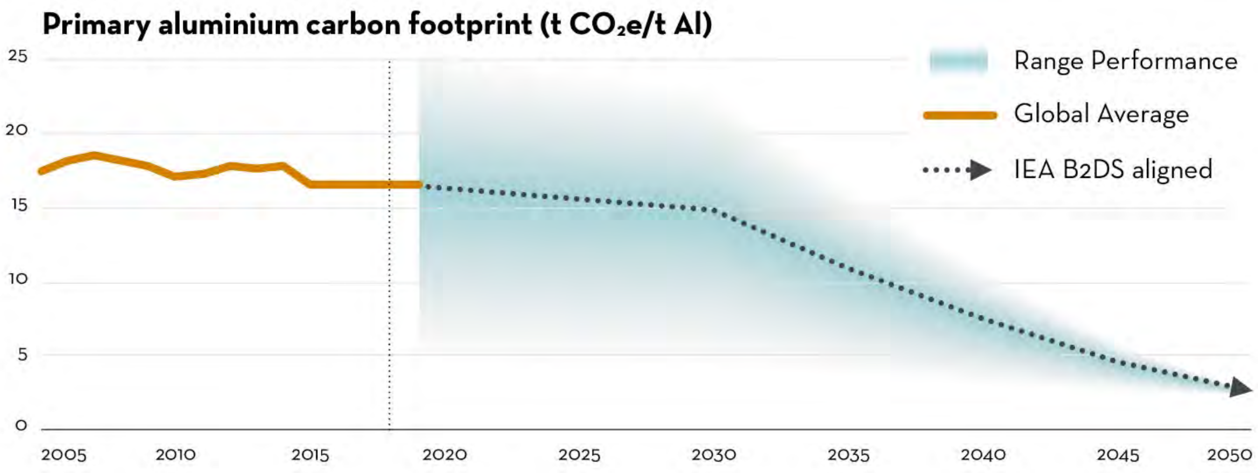


Figure 8 Global average primary aluminium carbon footprint under B2DS aligned 2050 scenario, t CO_2e/t Al

5. GHG emission reduction pathways

There are three broad areas that have the potential to contribute to this delinking of growth and emissions, each with distinct innovation, policy and financial drivers, barriers, costs and materiality:

1. Electricity decarbonisation
2. Direct emissions reduction
3. Recycling & resource efficiency

The following exploration of greenhouse gas emissions pathways identifies the most significant (greatest emissions reduction potential) technological and policy changes that can/may be implemented in order to realise sectoral B2DS-aligned decarbonisation.

Depending on where they sit within the aluminium value chain, the processes currently employed and the future availability of energy and material resources, different corporate actors will follow different (or a range of different) pathways, at different rates and from different starting points.

Electricity decarbonisation

The generation of electricity was responsible for 60% of the sector's emissions in 2018.

Decarbonised power generation and the accelerated deployment of carbon capture utilisation and storage (CCUS) offer the most significant opportunity for emissions reduction.

Decarbonisation of electricity grids (currently supplying a third of the industry's power needs) and a shift in captive (self-generating) power plants to low/near-zero emissions sources will require significant investment, both for the existing 45 million tonnes of primary aluminium currently powered by fossil fuel-generated electricity, and for the additional 20-25 million tonnes of aluminium production capacity required to meet 2050 demand.

Existing producers are presented with a wide range of significantly different opportunities, technologies and pathways depending on local circumstances and energy endowment.

Aluminium production in fossil fuel heavy regions is predominantly powered by self-generated electricity. In some cases, this is due to grid power being unreliable during the construction of smelters, which require 24/7 power. IAI data indicates that 97% of electricity in Asia (ex-China), for instance, is self-generated (IAI, 2020d).

Depending on the pathway(s) followed, the capital investment required for electricity decarbonisation is in the range of US$ 0.5 to 1.5 trillion over the next 30 years.

Aside from this capital investment, it is recognised that the sector (and society in general) will likely pay more per unit of energy and that further investments will be required to upgrade or install new aluminium production facilities.

Hydropower was the dominant source of electricity for aluminium smelters throughout the 20th century (IAI, 2020d). While hydro-based production has remained relatively flat since the 1970s, recent years have seen plans for significant growth. This has occurred as a number of aluminium producers in China begin to replace coal-fired capacity (much of it relatively young, less than 10 years old) in central and eastern China with new capacity in Yunnan Province. Three million tonnes of aluminium have relocated in the last year with a further 3-5 million tonnes scheduled to shift in the coming years. This is part of a broader plan for low carbon aluminium production proposed by the largest Chinese producers (China Hongqiao & China Aluminum Corporation, 2021).

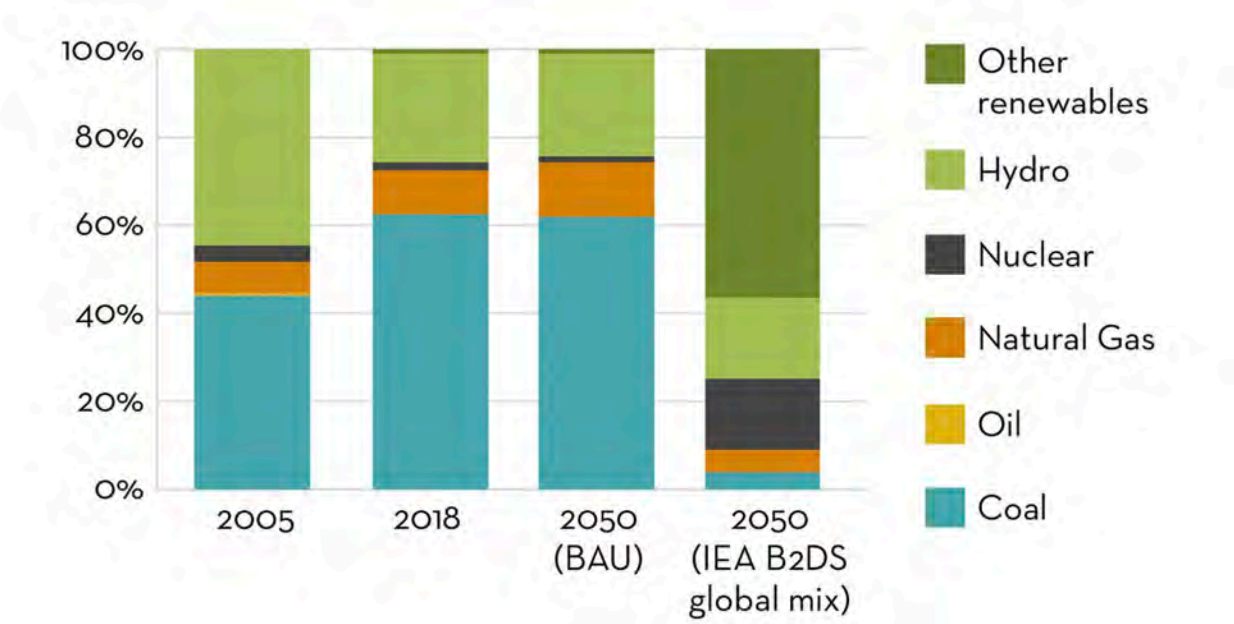


Figure 9 Changing smelter power mix under 2050 BAU compared to IEA Beyond 2 Degree Scenario (B2DS). (Fossil fuel in B2DS predominantly with CCUS).

The United Arab Emirates (UAE) Energy Strategy 2050 (UAE Government, 2017) aims to reduce the carbon footprint of power generation by 70% (with an energy mix that combines renewable, nuclear and other clean energy sources). It will also improve the energy efficiency of consumers by 40%, through an AED 600 billion (USD$ 165 bn) investment over the next 30 years, while delivering savings of AED 700 billion (USD$ 190 bn).

Carbon capture utilisation and storage (CCUS) from power plants has the potential to reduce emissions from electricity supply at a similar level as grid decarbonisation at similar costs per tonne of carbon, with the IEA identifying costs of US$ 40-80/tCO_2 for coal- and gas-fired power plants (IEA, 2019).

Energy efficiency gains in existing facilities through incremental improvement ("creep") and retrofitting and installing new capacity would contribute only 10% to emissions reduction.

As grids transition to lower inertia (intermittent renewable electricity generation sources, with a changing demand base including more electric vehicles that lead to peak loads at given times), large and consistent electricity consumers, like aluminium smelters, will play an increasingly important role in stabilising grids. This enabling role will be important in giving smelters access to renewables grids – in the same way that many 20th century smelters enabled the development of new power networks in regions such as Brazil and southern Africa.

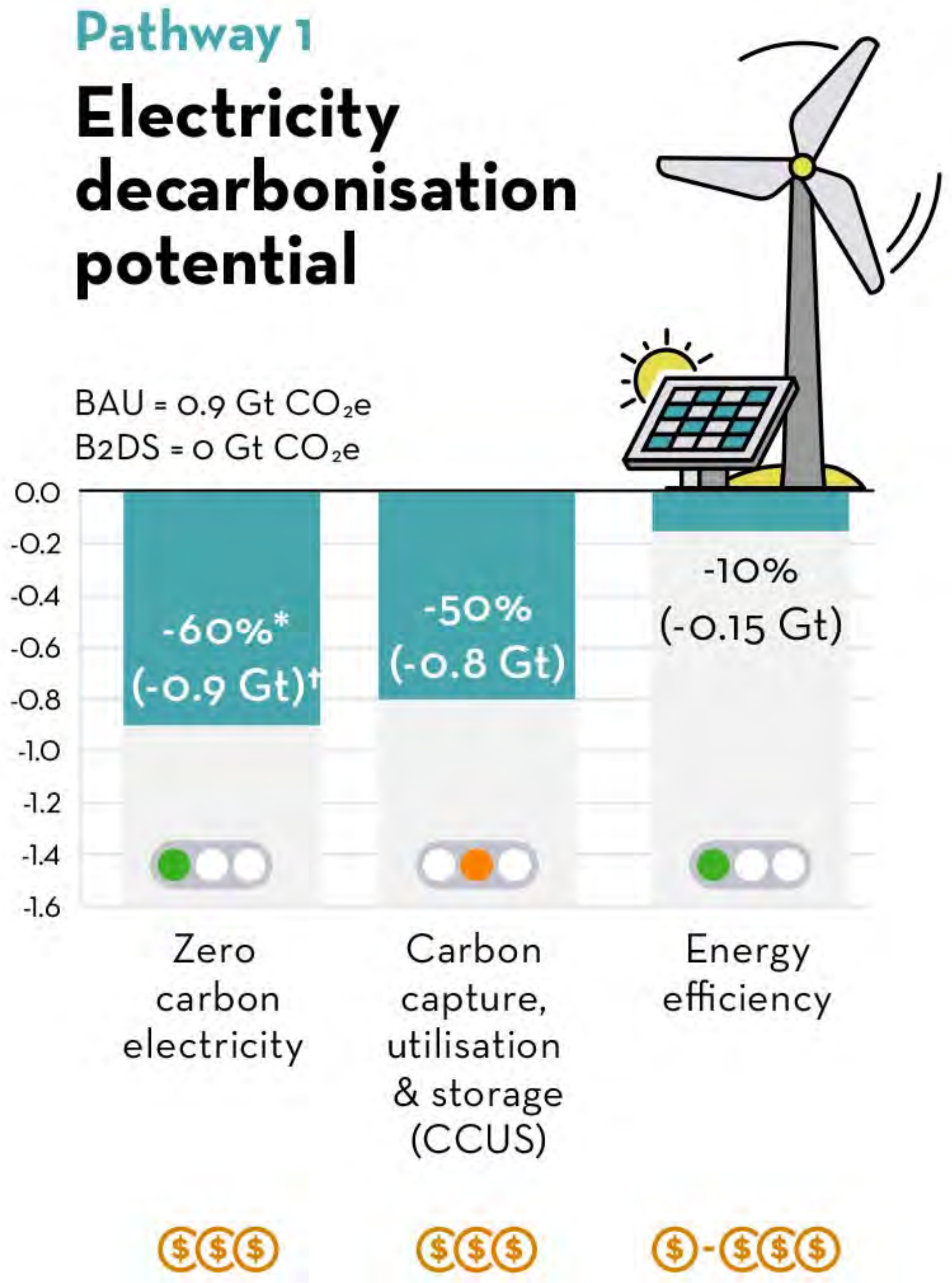


Figure 10 Pathway 1: Electricity decarbonisation

Direct emissions reduction

The past 20 years have seen a dramatic reduction in the proportion of sectoral emissions that are directly emitted from the aluminium production process (as opposed to the electricity and raw materials they consume) and of that share, those which are evolved from the combustion of fuels (to provide heat and steam) and other sources.

This is partly a consequence of the growth in fossil fuel power and the focus of the industry on eliminating process-related emissions, such as the high global warming potential gases perfluorocarbons (PFCs) from anode effects, improving energy efficiency and adding new (and best available) refining and smelting technologies.

In 1990, with sector-wide emissions at less than 300 Mt CO_2e per annum, direct emissions made up around two-thirds of this total. Of this approximately 200 Mt CO_2e, PFCs constituted 100 Mt CO_2e (33%).

Today, direct emissions constitute less than one-third of the total sectoral emissions (300 Mt CO_2e of the 2018 total of 1.1 Gt CO_2e), with PFCs making up only 35 Mt CO_2e (3%) (IAI, 2020a). This is due to a concerted effort to improve management of the smelting process in the 1990s and 2000s, as well as the addition of new technologies in the 2000s and 2010s. Anode consumption in the smelting process and fuel combustion across all production processes make up almost all of the direct emissions from the sector.

Thus, the promising pathways to emissions reduction in this category are focused on two things:

- novel (inert anode) technologies that eliminate the need for carbon anodes in smelting, and
- the development of technologies that can provide heat and steam without the combustion of fossil fuels (e.g. electrification with renewable power sources, combustion of renewables-produced hydrogen, concentrated solar thermal as a share of the energy mix and mechanical vapour re-compression of steam).

In addition, the capture and sequestration of greenhouse gases from each source at point of emission or evolution is another potential pathway.

Challenges with CCUS are not unique to the aluminium sector and costs reflect wider issues that emitters will face in developing and deploying these technologies appropriately. For aluminium smelting however, the low concentration of CO_2 in the flow of gases from electrolytic cells at 500-15,000 ppm presents an additional challenge, requiring redesign or retrofitting of cells and consequent costs of design, realisation and deployment. This is without counting the cost of scrubbing the other contaminants before the carbon is captured (to reduce contamination of captured CO_2).

Removal of direct emissions from the electrolytic smelting process (transforming alumina into aluminium) is a challenge common to all primary aluminium producers and will require a step change in technology to realise. Novel cell technologies, such as inert anodes, will play an important role in emissions reduction, but it should be noted that the sources they mitigate make up around 15% of global sector-wide emissions.

These technologies will also need to operate at similar or better energy intensity than existing carbon anodes during the transition to zero-carbon power environments. This is because any reductions in direct emissions could be outweighed by indirect electricity-related emissions if deployed at a higher energy consumption in fossil fuel powered grids. However, in the long-term, inert anodes will be an important component of a B2DS-aligned sectoral pathway.

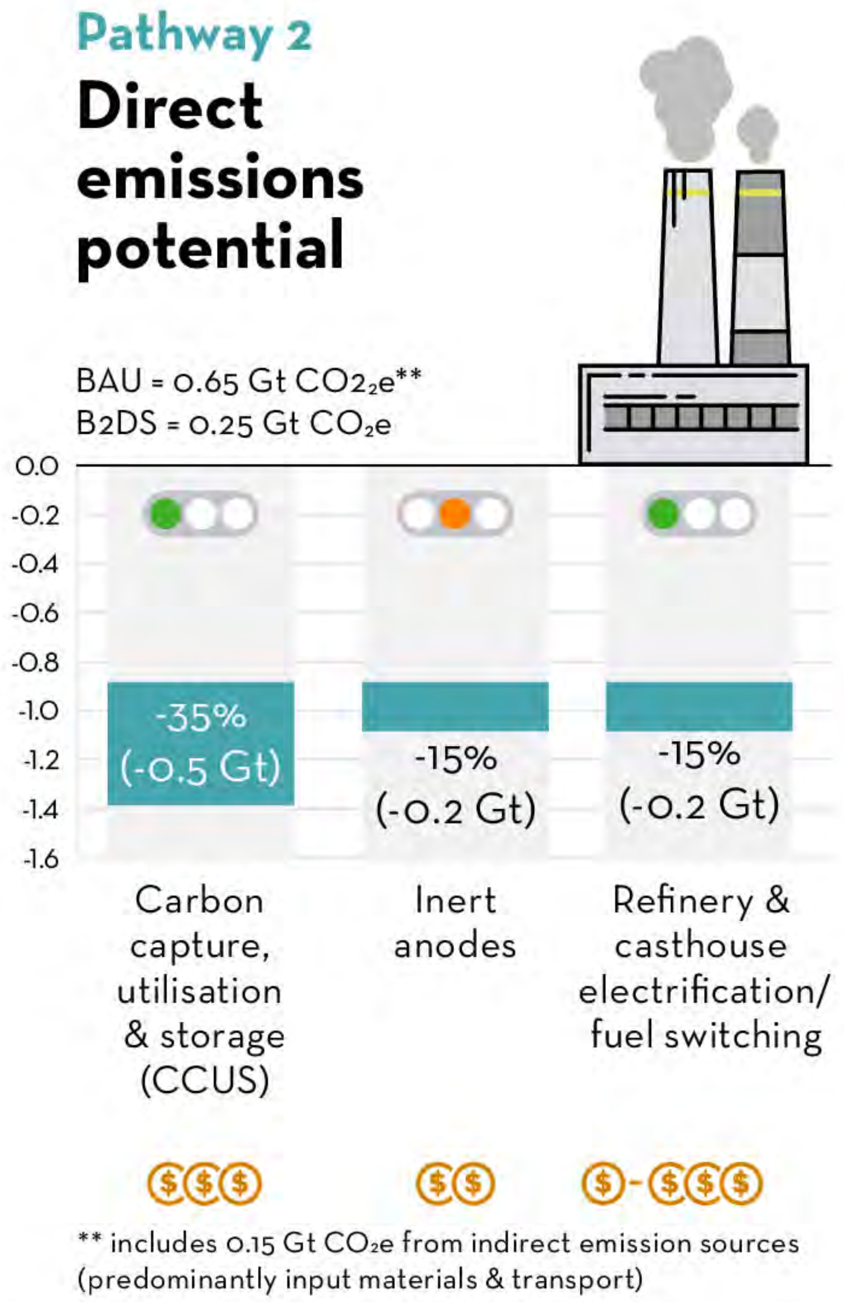


Figure 11 Pathway 2: Direct emissions

Alumina production (from bauxite ore) requires significant amounts of heat and steam (IAI, 2020e). The challenges associated with technologies to decarbonise these energy carriers are not unique to the aluminium industry.

For these thermal processes, electrification with renewables offers a potential pathway to decarbonisation. Fuel switching to green hydrogen, concentrated solar thermal energy and carbon capture utilisation and storage (CCUS) are opportunities where electrification is not feasible, such as alumina calcining, where direct replacement of fossil fuel-fed boilers with electric boilers could have product quality implications and thus higher emissions downstream.

Other fuel combustion processes (mobile equipment in mining, ovens for baking anodes, casthouse furnaces, remelting & recycling) will follow similar pathways (electrification, fuel switching and CCUS), while already electrified processes (extrusion, rolling, etc.) will require renewables deployment at the same rate as smelting (zero emissions by 2050).

Ancillary materials and transport emissions (representing around 8% of sector emissions under BAU) will be reduced at the same rate as direct emissions through pathway changes in other sectors and purchasing choices by aluminium producers.

Recycling & resource efficiency

Infinite recyclability, without loss of properties, is one of aluminium's unique benefits, making it an enabling material for circular economies (IAI, 2018). Current end-of-life (post-consumer) recycling (collection) rates for the metal in its largest market segments (transport, building and construction) are high – above 90%. However, these applications tend to have long lifetimes (taking advantage of aluminium's durability) and so scrap availability is as much constrained by product life as it is by recycling rates.

Thus, three quarters of the more than 1.4 billion tonnes of aluminium ever produced is still in productive use, providing services globally today and available for collection and recycling/reuse in the future (IAI, 2021a).

Aluminium in packaging applications has a much shorter lifetime and a range of collection and recycling rates depending on the application (cans tend to be higher than flexible packaging) and local market, consumer behaviour and political conditions.

The aluminium scrap that is collected at the end of product life also has a diversity of qualities, depending on the constituent alloy classes and how well the scrap has been sorted. Lower quality, mixed scrap, while of use for certain applications today, will have fewer “places to go” in a future that will require higher value, wrought alloys (in applications such as electric vehicle light-weighting).

The onus is on producers and consumers (and waste management actors) to ensure that material is brought back into the system at end of life. It is also a responsibility of those who design and transform the metal into products to create applications from which aluminium components can be easily and efficiently separated, collected and sorted to ensure that the metal's value and its alloys are retained.

The recycling of post-consumer scrap today avoids the need for almost 20 million tonnes of primary aluminium and thus around 300 million tonnes of CO_2e. Once collected, metal losses during scrap processing (3%) and melting (6%) are relatively low.

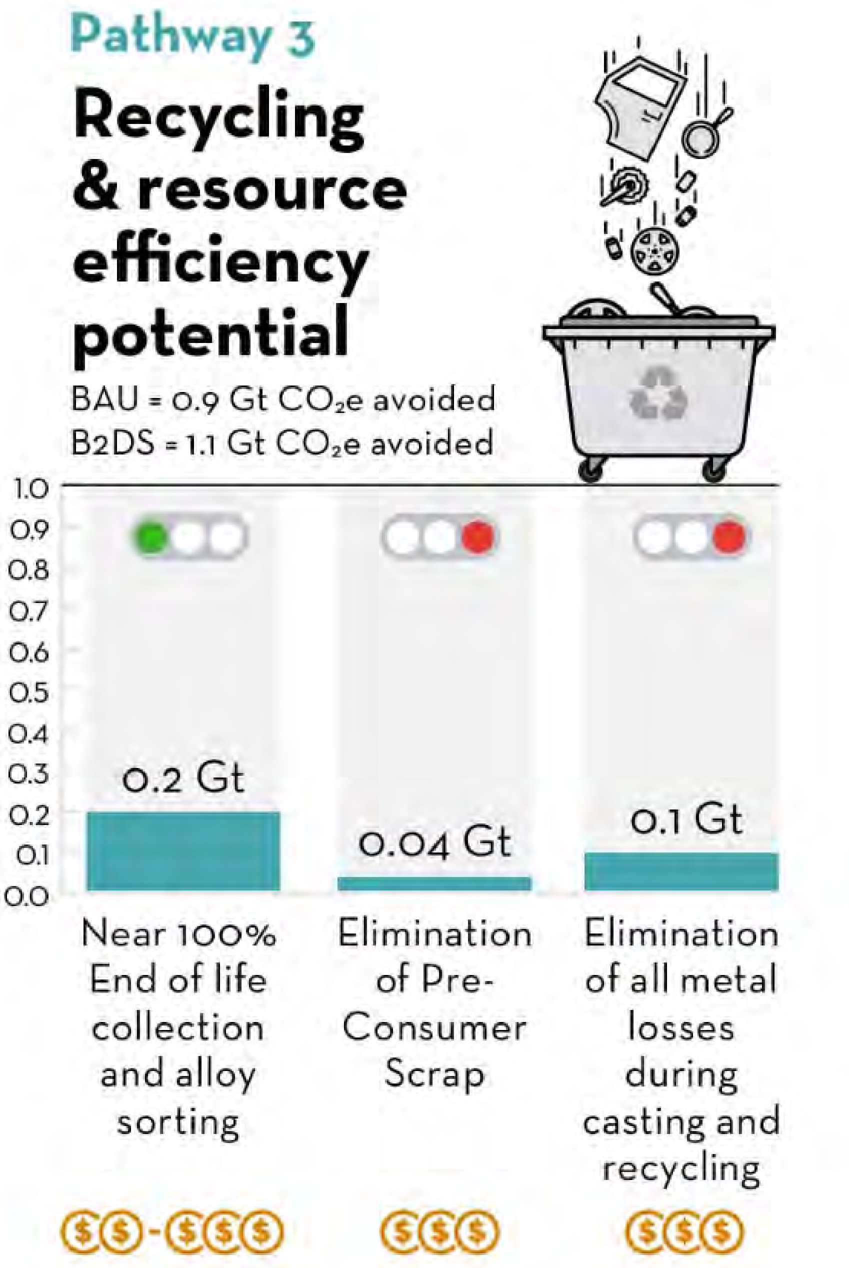


Figure 12 Pathway 3: Recycling & resource efficiency

There are high recycling rates (>90%) in building and construction and automotive segments. In some regions recycling of cans is almost 100%, though lower rate regions consume significant volumes of metal. In 2018, 1.2 million tonnes of aluminium in the form of used beverage cans and other rigid packaging was not collected at end of life.

Across all segments, around 7 million tonnes of aluminium is not recycled every year due to collection and processing losses at the end of its life (2018), and this will rise to 17 million tonnes per annum by 2050 with no change to current recycling rates (IAI, 2021a).

When this metal is not retained in the economy, it must be replaced by primary aluminium. Primary production today has a greenhouse gas emissions profile on average twenty times higher than recovery of metal from scrap.

Recovery of 95% of this material through improved collection, sorting and recycling processes would reduce the need for primary aluminium by 15% and deliver 250 million tonnes of absolute CO_2e emissions reduction per year, second in magnitude only to the decarbonisation of smelter electricity.

New and internal scrap (the scrap that is generated in the various production and fabrication processes prior to final product manufacture) has a very high collection rate and low post-collection losses. This is due to the fact that it tends to be a clean, well-sorted material stream, already under the management and control of producers, who understand its value and for whom material losses impact profitability. Thus, while the volumes of new scrap generated today (13 million tonnes in 2018) and in 2050 (24 Mt) are high, losses are extremely low.

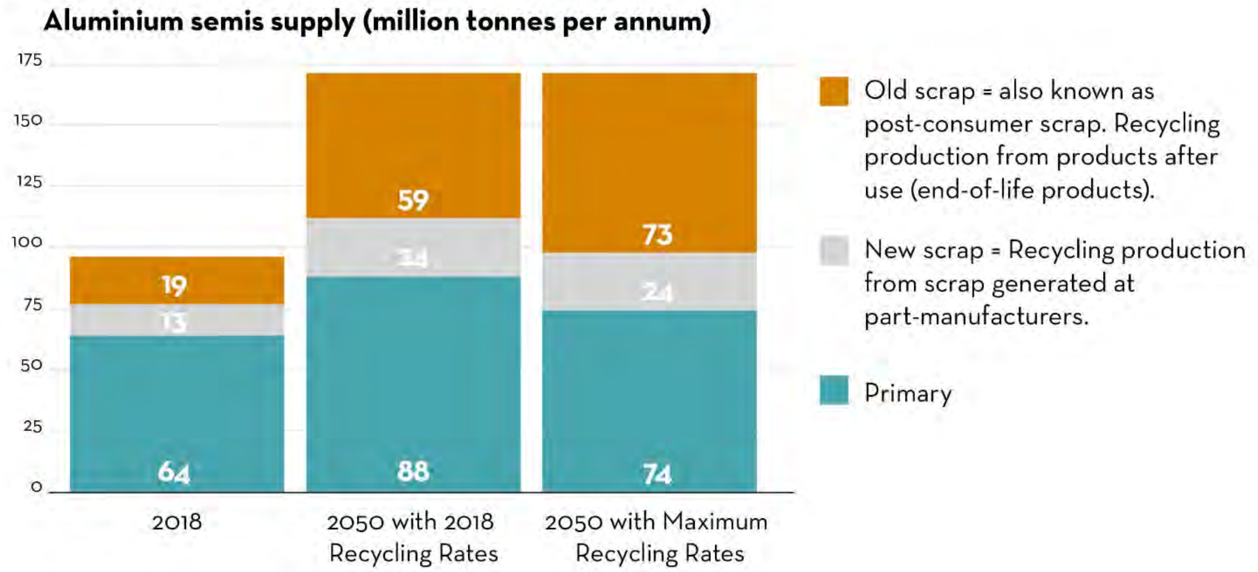
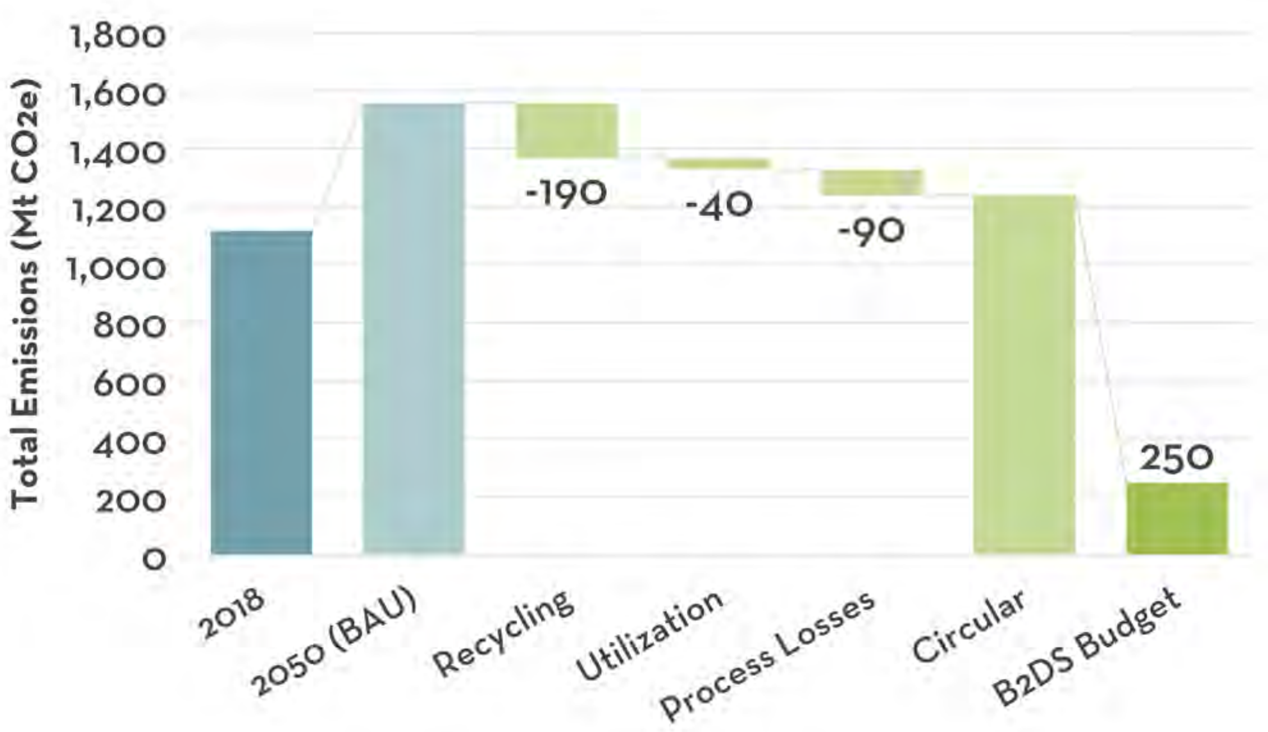


Figure 13 Aluminium supplied from primary and recycled sources in 2018 and 2050, under alternative recycling rate scenarios, Mt Al

New and internal scrap is remelted (through a thermal process), which generates CO_2, albeit at a very low level compared to primary production (IAI, 2020a). The reduction in new scrap generation, through some yet unknown processes (e.g. 3D printing), while seemingly attractive to reduce the number of internal scrap loops, has a limited impact (1.5% or 38 Mt CO_2e) on emissions reduction.

A fully circular system without any (collection, process and melt) losses and no generation of new and internal scrap would deliver a 20% reduction on BAU sector emissions.



2050 (BAU)	with 2018 recycling rates
Recycling	with maximised recycling rates
Utilization	zero new scrap generation
Process Losses	zero pre-melting and melting losses
Circular	maximum recycling & resource efficiency potential

Figure 14 Cumulative impacts of recycling & resource efficiency potential, Mt CO_2e

This transformation of the supply of aluminium requires action from all actors along the value chain - including consumers - and policy frameworks that incentivise circularity, including investments in scrap recycling capacity and design for disassembly/recycling, including novel metal/material joining technologies.

6. What is needed to deliver a Paris-aligned aluminium industry?

As an integrated and global industry, supplying energy-saving and emissions-reducing lightweight, recyclable products to some of the highest GHG emitting sectors, a full value chain approach to emissions reduction is critical for the aluminium sector. This lifecycle approach requires that, in addition to reducing the global industry's footprint, the in-use benefits of aluminium products and savings from recycling are maximised.

As an industry, moving from a 1.1 Gt CO_2e base to 250 Mt CO_2e by 2050, while growing production by up to 80%, will require action from all actors along the value chain, including technology providers, governments and investors.

Commitments from producers to mid-century targets that are B2DS or SDS aligned will need to be bolstered and enabled by policies that secure long-term aluminium sector access to competitively priced renewable electricity and drive increased investment in research, development and the deployment of electrified processes, green hydrogen, inert anode and CCUS (in concert with co-located industries). In addition, circular economy policies that promote both improved scrap collection (particularly in packaging) and scrap alloy sorting (particularly in automotive) will be critical to ensuring that the value of aluminium (and the significant energy required in its initial production) is not lost at the end of products' life.

Here, customers have a role to play too in designing aluminium containing products in a way that maximises metal recovery and recycling, as well as sorting production scrap by alloy class at the point of generation.

Finally, and crucially, with the cost of decarbonisation of the aluminium sector in the order of trillions of dollars, the key enabler of a 2050 low carbon aluminium sector is investment:

- to deliver up to 25 million tonnes of new smelting capacity and the decarbonisation of an existing 65 Mt capacity.
- for the 180 million tonnes of alumina capacity required to meet smelter demand.
- in the new carbon-free or CCUS technologies that currently make up less than 1% of aluminium production, but by 2050 will need to fulfil over 50%.
- in the electrification of operations all along the value chain and the renewables grids that power them.
- in an industry that is critical to the global achievement of net zero emissions across all sectors by the end of this century.

7. References

China Hongqiao & China Aluminum Corporation. (2021, January 15). Accelerating Aluminum Industrial Green and Low-Carbon Development Joint Proposal. Retrieved March 10, 2021, from http://en.hongqiaochina.com/details/750.html

IAI. (2018). *The Aluminium Story*. Retrieved March 10, 2021, from www.thealuminiumstory.com

IAI. (2020a, July 21). *GHG Emission Data for the Aluminium Sector (2005-2019).* Retrieved March 9, 2021, from World Aluminium: https://www.world-aluminium.org/media/filer_public/2020/10/01/ghg_emissions_aluminium_sector_21_july_2020_read_only_25_september_2020.xlsx

IAI. (2020b, October). *Aluminium Recycling Factsheet.* Retrieved March 10, 2021, from World Aluminium: https://www.world-aluminium.org/media/filer_public/2020/10/20/wa_factsheet_final.pdf

IAI. (2020c, August 5). *Primary Aluminium Smelting Energy Intensity*. Retrieved March 10, 2021, from World Aluminium: https://www.world-aluminium.org/statistics/primary-aluminium-smelting-energy-intensity/

IAI. (2020d, July 8). *Primary Aluminium Smelting Power Consumption*. Retrieved March 10, 2021, from World Aluminium: https://www.world-aluminium.org/statistics/primary-aluminium-smelting-power-consumption/

IAI. (2020e, June 22). *Metallurgical Alumina Refining Energy Intensity*. Retrieved March 10, 2021, from World Aluminium: https://www.world-aluminium.org/statistics/metallurgical-alumina-refining-energy-intensity/

IAI. (2021a). *Global Aluminium Cycle 2018*. Retrieved March 9, 2021, from The Global Aluminium Cycle: https://alucycle.world-aluminium.org/

IAI. (2021b, February 22). *Primary Aluminium Production*. Retrieved March 10, 2021, from World Aluminium: https://www.world-aluminium.org/statistics/primary-aluminium-production/

IEA. (2017). *Energy Technology Perspectives 2017.* Paris: IEA. Retrieved March 10, 2021, from https://www.iea.org/reports/energy-technology-perspectives-2017

IEA. (2019). *Transforming Industry through CCUS.* Paris. Retrieved March 10, 2021, from https://www.iea.org/reports/transforming-industry-through-ccus

IEA. (2020). *Energy Technology Perspectives 2020.* Paris: IEA. Retrieved March 10, 2021, from https://www.iea.org/reports/energy-technology-perspectives-2020

UAE Government. (2017). Energy Strategy 2050. United Arab Emirates. Retrieved March 10, 2021, from https://u.ae/en/about-the-uae/strategies-initiatives-and-awards/federal-governments-strategies-and-plans/uae-energy-strategy-2050

International Aluminium Institute
2 Duke Street, St James's
London
SW1Y 6BN
United Kingdom

+44 (0) 20 7930 0528

www.world-aluminium.org

Summary for Policymakers

SPM

Summary for Policymakers

Drafting Authors:
Myles Allen (UK), Mustafa Babiker (Sudan), Yang Chen (China), Heleen de Coninck (Netherlands/EU), Sarah Connors (UK), Renée van Diemen (Netherlands), Opha Pauline Dube (Botswana), Kristie L. Ebi (USA), Francois Engelbrecht (South Africa), Marion Ferrat (UK/France), James Ford (UK/Canada), Piers Forster (UK), Sabine Fuss (Germany), Tania Guillén Bolaños (Germany/Nicaragua), Jordan Harold (UK), Ove Hoegh-Guldberg (Australia), Jean-Charles Hourcade (France), Daniel Huppmann (Austria), Daniela Jacob (Germany), Kejun Jiang (China), Tom Gabriel Johansen (Norway), Mikiko Kainuma (Japan), Kiane de Kleijne (Netherlands/EU), Elmar Kriegler (Germany), Debora Ley (Guatemala/Mexico), Diana Liverman (USA), Natalie Mahowald (USA), Valérie Masson-Delmotte (France), J. B. Robin Matthews (UK), Richard Millar (UK), Katja Mintenbeck (Germany), Angela Morelli (Norway/Italy), Wilfran Moufouma-Okia (France/Congo), Luis Mundaca (Sweden/Chile), Maike Nicolai (Germany), Chukwumerije Okereke (UK/Nigeria), Minal Pathak (India), Antony Payne (UK), Roz Pidcock (UK), Anna Pirani (Italy), Elvira Poloczanska (UK/Australia), Hans-Otto Pörtner (Germany), Aromar Revi (India), Keywan Riahi (Austria), Debra C. Roberts (South Africa), Joeri Rogelj (Austria/Belgium), Joyashree Roy (India), Sonia I. Seneviratne (Switzerland), Priyadarshi R. Shukla (India), James Skea (UK), Raphael Slade (UK), Drew Shindell (USA), Chandni Singh (India), William Solecki (USA), Linda Steg (Netherlands), Michael Taylor (Jamaica), Petra Tschakert (Australia/Austria), Henri Waisman (France), Rachel Warren (UK), Panmao Zhai (China), Kirsten Zickfeld (Canada).

This Summary for Policymakers should be cited as:
IPCC, 2018: Summary for Policymakers. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. In Press.

Introduction

This Report responds to the invitation for IPCC '... to provide a Special Report in 2018 on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways' contained in the Decision of the 21st Conference of Parties of the United Nations Framework Convention on Climate Change to adopt the Paris Agreement.[1]

The IPCC accepted the invitation in April 2016, deciding to prepare this Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.

This Summary for Policymakers (SPM) presents the key findings of the Special Report, based on the assessment of the available scientific, technical and socio-economic literature[2] relevant to global warming of 1.5°C and for the comparison between global warming of 1.5°C and 2°C above pre-industrial levels. The level of confidence associated with each key finding is reported using the IPCC calibrated language.[3] The underlying scientific basis of each key finding is indicated by references provided to chapter elements. In the SPM, knowledge gaps are identified associated with the underlying chapters of the Report.

A. Understanding Global Warming of 1.5°C[4]

A.1 Human activities are estimated to have caused approximately 1.0°C of global warming[5] above pre-industrial levels, with a *likely* range of 0.8°C to 1.2°C. Global warming is *likely* to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate. (*high confidence*) (Figure SPM.1) {1.2}

A.1.1 Reflecting the long-term warming trend since pre-industrial times, observed global mean surface temperature (GMST) for the decade 2006–2015 was 0.87°C (*likely* between 0.75°C and 0.99°C)[6] higher than the average over the 1850–1900 period (*very high confidence*). Estimated anthropogenic global warming matches the level of observed warming to within ±20% (*likely range*). Estimated anthropogenic global warming is currently increasing at 0.2°C (*likely* between 0.1°C and 0.3°C) per decade due to past and ongoing emissions (*high confidence*). {1.2.1, Table 1.1, 1.2.4}

A.1.2 Warming greater than the global annual average is being experienced in many land regions and seasons, including two to three times higher in the Arctic. Warming is generally higher over land than over the ocean. (*high confidence*) {1.2.1, 1.2.2, Figure 1.1, Figure 1.3, 3.3.1, 3.3.2}

A.1.3 Trends in intensity and frequency of some climate and weather extremes have been detected over time spans during which about 0.5°C of global warming occurred (*medium confidence*). This assessment is based on several lines of evidence, including attribution studies for changes in extremes since 1950. {3.3.1, 3.3.2, 3.3.3}

1 Decision 1/CP.21, paragraph 21.

2 The assessment covers literature accepted for publication by 15 May 2018.

3 Each finding is grounded in an evaluation of underlying evidence and agreement. A level of confidence is expressed using five qualifiers: very low, low, medium, high and very high, and typeset in italics, for example, *medium confidence*. The following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100% probability, very likely 90–100%, likely 66–100%, about as likely as not 33–66%, unlikely 0–33%, very unlikely 0–10%, exceptionally unlikely 0–1%. Additional terms (extremely likely 95–100%, more likely than not >50–100%, more unlikely than likely 0–<50%, extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, for example, *very likely*. This is consistent with AR5.

4 See also Box SPM.1: Core Concepts Central to this Special Report.

5 Present level of global warming is defined as the average of a 30-year period centred on 2017 assuming the recent rate of warming continues.

6 This range spans the four available peer-reviewed estimates of the observed GMST change and also accounts for additional uncertainty due to possible short-term natural variability. {1.2.1, Table 1.1}

A.2 Warming from anthropogenic emissions from the pre-industrial period to the present will persist for centuries to millennia and will continue to cause further long-term changes in the climate system, such as sea level rise, with associated impacts (*high confidence*), but these emissions alone are *unlikely* to cause global warming of 1.5°C (*medium confidence*). (Figure SPM.1) {1.2, 3.3, Figure 1.5}

A.2.1 Anthropogenic emissions (including greenhouse gases, aerosols and their precursors) up to the present are *unlikely* to cause further warming of more than 0.5°C over the next two to three decades (*high confidence*) or on a century time scale (*medium confidence*). {1.2.4, Figure 1.5}

A.2.2 Reaching and sustaining net zero global anthropogenic CO_2 emissions and declining net non-CO_2 radiative forcing would halt anthropogenic global warming on multi-decadal time scales (*high confidence*). The maximum temperature reached is then determined by cumulative net global anthropogenic CO_2 emissions up to the time of net zero CO_2 emissions (*high confidence*) and the level of non-CO_2 radiative forcing in the decades prior to the time that maximum temperatures are reached (*medium confidence*). On longer time scales, sustained net negative global anthropogenic CO_2 emissions and/or further reductions in non-CO_2 radiative forcing may still be required to prevent further warming due to Earth system feedbacks and to reverse ocean acidification (*medium confidence*) and will be required to minimize sea level rise (*high confidence*). {Cross-Chapter Box 2 in Chapter 1, 1.2.3, 1.2.4, Figure 1.4, 2.2.1, 2.2.2, 3.4.4.8, 3.4.5.1, 3.6.3.2}

A.3 Climate-related risks for natural and human systems are higher for global warming of 1.5°C than at present, but lower than at 2°C (*high confidence*). These risks depend on the magnitude and rate of warming, geographic location, levels of development and vulnerability, and on the choices and implementation of adaptation and mitigation options (*high confidence*). (Figure SPM.2) {1.3, 3.3, 3.4, 5.6}

A.3.1 Impacts on natural and human systems from global warming have already been observed (*high confidence*). Many land and ocean ecosystems and some of the services they provide have already changed due to global warming (*high confidence*). (Figure SPM.2) {1.4, 3.4, 3.5}

A.3.2 Future climate-related risks depend on the rate, peak and duration of warming. In the aggregate, they are larger if global warming exceeds 1.5°C before returning to that level by 2100 than if global warming gradually stabilizes at 1.5°C, especially if the peak temperature is high (e.g., about 2°C) (*high confidence*). Some impacts may be long-lasting or irreversible, such as the loss of some ecosystems (*high confidence*). {3.2, 3.4.4, 3.6.3, Cross-Chapter Box 8 in Chapter 3}

A.3.3 Adaptation and mitigation are already occurring (*high confidence*). Future climate-related risks would be reduced by the upscaling and acceleration of far-reaching, multilevel and cross-sectoral climate mitigation and by both incremental and transformational adaptation (*high confidence*). {1.2, 1.3, Table 3.5, 4.2.2, Cross-Chapter Box 9 in Chapter 4, Box 4.2, Box 4.3, Box 4.6, 4.3.1, 4.3.2, 4.3.3, 4.3.4, 4.3.5, 4.4.1, 4.4.4, 4.4.5, 4.5.3}

SPM

Cumulative emissions of CO_2 and future non-CO_2 radiative forcing determine the probability of limiting warming to 1.5°C

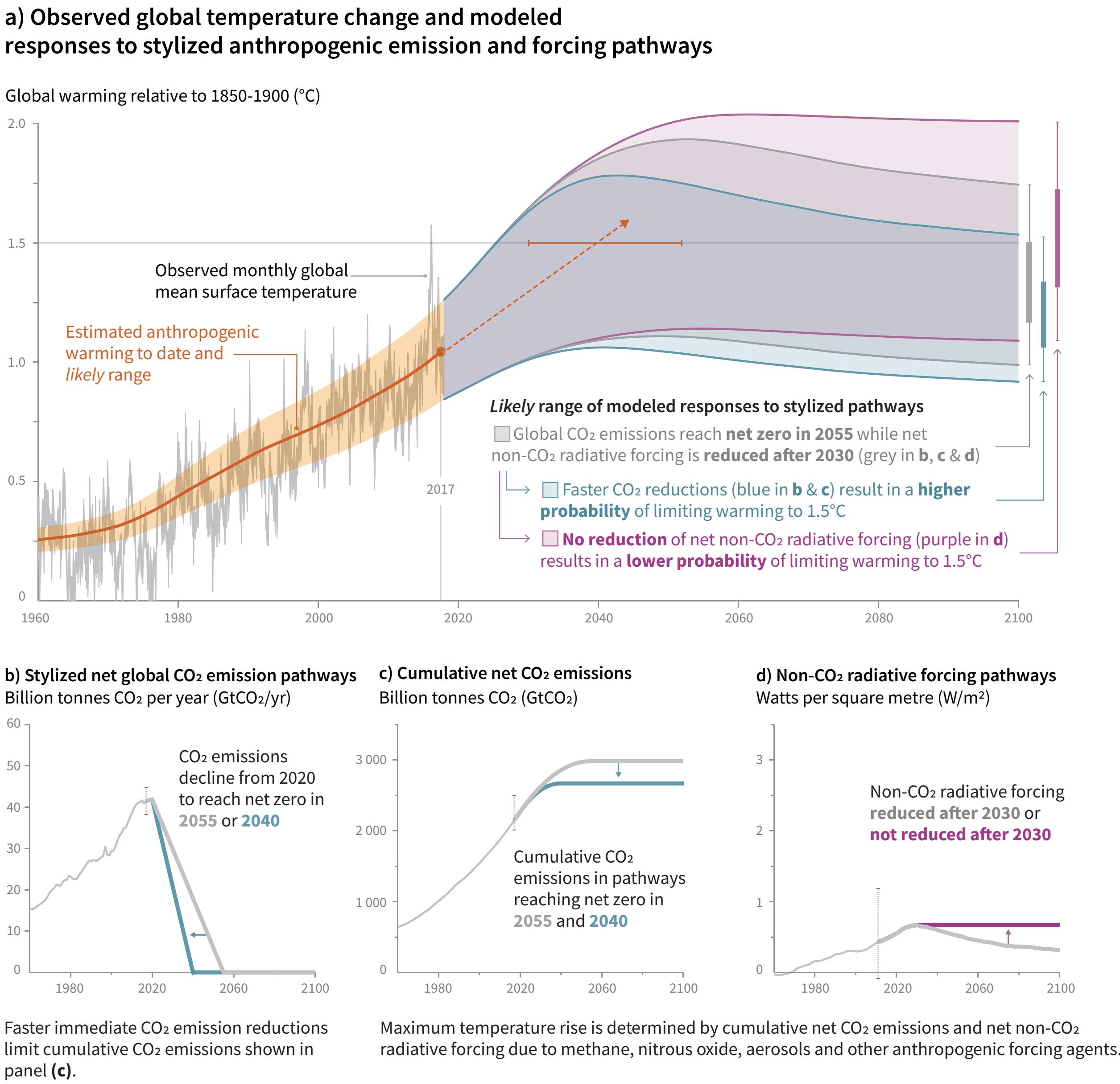


Figure SPM.1 | Panel a: Observed monthly global mean surface temperature (GMST, grey line up to 2017, from the HadCRUT4, GISTEMP, Cowtan–Way, and NOAA datasets) change and estimated anthropogenic global warming (solid orange line up to 2017, with orange shading indicating assessed *likely* range). Orange dashed arrow and horizontal orange error bar show respectively the central estimate and *likely* range of the time at which 1.5°C is reached if the current rate of warming continues. The grey plume on the right of panel a shows the *likely* range of warming responses, computed with a simple climate model, to a stylized pathway (hypothetical future) in which net CO_2 emissions (grey line in panels b and c) decline in a straight line from 2020 to reach net zero in 2055 and net non-CO_2 radiative forcing (grey line in panel d) increases to 2030 and then declines. The blue plume in panel a) shows the response to faster CO_2 emissions reductions (blue line in panel b), reaching net zero in 2040, reducing cumulative CO_2 emissions (panel c). The purple plume shows the response to net CO_2 emissions declining to zero in 2055, with net non-CO_2 forcing remaining constant after 2030. The vertical error bars on right of panel a) show the *likely* ranges (thin lines) and central terciles (33rd – 66th percentiles, thick lines) of the estimated distribution of warming in 2100 under these three stylized pathways. Vertical dotted error bars in panels b, c and d show the *likely* range of historical annual and cumulative global net CO_2 emissions in 2017 (data from the Global Carbon Project) and of net non-CO_2 radiative forcing in 2011 from AR5, respectively. Vertical axes in panels c and d are scaled to represent approximately equal effects on GMST. {1.2.1, 1.2.3, 1.2.4, 2.3, Figure 1.2 and Chapter 1 Supplementary Material, Cross-Chapter Box 2 in Chapter 1}

B. Projected Climate Change, Potential Impacts and Associated Risks

B.1 Climate models project robust[7] differences in regional climate characteristics between present-day and global warming of 1.5°C,[8] and between 1.5°C and 2°C.[8] These differences include increases in: mean temperature in most land and ocean regions (*high confidence*), hot extremes in most inhabited regions (*high confidence*), heavy precipitation in several regions *(medium confidence*), and the probability of drought and precipitation deficits in some regions (*medium confidence*). {3.3}

B.1.1 Evidence from attributed changes in some climate and weather extremes for a global warming of about 0.5°C supports the assessment that an additional 0.5°C of warming compared to present is associated with further detectable changes in these extremes (*medium confidence*). Several regional changes in climate are assessed to occur with global warming up to 1.5°C compared to pre-industrial levels, including warming of extreme temperatures in many regions (*high confidence*), increases in frequency, intensity, and/or amount of heavy precipitation in several regions (*high confidence*), and an increase in intensity or frequency of droughts in some regions (*medium confidence*). {3.2, 3.3.1, 3.3.2, 3.3.3, 3.3.4, Table 3.2}

B.1.2 Temperature extremes on land are projected to warm more than GMST (*high confidence*): extreme hot days in mid-latitudes warm by up to about 3°C at global warming of 1.5°C and about 4°C at 2°C, and extreme cold nights in high latitudes warm by up to about 4.5°C at 1.5°C and about 6°C at 2°C (*high confidence*). The number of hot days is projected to increase in most land regions, with highest increases in the tropics (*high confidence*). {3.3.1, 3.3.2, Cross-Chapter Box 8 in Chapter 3}

B.1.3 Risks from droughts and precipitation deficits are projected to be higher at 2°C compared to 1.5°C of global warming in some regions (*medium confidence*). Risks from heavy precipitation events are projected to be higher at 2°C compared to 1.5°C of global warming in several northern hemisphere high-latitude and/or high-elevation regions, eastern Asia and eastern North America (*medium confidence)*. Heavy precipitation associated with tropical cyclones is projected to be higher at 2°C compared to 1.5°C global warming (*medium confidence*). There is generally *low confidence* in projected changes in heavy precipitation at 2°C compared to 1.5°C in other regions. Heavy precipitation when aggregated at global scale is projected to be higher at 2°C than at 1.5°C of global warming (*medium confidence*). As a consequence of heavy precipitation, the fraction of the global land area affected by flood hazards is projected to be larger at 2°C compared to 1.5°C of global warming (*medium confidence*). {3.3.1, 3.3.3, 3.3.4, 3.3.5, 3.3.6}

B.2 By 2100, global mean sea level rise is projected to be around 0.1 metre lower with global warming of 1.5°C compared to 2°C (*medium confidence*). Sea level will continue to rise well beyond 2100 (*high confidence*), and the magnitude and rate of this rise depend on future emission pathways. A slower rate of sea level rise enables greater opportunities for adaptation in the human and ecological systems of small islands, low-lying coastal areas and deltas (*medium confidence*). {3.3, 3.4, 3.6}

B.2.1 Model-based projections of global mean sea level rise (relative to 1986–2005) suggest an indicative range of 0.26 to 0.77 m by 2100 for 1.5°C of global warming, 0.1 m (0.04–0.16 m) less than for a global warming of 2°C (*medium confidence*). A reduction of 0.1 m in global sea level rise implies that up to 10 million fewer people would be exposed to related risks, based on population in the year 2010 and assuming no adaptation (*medium confidence*). {3.4.4, 3.4.5, 4.3.2}

B.2.2 Sea level rise will continue beyond 2100 even if global warming is limited to 1.5°C in the 21st century (*high confidence*). Marine ice sheet instability in Antarctica and/or irreversible loss of the Greenland ice sheet could result in multi-metre rise in sea level over hundreds to thousands of years. These instabilities could be triggered at around 1.5°C to 2°C of global warming (*medium confidence*). (Figure SPM.2) {3.3.9, 3.4.5, 3.5.2, 3.6.3, Box 3.3}

7 Robust is here used to mean that at least two thirds of climate models show the same sign of changes at the grid point scale, and that differences in large regions are statistically significant.

8 Projected changes in impacts between different levels of global warming are determined with respect to changes in global mean surface air temperature.

B.2.3 Increasing warming amplifies the exposure of small islands, low-lying coastal areas and deltas to the risks associated with sea level rise for many human and ecological systems, including increased saltwater intrusion, flooding and damage to infrastructure (*high confidence*). Risks associated with sea level rise are higher at 2°C compared to 1.5°C. The slower rate of sea level rise at global warming of 1.5°C reduces these risks, enabling greater opportunities for adaptation including managing and restoring natural coastal ecosystems and infrastructure reinforcement (*medium confidence*). (Figure SPM.2) {3.4.5, Box 3.5}

B.3 On land, impacts on biodiversity and ecosystems, including species loss and extinction, are projected to be lower at 1.5°C of global warming compared to 2°C. Limiting global warming to 1.5°C compared to 2°C is projected to lower the impacts on terrestrial, freshwater and coastal ecosystems and to retain more of their services to humans (*high confidence*). (Figure SPM.2) {3.4, 3.5, Box 3.4, Box 4.2, Cross-Chapter Box 8 in Chapter 3}

B.3.1 Of 105,000 species studied,[9] 6% of insects, 8% of plants and 4% of vertebrates are projected to lose over half of their climatically determined geographic range for global warming of 1.5°C, compared with 18% of insects, 16% of plants and 8% of vertebrates for global warming of 2°C (*medium confidence*). Impacts associated with other biodiversity-related risks such as forest fires and the spread of invasive species are lower at 1.5°C compared to 2°C of global warming (*high confidence*). {3.4.3, 3.5.2}

B.3.2 Approximately 4% (interquartile range 2–7%) of the global terrestrial land area is projected to undergo a transformation of ecosystems from one type to another at 1°C of global warming, compared with 13% (interquartile range 8–20%) at 2°C (*medium confidence*). This indicates that the area at risk is projected to be approximately 50% lower at 1.5°C compared to 2°C (*medium confidence*). {3.4.3.1, 3.4.3.5}

B.3.3 High-latitude tundra and boreal forests are particularly at risk of climate change-induced degradation and loss, with woody shrubs already encroaching into the tundra (*high confidence*) and this will proceed with further warming. Limiting global warming to 1.5°C rather than 2°C is projected to prevent the thawing over centuries of a permafrost area in the range of 1.5 to 2.5 million km^2 (*medium confidence*). {3.3.2, 3.4.3, 3.5.5}

B.4 Limiting global warming to 1.5°C compared to 2°C is projected to reduce increases in ocean temperature as well as associated increases in ocean acidity and decreases in ocean oxygen levels (*high confidence*). Consequently, limiting global warming to 1.5°C is projected to reduce risks to marine biodiversity, fisheries, and ecosystems, and their functions and services to humans, as illustrated by recent changes to Arctic sea ice and warm-water coral reef ecosystems (*high confidence*). {3.3, 3.4, 3.5, Box 3.4, Box 3.5}

B.4.1 There is *high confidence* that the probability of a sea ice-free Arctic Ocean during summer is substantially lower at global warming of 1.5°C when compared to 2°C. With 1.5°C of global warming, one sea ice-free Arctic summer is projected per century. This likelihood is increased to at least one per decade with 2°C global warming. Effects of a temperature overshoot are reversible for Arctic sea ice cover on decadal time scales (*high confidence*). {3.3.8, 3.4.4.7}

B.4.2 Global warming of 1.5°C is projected to shift the ranges of many marine species to higher latitudes as well as increase the amount of damage to many ecosystems. It is also expected to drive the loss of coastal resources and reduce the productivity of fisheries and aquaculture (especially at low latitudes). The risks of climate-induced impacts are projected to be higher at 2°C than those at global warming of 1.5°C (*high confidence*). Coral reefs, for example, are projected to decline by a further 70–90% at 1.5°C (*high confidence*) with larger losses (>99%) at 2°C (*very high confidence*). The risk of irreversible loss of many marine and coastal ecosystems increases with global warming, especially at 2°C or more (*high confidence*). {3.4.4, Box 3.4}

9 Consistent with earlier studies, illustrative numbers were adopted from one recent meta-study.

B.4.3 The level of ocean acidification due to increasing CO_2 concentrations associated with global warming of 1.5°C is projected to amplify the adverse effects of warming, and even further at 2°C, impacting the growth, development, calcification, survival, and thus abundance of a broad range of species, for example, from algae to fish (*high confidence*). {3.3.10, 3.4.4}

B.4.4 Impacts of climate change in the ocean are increasing risks to fisheries and aquaculture via impacts on the physiology, survivorship, habitat, reproduction, disease incidence, and risk of invasive species (*medium confidence*) but are projected to be less at 1.5°C of global warming than at 2°C. One global fishery model, for example, projected a decrease in global annual catch for marine fisheries of about 1.5 million tonnes for 1.5°C of global warming compared to a loss of more than 3 million tonnes for 2°C of global warming (*medium confidence*). {3.4.4, Box 3.4}

B.5 Climate-related risks to health, livelihoods, food security, water supply, human security, and economic growth are projected to increase with global warming of 1.5°C and increase further with 2°C. (Figure SPM.2) {3.4, 3.5, 5.2, Box 3.2, Box 3.3, Box 3.5, Box 3.6, Cross-Chapter Box 6 in Chapter 3, Cross-Chapter Box 9 in Chapter 4, Cross-Chapter Box 12 in Chapter 5, 5.2}

B.5.1 Populations at disproportionately higher risk of adverse consequences with global warming of 1.5°C and beyond include disadvantaged and vulnerable populations, some indigenous peoples, and local communities dependent on agricultural or coastal livelihoods (*high confidence*). Regions at disproportionately higher risk include Arctic ecosystems, dryland regions, small island developing states, and Least Developed Countries (*high confidence*). Poverty and disadvantage are expected to increase in some populations as global warming increases; limiting global warming to 1.5°C, compared with 2°C, could reduce the number of people both exposed to climate-related risks and susceptible to poverty by up to several hundred million by 2050 (*medium confidence*). {3.4.10, 3.4.11, Box 3.5, Cross-Chapter Box 6 in Chapter 3, Cross-Chapter Box 9 in Chapter 4, Cross-Chapter Box 12 in Chapter 5, 4.2.2.2, 5.2.1, 5.2.2, 5.2.3, 5.6.3}

B.5.2 Any increase in global warming is projected to affect human health, with primarily negative consequences (*high confidence*). Lower risks are projected at 1.5°C than at 2°C for heat-related morbidity and mortality (*very high confidence*) and for ozone-related mortality if emissions needed for ozone formation remain high (*high confidence*). Urban heat islands often amplify the impacts of heatwaves in cities (*high confidence*). Risks from some vector-borne diseases, such as malaria and dengue fever, are projected to increase with warming from 1.5°C to 2°C, including potential shifts in their geographic range (*high confidence*). {3.4.7, 3.4.8, 3.5.5.8}

B.5.3 Limiting warming to 1.5°C compared with 2°C is projected to result in smaller net reductions in yields of maize, rice, wheat, and potentially other cereal crops, particularly in sub-Saharan Africa, Southeast Asia, and Central and South America, and in the CO_2-dependent nutritional quality of rice and wheat (*high confidence*). Reductions in projected food availability are larger at 2°C than at 1.5°C of global warming in the Sahel, southern Africa, the Mediterranean, central Europe, and the Amazon (*medium confidence*). Livestock are projected to be adversely affected with rising temperatures, depending on the extent of changes in feed quality, spread of diseases, and water resource availability (*high confidence*). {3.4.6, 3.5.4, 3.5.5, Box 3.1, Cross-Chapter Box 6 in Chapter 3, Cross-Chapter Box 9 in Chapter 4}

B.5.4 Depending on future socio-economic conditions, limiting global warming to 1.5°C compared to 2°C may reduce the proportion of the world population exposed to a climate change-induced increase in water stress by up to 50%, although there is considerable variability between regions (*medium confidence*). Many small island developing states could experience lower water stress as a result of projected changes in aridity when global warming is limited to 1.5°C, as compared to 2°C (*medium confidence*). {3.3.5, 3.4.2, 3.4.8, 3.5.5, Box 3.2, Box 3.5, Cross-Chapter Box 9 in Chapter 4}

B.5.5 Risks to global aggregated economic growth due to climate change impacts are projected to be lower at 1.5°C than at 2°C by the end of this century[10] (*medium confidence*). This excludes the costs of mitigation, adaptation investments and the benefits of adaptation. Countries in the tropics and Southern Hemisphere subtropics are projected to experience the largest impacts on economic growth due to climate change should global warming increase from 1.5°C to 2°C (*medium confidence*). {3.5.2, 3.5.3}

---

10 Here, impacts on economic growth refer to changes in gross domestic product (GDP). Many impacts, such as loss of human lives, cultural heritage and ecosystem services, are difficult to value and monetize.

B.5.6 Exposure to multiple and compound climate-related risks increases between 1.5°C and 2°C of global warming, with greater proportions of people both so exposed and susceptible to poverty in Africa and Asia (*high confidence*). For global warming from 1.5°C to 2°C, risks across energy, food, and water sectors could overlap spatially and temporally, creating new and exacerbating current hazards, exposures, and vulnerabilities that could affect increasing numbers of people and regions (*medium confidence*). {Box 3.5, 3.3.1, 3.4.5.3, 3.4.5.6, 3.4.11, 3.5.4.9}

B.5.7 There are multiple lines of evidence that since AR5 the assessed levels of risk increased for four of the five Reasons for Concern (RFCs) for global warming to 2°C (*high confidence*). The risk transitions by degrees of global warming are now: from high to very high risk between 1.5°C and 2°C for RFC1 (Unique and threatened systems) (*high confidence*); from moderate to high risk between 1°C and 1.5°C for RFC2 (Extreme weather events) (*medium confidence*); from moderate to high risk between 1.5°C and 2°C for RFC3 (Distribution of impacts) (*high confidence*); from moderate to high risk between 1.5°C and 2.5°C for RFC4 (Global aggregate impacts) (*medium confidence*); and from moderate to high risk between 1°C and 2.5°C for RFC5 (Large-scale singular events) (*medium confidence*). (Figure SPM.2) {3.4.13; 3.5, 3.5.2}

B.6 Most adaptation needs will be lower for global warming of 1.5°C compared to 2°C (*high confidence*). There are a wide range of adaptation options that can reduce the risks of climate change (*high confidence*). There are limits to adaptation and adaptive capacity for some human and natural systems at global warming of 1.5°C, with associated losses (*medium confidence*). The number and availability of adaptation options vary by sector (*medium confidence*). {Table 3.5, 4.3, 4.5, Cross-Chapter Box 9 in Chapter 4, Cross-Chapter Box 12 in Chapter 5}

B.6.1 A wide range of adaptation options are available to reduce the risks to natural and managed ecosystems (e.g., ecosystem-based adaptation, ecosystem restoration and avoided degradation and deforestation, biodiversity management, sustainable aquaculture, and local knowledge and indigenous knowledge), the risks of sea level rise (e.g., coastal defence and hardening), and the risks to health, livelihoods, food, water, and economic growth, especially in rural landscapes (e.g., efficient irrigation, social safety nets, disaster risk management, risk spreading and sharing, and community-based adaptation) and urban areas (e.g., green infrastructure, sustainable land use and planning, and sustainable water management) (*medium confidence*). {4.3.1, 4.3.2, 4.3.3, 4.3.5, 4.5.3, 4.5.4, 5.3.2, Box 4.2, Box 4.3, Box 4.6, Cross-Chapter Box 9 in Chapter 4}.

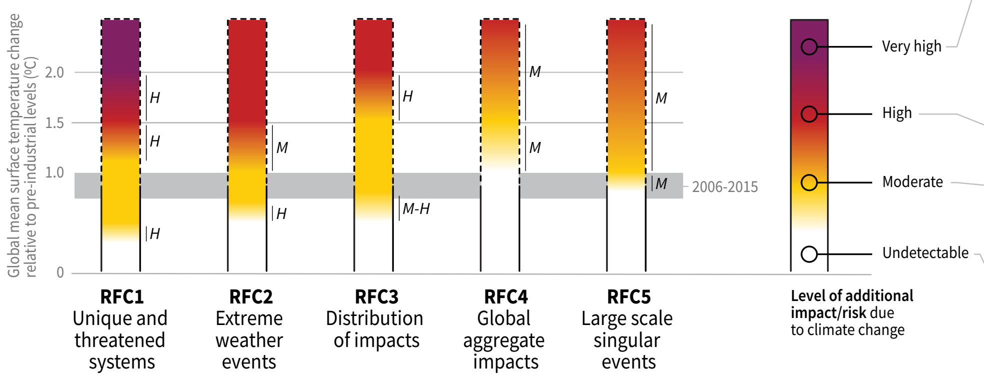
B.6.2 Adaptation is expected to be more challenging for ecosystems, food and health systems at 2°C of global warming than for 1.5°C (*medium confidence*). Some vulnerable regions, including small islands and Least Developed Countries, are projected to experience high multiple interrelated climate risks even at global warming of 1.5°C (*high confidence*). {3.3.1, 3.4.5, Box 3.5, Table 3.5, Cross-Chapter Box 9 in Chapter 4, 5.6, Cross-Chapter Box 12 in Chapter 5, Box 5.3}

B.6.3 Limits to adaptive capacity exist at 1.5°C of global warming, become more pronounced at higher levels of warming and vary by sector, with site-specific implications for vulnerable regions, ecosystems and human health (*medium confidence*). {Cross-Chapter Box 12 in Chapter 5, Box 3.5, Table 3.5}

How the level of global warming affects impacts and/or risks associated with the Reasons for Concern (RFCs) and selected natural, managed and human systems

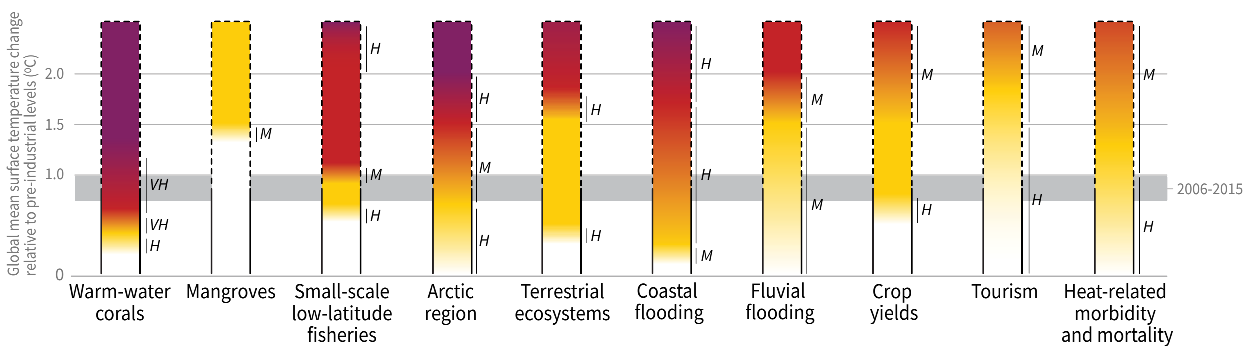
Five Reasons For Concern (RFCs) illustrate the impacts and risks of different levels of global warming for people, economies and ecosystems across sectors and regions.

Impacts and risks associated with the Reasons for Concern (RFCs)



Purple indicates very high risks of severe impacts/risks and the presence of significant irreversibility or the persistence of climate-related hazards, combined with limited ability to adapt due to the nature of the hazard or impacts/risks.
Red indicates severe and widespread impacts/risks.
Yellow indicates that impacts/risks are detectable and attributable to climate change with at least medium confidence.
White indicates that no impacts are detectable and attributable to climate change.

Impacts and risks for selected natural, managed and human systems



Confidence level for transition: *L*=Low, *M*=Medium, *H*=High and *VH*=Very high

Figure SPM.2 | Five integrative reasons for concern (RFCs) provide a framework for summarizing key impacts and risks across sectors and regions, and were introduced in the IPCC Third Assessment Report. RFCs illustrate the implications of global warming for people, economies and ecosystems. Impacts and/or risks for each RFC are based on assessment of the new literature that has appeared. As in AR5, this literature was used to make expert judgments to assess the levels of global warming at which levels of impact and/or risk are undetectable, moderate, high or very high. The selection of impacts and risks to natural, managed and human systems in the lower panel is illustrative and is not intended to be fully comprehensive. {3.4, 3.5, 3.5.2.1, 3.5.2.2, 3.5.2.3, 3.5.2.4, 3.5.2.5, 5.4.1, 5.5.3, 5.6.1, Box 3.4}

RFC1 Unique and threatened systems: ecological and human systems that have restricted geographic ranges constrained by climate-related conditions and have high endemism or other distinctive properties. Examples include coral reefs, the Arctic and its indigenous people, mountain glaciers and biodiversity hotspots.

RFC2 Extreme weather events: risks/impacts to human health, livelihoods, assets and ecosystems from extreme weather events such as heat waves, heavy rain, drought and associated wildfires, and coastal flooding.

RFC3 Distribution of impacts: risks/impacts that disproportionately affect particular groups due to uneven distribution of physical climate change hazards, exposure or vulnerability.

RFC4 Global aggregate impacts: global monetary damage, global-scale degradation and loss of ecosystems and biodiversity.

RFC5 Large-scale singular events: are relatively large, abrupt and sometimes irreversible changes in systems that are caused by global warming. Examples include disintegration of the Greenland and Antarctic ice sheets.

SPM

C. Emission Pathways and System Transitions Consistent with 1.5°C Global Warming

C.1 In model pathways with no or limited overshoot of 1.5°C, global net anthropogenic CO_2 emissions decline by about 45% from 2010 levels by 2030 (40–60% interquartile range), reaching net zero around 2050 (2045–2055 interquartile range). For limiting global warming to below 2°C[11] CO_2 emissions are projected to decline by about 25% by 2030 in most pathways (10–30% interquartile range) and reach net zero around 2070 (2065–2080 interquartile range). Non-CO_2 emissions in pathways that limit global warming to 1.5°C show deep reductions that are similar to those in pathways limiting warming to 2°C. (*high confidence*) (Figure SPM.3a) {2.1, 2.3, Table 2.4}

C.1.1 CO_2 emissions reductions that limit global warming to 1.5°C with no or limited overshoot can involve different portfolios of mitigation measures, striking different balances between lowering energy and resource intensity, rate of decarbonization, and the reliance on carbon dioxide removal. Different portfolios face different implementation challenges and potential synergies and trade-offs with sustainable development. (*high confidence*) (Figure SPM.3b) {2.3.2, 2.3.4, 2.4, 2.5.3}

C.1.2 Modelled pathways that limit global warming to 1.5°C with no or limited overshoot involve deep reductions in emissions of methane and black carbon (35% or more of both by 2050 relative to 2010). These pathways also reduce most of the cooling aerosols, which partially offsets mitigation effects for two to three decades. Non-CO_2 emissions[12] can be reduced as a result of broad mitigation measures in the energy sector. In addition, targeted non-CO_2 mitigation measures can reduce nitrous oxide and methane from agriculture, methane from the waste sector, some sources of black carbon, and hydrofluorocarbons. High bioenergy demand can increase emissions of nitrous oxide in some 1.5°C pathways, highlighting the importance of appropriate management approaches. Improved air quality resulting from projected reductions in many non-CO_2 emissions provide direct and immediate population health benefits in all 1.5°C model pathways. (*high confidence*) (Figure SPM.3a) {2.2.1, 2.3.3, 2.4.4, 2.5.3, 4.3.6, 5.4.2}

C.1.3 Limiting global warming requires limiting the total cumulative global anthropogenic emissions of CO_2 since the pre-industrial period, that is, staying within a total carbon budget (*high confidence*).[13] By the end of 2017, anthropogenic CO_2 emissions since the pre-industrial period are estimated to have reduced the total carbon budget for 1.5°C by approximately 2200 ± 320 $GtCO_2$ (*medium confidence*). The associated remaining budget is being depleted by current emissions of 42 ± 3 $GtCO_2$ per year (*high confidence*). The choice of the measure of global temperature affects the estimated remaining carbon budget. Using global mean surface air temperature, as in AR5, gives an estimate of the remaining carbon budget of 580 $GtCO_2$ for a 50% probability of limiting warming to 1.5°C, and 420 $GtCO_2$ for a 66% probability (*medium confidence*).[14] Alternatively, using GMST gives estimates of 770 and 570 $GtCO_2$, for 50% and 66% probabilities,[15] respectively (*medium confidence*). Uncertainties in the size of these estimated remaining carbon budgets are substantial and depend on several factors. Uncertainties in the climate response to CO_2 and non-CO_2 emissions contribute ±400 $GtCO_2$ and the level of historic warming contributes ±250 $GtCO_2$ (*medium confidence*). Potential additional carbon release from future permafrost thawing and methane release from wetlands would reduce budgets by up to 100 $GtCO_2$ over the course of this century and more thereafter (*medium confidence*). In addition, the level of non-CO_2 mitigation in the future could alter the remaining carbon budget by 250 $GtCO_2$ in either direction (*medium confidence*). {1.2.4, 2.2.2, 2.6.1, Table 2.2, Chapter 2 Supplementary Material}

C.1.4 Solar radiation modification (SRM) measures are not included in any of the available assessed pathways. Although some SRM measures may be theoretically effective in reducing an overshoot, they face large uncertainties and knowledge gaps

11 References to pathways limiting global warming to 2°C are based on a 66% probability of staying below 2°C.

12 Non-CO_2 emissions included in this Report are all anthropogenic emissions other than CO_2 that result in radiative forcing. These include short-lived climate forcers, such as methane, some fluorinated gases, ozone precursors, aerosols or aerosol precursors, such as black carbon and sulphur dioxide, respectively, as well as long-lived greenhouse gases, such as nitrous oxide or some fluorinated gases. The radiative forcing associated with non-CO_2 emissions and changes in surface albedo is referred to as non-CO_2 radiative forcing. {2.2.1}

13 There is a clear scientific basis for a total carbon budget consistent with limiting global warming to 1.5°C. However, neither this total carbon budget nor the fraction of this budget taken up by past emissions were assessed in this Report.

14 Irrespective of the measure of global temperature used, updated understanding and further advances in methods have led to an increase in the estimated remaining carbon budget of about 300 $GtCO_2$ compared to AR5. (*medium confidence*) {2.2.2}

15 These estimates use observed GMST to 2006–2015 and estimate future temperature changes using near surface air temperatures.

as well as substantial risks and institutional and social constraints to deployment related to governance, ethics, and impacts on sustainable development. They also do not mitigate ocean acidification. (*medium confidence*) {4.3.8, Cross-Chapter Box 10 in Chapter 4}

Global emissions pathway characteristics

General characteristics of the evolution of anthropogenic net emissions of CO_2, and total emissions of methane, black carbon, and nitrous oxide in model pathways that limit global warming to 1.5°C with no or limited overshoot. Net emissions are defined as anthropogenic emissions reduced by anthropogenic removals. Reductions in net emissions can be achieved through different portfolios of mitigation measures illustrated in Figure SPM.3b.

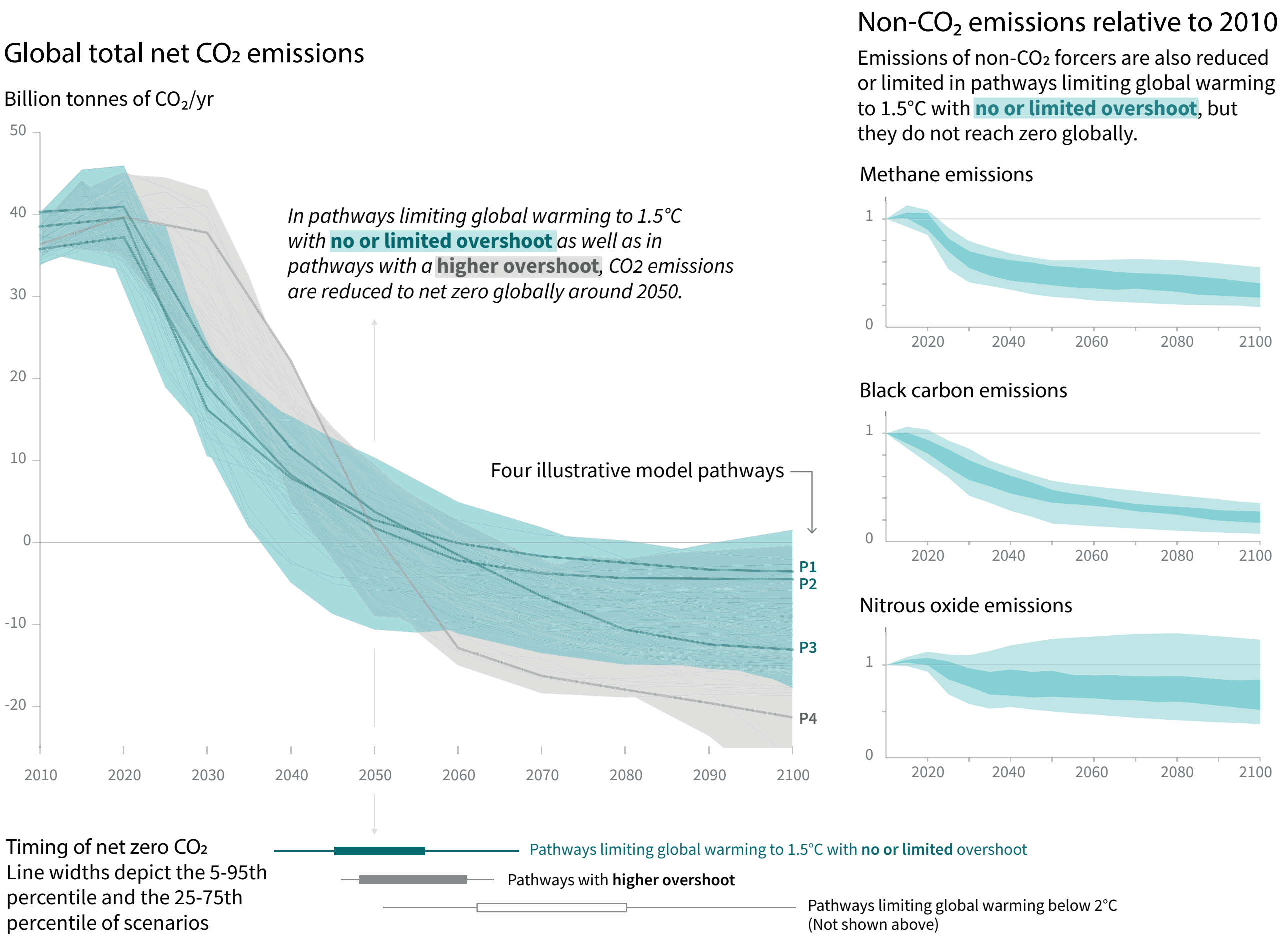


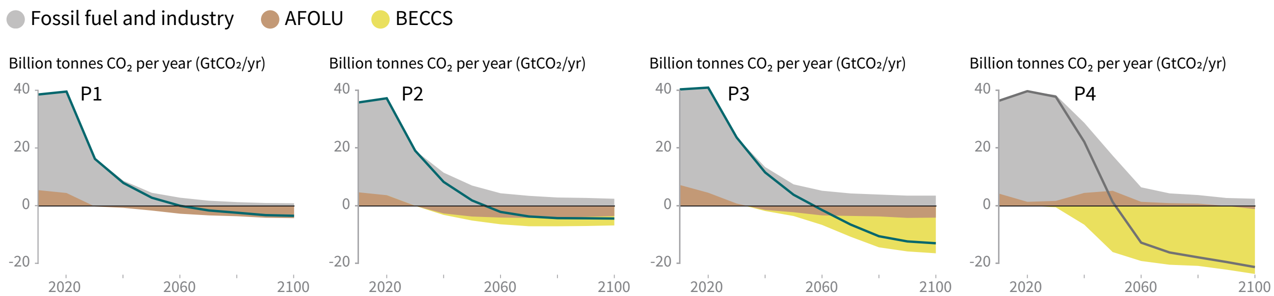
Figure SPM.3a | Global emissions pathway characteristics. The main panel shows global net anthropogenic CO_2 emissions in pathways limiting global warming to 1.5°C with no or limited (less than 0.1°C) overshoot and pathways with higher overshoot. The shaded area shows the full range for pathways analysed in this Report. The panels on the right show non-CO_2 emissions ranges for three compounds with large historical forcing and a substantial portion of emissions coming from sources distinct from those central to CO_2 mitigation. Shaded areas in these panels show the 5–95% (light shading) and interquartile (dark shading) ranges of pathways limiting global warming to 1.5°C with no or limited overshoot. Box and whiskers at the bottom of the figure show the timing of pathways reaching global net zero CO_2 emission levels, and a comparison with pathways limiting global warming to 2°C with at least 66% probability. Four illustrative model pathways are highlighted in the main panel and are labelled P1, P2, P3 and P4, corresponding to the LED, S1, S2, and S5 pathways assessed in Chapter 2. Descriptions and characteristics of these pathways are available in Figure SPM.3b. {2.1, 2.2, 2.3, Figure 2.5, Figure 2.10, Figure 2.11}

SPM

Characteristics of four illustrative model pathways

Different mitigation strategies can achieve the net emissions reductions that would be required to follow a pathway that limits global warming to 1.5°C with no or limited overshoot. All pathways use Carbon Dioxide Removal (CDR), but the amount varies across pathways, as do the relative contributions of Bioenergy with Carbon Capture and Storage (BECCS) and removals in the Agriculture, Forestry and Other Land Use (AFOLU) sector. This has implications for emissions and several other pathway characteristics.

Breakdown of contributions to global net CO_2 emissions in four illustrative model pathways



P1: A scenario in which social, business and technological innovations result in lower energy demand up to 2050 while living standards rise, especially in the global South. A downsized energy system enables rapid decarbonization of energy supply. Afforestation is the only CDR option considered; neither fossil fuels with CCS nor BECCS are used.

P2: A scenario with a broad focus on sustainability including energy intensity, human development, economic convergence and international cooperation, as well as shifts towards sustainable and healthy consumption patterns, low-carbon technology innovation, and well-managed land systems with limited societal acceptability for BECCS.

P3: A middle-of-the-road scenario in which societal as well as technological development follows historical patterns. Emissions reductions are mainly achieved by changing the way in which energy and products are produced, and to a lesser degree by reductions in demand.

P4: A resource- and energy-intensive scenario in which economic growth and globalization lead to widespread adoption of greenhouse-gas-intensive lifestyles, including high demand for transportation fuels and livestock products. Emissions reductions are mainly achieved through technological means, making strong use of CDR through the deployment of BECCS.

Global indicators	P1	P2	P3	P4	**Interquartile range**
Pathway classification	No or limited overshoot	No or limited overshoot	No or limited overshoot	Higher overshoot	No or limited overshoot
CO_2 emission change in 2030 (% rel to 2010)	-58	-47	-41	4	(-58,-40)
└ in 2050 (% rel to 2010)	-93	-95	-91	-97	(-107,-94)
Kyoto-GHG emissions in 2030 (% rel to 2010)*	-50	-49	-35	-2	(-51,-39)
└ in 2050 (% rel to 2010)	-82	-89	-78	-80	(-93,-81)
*Final energy demand** in 2030 (% rel to 2010)*	-15	-5	17	39	(-12,7)
└ in 2050 (% rel to 2010)	-32	2	21	44	(-11,22)
Renewable share in electricity in 2030 (%)	60	58	48	25	(47,65)
└ in 2050 (%)	77	81	63	70	(69,86)
Primary energy from coal in 2030 (% rel to 2010)	-78	-61	-75	-59	(-78, -59)
└ in 2050 (% rel to 2010)	-97	-77	-73	-97	(-95, -74)
from oil in 2030 (% rel to 2010)	-37	-13	-3	86	(-34,3)
└ in 2050 (% rel to 2010)	-87	-50	-81	-32	(-78,-31)
from gas in 2030 (% rel to 2010)	-25	-20	33	37	(-26,21)
└ in 2050 (% rel to 2010)	-74	-53	21	-48	(-56,6)
from nuclear in 2030 (% rel to 2010)	59	83	98	106	(44,102)
└ in 2050 (% rel to 2010)	150	98	501	468	(91,190)
from biomass in 2030 (% rel to 2010)	-11	0	36	-1	(29,80)
└ in 2050 (% rel to 2010)	-16	49	121	418	(123,261)
from non-biomass renewables in 2030 (% rel to 2010)	430	470	315	110	(245,436)
└ in 2050 (% rel to 2010)	833	1327	878	1137	(576,1299)
Cumulative CCS until 2100 ($GtCO_2$)	0	348	687	1218	(550,1017)
└ of which BECCS ($GtCO_2$)	0	151	414	1191	(364,662)
Land area of bioenergy crops in 2050 (million km²)	0.2	0.9	2.8	7.2	(1.5,3.2)
Agricultural CH_4 emissions in 2030 (% rel to 2010)	-24	-48	1	14	(-30,-11)
in 2050 (% rel to 2010)	-33	-69	-23	2	(-47,-24)
Agricultural N_2O emissions in 2030 (% rel to 2010)	5	-26	15	3	(-21,3)
in 2050 (% rel to 2010)	6	-26	0	39	(-26,1)

NOTE: Indicators have been selected to show global trends identified by the Chapter 2 assessment. National and sectoral characteristics can differ substantially from the global trends shown above.

** Kyoto-gas emissions are based on IPCC Second Assessment Report GWP-100*
*** Changes in energy demand are associated with improvements in energy efficiency and behaviour change*

Figure SPM.3b | Characteristics of four illustrative model pathways in relation to global warming of 1.5°C introduced in Figure SPM.3a. These pathways were selected to show a range of potential mitigation approaches and vary widely in their projected energy and land use, as well as their assumptions about future socio-economic developments, including economic and population growth, equity and sustainability. A breakdown of the global net anthropogenic CO_2 emissions into the contributions in terms of CO_2 emissions from fossil fuel and industry; agriculture, forestry and other land use (AFOLU); and bioenergy with carbon capture and storage (BECCS) is shown. AFOLU estimates reported here are not necessarily comparable with countries' estimates. Further characteristics for each of these pathways are listed below each pathway. These pathways illustrate relative global differences in mitigation strategies, but do not represent central estimates, national strategies, and do not indicate requirements. For comparison, the right-most column shows the interquartile ranges across pathways with no or limited overshoot of 1.5°C. Pathways P1, P2, P3 and P4 correspond to the LED, S1, S2 and S5 pathways assessed in Chapter 2 (Figure SPM.3a). {2.2.1, 2.3.1, 2.3.2, 2.3.3, 2.3.4, 2.4.1, 2.4.2, 2.4.4, 2.5.3, Figure 2.5, Figure 2.6, Figure 2.9, Figure 2.10, Figure 2.11, Figure 2.14, Figure 2.15, Figure 2.16, Figure 2.17, Figure 2.24, Figure 2.25, Table 2.4, Table 2.6, Table 2.7, Table 2.9, Table 4.1}

C.2 Pathways limiting global warming to 1.5°C with no or limited overshoot would require rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems (*high confidence*). These systems transitions are unprecedented in terms of scale, but not necessarily in terms of speed, and imply deep emissions reductions in all sectors, a wide portfolio of mitigation options and a significant upscaling of investments in those options (*medium confidence*). {2.3, 2.4, 2.5, 4.2, 4.3, 4.4, 4.5}

C.2.1 Pathways that limit global warming to 1.5°C with no or limited overshoot show system changes that are more rapid and pronounced over the next two decades than in 2°C pathways (*high confidence*). The rates of system changes associated with limiting global warming to 1.5°C with no or limited overshoot have occurred in the past within specific sectors, technologies and spatial contexts, but there is no documented historic precedent for their scale (*medium confidence*). {2.3.3, 2.3.4, 2.4, 2.5, 4.2.1, 4.2.2, Cross-Chapter Box 11 in Chapter 4}

C.2.2 In energy systems, modelled global pathways (considered in the literature) limiting global warming to 1.5°C with no or limited overshoot (for more details see Figure SPM.3b) generally meet energy service demand with lower energy use, including through enhanced energy efficiency, and show faster electrification of energy end use compared to 2°C (*high confidence*). In 1.5°C pathways with no or limited overshoot, low-emission energy sources are projected to have a higher share, compared with 2°C pathways, particularly before 2050 (*high confidence*). In 1.5°C pathways with no or limited overshoot, renewables are projected to supply 70–85% (interquartile range) of electricity in 2050 (*high confidence*). In electricity generation, shares of nuclear and fossil fuels with carbon dioxide capture and storage (CCS) are modelled to increase in most 1.5°C pathways with no or limited overshoot. In modelled 1.5°C pathways with limited or no overshoot, the use of CCS would allow the electricity generation share of gas to be approximately 8% (3–11% interquartile range) of global electricity in 2050, while the use of coal shows a steep reduction in all pathways and would be reduced to close to 0% (0–2% interquartile range) of electricity (*high confidence*). While acknowledging the challenges, and differences between the options and national circumstances, political, economic, social and technical feasibility of solar energy, wind energy and electricity storage technologies have substantially improved over the past few years (*high confidence*). These improvements signal a potential system transition in electricity generation. (Figure SPM.3b) {2.4.1, 2.4.2, Figure 2.1, Table 2.6, Table 2.7, Cross-Chapter Box 6 in Chapter 3, 4.2.1, 4.3.1, 4.3.3, 4.5.2}

C.2.3 CO_2 emissions from industry in pathways limiting global warming to 1.5°C with no or limited overshoot are projected to be about 65–90% (interquartile range) lower in 2050 relative to 2010, as compared to 50–80% for global warming of 2°C (*medium confidence*). Such reductions can be achieved through combinations of new and existing technologies and practices, including electrification, hydrogen, sustainable bio-based feedstocks, product substitution, and carbon capture, utilization and storage (CCUS). These options are technically proven at various scales but their large-scale deployment may be limited by economic, financial, human capacity and institutional constraints in specific contexts, and specific characteristics of large-scale industrial installations. In industry, emissions reductions by energy and process efficiency by themselves are insufficient for limiting warming to 1.5°C with no or limited overshoot (*high confidence*). {2.4.3, 4.2.1, Table 4.1, Table 4.3, 4.3.3, 4.3.4, 4.5.2}

C.2.4 The urban and infrastructure system transition consistent with limiting global warming to 1.5°C with no or limited overshoot would imply, for example, changes in land and urban planning practices, as well as deeper emissions reductions in transport and buildings compared to pathways that limit global warming below 2°C (*medium confidence*). Technical measures and practices enabling deep emissions reductions include various energy efficiency options. In pathways limiting global warming to 1.5°C with no or limited overshoot, the electricity share of energy demand in buildings would be about 55–75% in 2050 compared to 50–70% in 2050 for 2°C global warming (*medium confidence*). In the transport sector, the share of low-emission final energy would rise from less than 5% in 2020 to about 35–65% in 2050 compared to 25–45% for 2°C of global warming (*medium confidence*). Economic, institutional and socio-cultural barriers may inhibit these urban and infrastructure system transitions, depending on national, regional and local circumstances, capabilities and the availability of capital (*high confidence*). {2.3.4, 2.4.3, 4.2.1, Table 4.1, 4.3.3, 4.5.2}

C.2.5 Transitions in global and regional land use are found in all pathways limiting global warming to 1.5°C with no or limited overshoot, but their scale depends on the pursued mitigation portfolio. Model pathways that limit global warming to 1.5°C with no or limited overshoot project a 4 million km^2 reduction to a 2.5 million km^2 increase of non-pasture agricultural land for food and feed crops and a 0.5–11 million km^2 reduction of pasture land, to be converted into a 0–6 million km^2 increase of agricultural land for energy crops and a 2 million km^2 reduction to 9.5 million km^2 increase in forests by 2050 relative to 2010 (*medium confidence*).[16] Land-use transitions of similar magnitude can be observed in modelled 2°C pathways (*medium confidence*). Such large transitions pose profound challenges for sustainable management of the various demands on land for human settlements, food, livestock feed, fibre, bioenergy, carbon storage, biodiversity and other ecosystem services (*high confidence*). Mitigation options limiting the demand for land include sustainable intensification of land-use practices, ecosystem restoration and changes towards less resource-intensive diets (*high confidence*). The implementation of land-based mitigation options would require overcoming socio-economic, institutional, technological, financing and environmental barriers that differ across regions (*high confidence*). {2.4.4, Figure 2.24, 4.3.2, 4.3.7, 4.5.2, Cross-Chapter Box 7 in Chapter 3}

C.2.6 Additional annual average energy-related investments for the period 2016 to 2050 in pathways limiting warming to 1.5°C compared to pathways without new climate policies beyond those in place today are estimated to be around 830 billion USD2010 (range of 150 billion to 1700 billion USD2010 across six models[17]). This compares to total annual average energy supply investments in 1.5°C pathways of 1460 to 3510 billion USD2010 and total annual average energy demand investments of 640 to 910 billion USD2010 for the period 2016 to 2050. Total energy-related investments increase by about 12% (range of 3% to 24%) in 1.5°C pathways relative to 2°C pathways. Annual investments in low-carbon energy technologies and energy efficiency are upscaled by roughly a factor of six (range of factor of 4 to 10) by 2050 compared to 2015 (*medium confidence*). {2.5.2, Box 4.8, Figure 2.27}

C.2.7 Modelled pathways limiting global warming to 1.5°C with no or limited overshoot project a wide range of global average discounted marginal abatement costs over the 21st century. They are roughly 3-4 times higher than in pathways limiting global warming to below 2°C (*high confidence*). The economic literature distinguishes marginal abatement costs from total mitigation costs in the economy. The literature on total mitigation costs of 1.5°C mitigation pathways is limited and was not assessed in this Report. Knowledge gaps remain in the integrated assessment of the economy-wide costs and benefits of mitigation in line with pathways limiting warming to 1.5°C. {2.5.2; 2.6; Figure 2.26}

16 The projected land-use changes presented are not deployed to their upper limits simultaneously in a single pathway.

17 Including two pathways limiting warming to 1.5°C with no or limited overshoot and four pathways with higher overshoot.

C.3 All pathways that limit global warming to 1.5°C with limited or no overshoot project the use of carbon dioxide removal (CDR) on the order of 100–1000 $GtCO_2$ over the 21st century. CDR would be used to compensate for residual emissions and, in most cases, achieve net negative emissions to return global warming to 1.5°C following a peak (*high confidence*). CDR deployment of several hundreds of $GtCO_2$ is subject to multiple feasibility and sustainability constraints (*high confidence*). Significant near-term emissions reductions and measures to lower energy and land demand can limit CDR deployment to a few hundred $GtCO_2$ without reliance on bioenergy with carbon capture and storage (BECCS) (*high confidence*). {2.3, 2.4, 3.6.2, 4.3, 5.4}

C.3.1 Existing and potential CDR measures include afforestation and reforestation, land restoration and soil carbon sequestration, BECCS, direct air carbon capture and storage (DACCS), enhanced weathering and ocean alkalinization. These differ widely in terms of maturity, potentials, costs, risks, co-benefits and trade-offs (*high confidence*). To date, only a few published pathways include CDR measures other than afforestation and BECCS. {2.3.4, 3.6.2, 4.3.2, 4.3.7}

C.3.2 In pathways limiting global warming to 1.5°C with limited or no overshoot, BECCS deployment is projected to range from 0–1, 0–8, and 0–16 $GtCO_2$ yr^{-1} in 2030, 2050, and 2100, respectively, while agriculture, forestry and land-use (AFOLU) related CDR measures are projected to remove 0–5, 1–11, and 1–5 $GtCO_2$ yr^{-1} in these years (*medium confidence*). The upper end of these deployment ranges by mid-century exceeds the BECCS potential of up to 5 $GtCO_2$ yr^{-1} and afforestation potential of up to 3.6 $GtCO_2$ yr^{-1} assessed based on recent literature (*medium confidence*). Some pathways avoid BECCS deployment completely through demand-side measures and greater reliance on AFOLU-related CDR measures (*medium confidence*). The use of bioenergy can be as high or even higher when BECCS is excluded compared to when it is included due to its potential for replacing fossil fuels across sectors (*high confidence*). (Figure SPM.3b) {2.3.3, 2.3.4, 2.4.2, 3.6.2, 4.3.1, 4.2.3, 4.3.2, 4.3.7, 4.4.3, Table 2.4}

C.3.3 Pathways that overshoot 1.5°C of global warming rely on CDR exceeding residual CO_2 emissions later in the century to return to below 1.5°C by 2100, with larger overshoots requiring greater amounts of CDR (Figure SPM.3b) (*high confidence*). Limitations on the speed, scale, and societal acceptability of CDR deployment hence determine the ability to return global warming to below 1.5°C following an overshoot. Carbon cycle and climate system understanding is still limited about the effectiveness of net negative emissions to reduce temperatures after they peak (*high confidence*). {2.2, 2.3.4, 2.3.5, 2.6, 4.3.7, 4.5.2, Table 4.11}

C.3.4 Most current and potential CDR measures could have significant impacts on land, energy, water or nutrients if deployed at large scale (*high confidence*). Afforestation and bioenergy may compete with other land uses and may have significant impacts on agricultural and food systems, biodiversity, and other ecosystem functions and services (*high confidence*). Effective governance is needed to limit such trade-offs and ensure permanence of carbon removal in terrestrial, geological and ocean reservoirs (*high confidence*). Feasibility and sustainability of CDR use could be enhanced by a portfolio of options deployed at substantial, but lesser scales, rather than a single option at very large scale (*high confidence*). (Figure SPM.3b) {2.3.4, 2.4.4, 2.5.3, 2.6, 3.6.2, 4.3.2, 4.3.7, 4.5.2, 5.4.1, 5.4.2; Cross-Chapter Boxes 7 and 8 in Chapter 3, Table 4.11, Table 5.3, Figure 5.3}

C.3.5 Some AFOLU-related CDR measures such as restoration of natural ecosystems and soil carbon sequestration could provide co-benefits such as improved biodiversity, soil quality, and local food security. If deployed at large scale, they would require governance systems enabling sustainable land management to conserve and protect land carbon stocks and other ecosystem functions and services (*medium confidence*). (Figure SPM.4) {2.3.3, 2.3.4, 2.4.2, 2.4.4, 3.6.2, 5.4.1, Cross-Chapter Boxes 3 in Chapter 1 and 7 in Chapter 3, 4.3.2, 4.3.7, 4.4.1, 4.5.2, Table 2.4}

D. Strengthening the Global Response in the Context of Sustainable Development and Efforts to Eradicate Poverty

D.1 Estimates of the global emissions outcome of current nationally stated mitigation ambitions as submitted under the Paris Agreement would lead to global greenhouse gas emissions[18] in 2030 of 52–58 $GtCO_2eq\ yr^{-1}$ (*medium confidence*). Pathways reflecting these ambitions would not limit global warming to 1.5°C, even if supplemented by very challenging increases in the scale and ambition of emissions reductions after 2030 (*high confidence*). Avoiding overshoot and reliance on future large-scale deployment of carbon dioxide removal (CDR) can only be achieved if global CO_2 emissions start to decline well before 2030 (*high confidence*). {1.2, 2.3, 3.3, 3.4, 4.2, 4.4, Cross-Chapter Box 11 in Chapter 4}

D.1.1 Pathways that limit global warming to 1.5°C with no or limited overshoot show clear emission reductions by 2030 (*high confidence*). All but one show a decline in global greenhouse gas emissions to below 35 $GtCO_2eq\ yr^{-1}$ in 2030, and half of available pathways fall within the 25–30 $GtCO_2eq\ yr^{-1}$ range (interquartile range), a 40–50% reduction from 2010 levels (*high confidence*). Pathways reflecting current nationally stated mitigation ambition until 2030 are broadly consistent with cost-effective pathways that result in a global warming of about 3°C by 2100, with warming continuing afterwards (*medium confidence*). {2.3.3, 2.3.5, Cross-Chapter Box 11 in Chapter 4, 5.5.3.2}

D.1.2 Overshoot trajectories result in higher impacts and associated challenges compared to pathways that limit global warming to 1.5°C with no or limited overshoot (*high confidence*). Reversing warming after an overshoot of 0.2°C or larger during this century would require upscaling and deployment of CDR at rates and volumes that might not be achievable given considerable implementation challenges (*medium confidence*). {1.3.3, 2.3.4, 2.3.5, 2.5.1, 3.3, 4.3.7, Cross-Chapter Box 8 in Chapter 3, Cross-Chapter Box 11 in Chapter 4}

D.1.3 The lower the emissions in 2030, the lower the challenge in limiting global warming to 1.5°C after 2030 with no or limited overshoot (*high confidence*). The challenges from delayed actions to reduce greenhouse gas emissions include the risk of cost escalation, lock-in in carbon-emitting infrastructure, stranded assets, and reduced flexibility in future response options in the medium to long term (*high confidence*). These may increase uneven distributional impacts between countries at different stages of development (*medium confidence*). {2.3.5, 4.4.5, 5.4.2}

D.2 The avoided climate change impacts on sustainable development, eradication of poverty and reducing inequalities would be greater if global warming were limited to 1.5°C rather than 2°C, if mitigation and adaptation synergies are maximized while trade-offs are minimized (*high confidence*). {1.1, 1.4, 2.5, 3.3, 3.4, 5.2, Table 5.1}

D.2.1 Climate change impacts and responses are closely linked to sustainable development which balances social well-being, economic prosperity and environmental protection. The United Nations Sustainable Development Goals (SDGs), adopted in 2015, provide an established framework for assessing the links between global warming of 1.5°C or 2°C and development goals that include poverty eradication, reducing inequalities, and climate action. (*high confidence*) {Cross-Chapter Box 4 in Chapter 1, 1.4, 5.1}

D.2.2 The consideration of ethics and equity can help address the uneven distribution of adverse impacts associated with 1.5°C and higher levels of global warming, as well as those from mitigation and adaptation, particularly for poor and disadvantaged populations, in all societies (*high confidence*). {1.1.1, 1.1.2, 1.4.3, 2.5.3, 3.4.10, 5.1, 5.2, 5.3. 5.4, Cross-Chapter Box 4 in Chapter 1, Cross-Chapter Boxes 6 and 8 in Chapter 3, and Cross-Chapter Box 12 in Chapter 5}

D.2.3 Mitigation and adaptation consistent with limiting global warming to 1.5°C are underpinned by enabling conditions, assessed in this Report across the geophysical, environmental-ecological, technological, economic, socio-cultural and institutional

18 GHG emissions have been aggregated with 100-year GWP values as introduced in the IPCC Second Assessment Report.

dimensions of feasibility. Strengthened multilevel governance, institutional capacity, policy instruments, technological innovation and transfer and mobilization of finance, and changes in human behaviour and lifestyles are enabling conditions that enhance the feasibility of mitigation and adaptation options for 1.5°C-consistent systems transitions. (*high confidence*) {1.4, Cross-Chapter Box 3 in Chapter 1, 2.5.1, 4.4, 4.5, 5.6}

D.3 Adaptation options specific to national contexts, if carefully selected together with enabling conditions, will have benefits for sustainable development and poverty reduction with global warming of 1.5°C, although trade-offs are possible (*high confidence*). {1.4, 4.3, 4.5}

D.3.1 Adaptation options that reduce the vulnerability of human and natural systems have many synergies with sustainable development, if well managed, such as ensuring food and water security, reducing disaster risks, improving health conditions, maintaining ecosystem services and reducing poverty and inequality (*high confidence*). Increasing investment in physical and social infrastructure is a key enabling condition to enhance the resilience and the adaptive capacities of societies. These benefits can occur in most regions with adaptation to 1.5°C of global warming (*high confidence*). {1.4.3, 4.2.2, 4.3.1, 4.3.2, 4.3.3, 4.3.5, 4.4.1, 4.4.3, 4.5.3, 5.3.1, 5.3.2}

D.3.2 Adaptation to 1.5°C global warming can also result in trade-offs or maladaptations with adverse impacts for sustainable development. For example, if poorly designed or implemented, adaptation projects in a range of sectors can increase greenhouse gas emissions and water use, increase gender and social inequality, undermine health conditions, and encroach on natural ecosystems (*high confidence*). These trade-offs can be reduced by adaptations that include attention to poverty and sustainable development (*high confidence*). {4.3.2, 4.3.3, 4.5.4, 5.3.2; Cross-Chapter Boxes 6 and 7 in Chapter 3}

D.3.3 A mix of adaptation and mitigation options to limit global warming to 1.5°C, implemented in a participatory and integrated manner, can enable rapid, systemic transitions in urban and rural areas (*high confidence*). These are most effective when aligned with economic and sustainable development, and when local and regional governments and decision makers are supported by national governments (*medium confidence*). {4.3.2, 4.3.3, 4.4.1, 4.4.2}

D.3.4 Adaptation options that also mitigate emissions can provide synergies and cost savings in most sectors and system transitions, such as when land management reduces emissions and disaster risk, or when low-carbon buildings are also designed for efficient cooling. Trade-offs between mitigation and adaptation, when limiting global warming to 1.5°C, such as when bioenergy crops, reforestation or afforestation encroach on land needed for agricultural adaptation, can undermine food security, livelihoods, ecosystem functions and services and other aspects of sustainable development. (*high confidence*) {3.4.3, 4.3.2, 4.3.4, 4.4.1, 4.5.2, 4.5.3, 4.5.4}

D.4 Mitigation options consistent with 1.5°C pathways are associated with multiple synergies and trade-offs across the Sustainable Development Goals (SDGs). While the total number of possible synergies exceeds the number of trade-offs, their net effect will depend on the pace and magnitude of changes, the composition of the mitigation portfolio and the management of the transition. (*high confidence*) (Figure SPM.4) {2.5, 4.5, 5.4}

D.4.1 1.5°C pathways have robust synergies particularly for the SDGs 3 (health), 7 (clean energy), 11 (cities and communities), 12 (responsible consumption and production) and 14 (oceans) (*very high confidence*). Some 1.5°C pathways show potential trade-offs with mitigation for SDGs 1 (poverty), 2 (hunger), 6 (water) and 7 (energy access), if not managed carefully (*high confidence*). (Figure SPM.4) {5.4.2; Figure 5.4, Cross-Chapter Boxes 7 and 8 in Chapter 3}

D.4.2 1.5°C pathways that include low energy demand (e.g., see P1 in Figure SPM.3a and SPM.3b), low material consumption, and low GHG-intensive food consumption have the most pronounced synergies and the lowest number of trade-offs with respect to sustainable development and the SDGs (*high confidence*). Such pathways would reduce dependence on CDR. In modelled pathways, sustainable development, eradicating poverty and reducing inequality can support limiting warming to 1.5°C (*high confidence*). (Figure SPM.3b, Figure SPM.4) {2.4.3, 2.5.1, 2.5.3, Figure 2.4, Figure 2.28, 5.4.1, 5.4.2, Figure 5.4}

Indicative linkages between mitigation options and sustainable development using SDGs (The linkages do not show costs and benefits)

Mitigation options deployed in each sector can be associated with potential positive effects (synergies) or negative effects (trade-offs) with the Sustainable Development Goals (SDGs). The degree to which this potential is realized will depend on the selected portfolio of mitigation options, mitigation policy design, and local circumstances and context. Particularly in the energy-demand sector, the potential for synergies is larger than for trade-offs. The bars group individually assessed options by level of confidence and take into account the relative strength of the assessed mitigation-SDG connections.

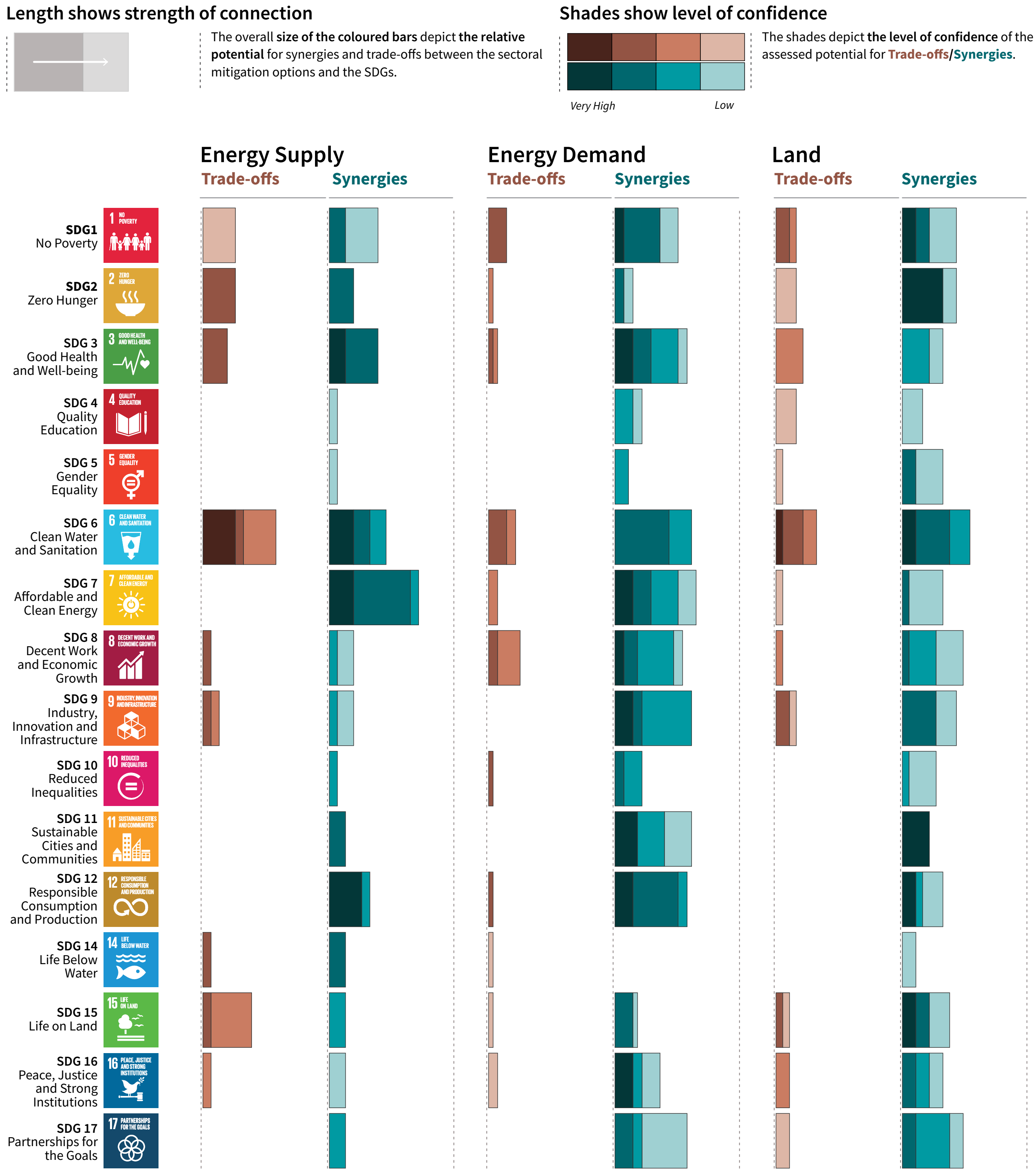


Figure SPM.4 | Potential synergies and trade-offs between the sectoral portfolio of climate change mitigation options and the Sustainable Development Goals (SDGs). The SDGs serve as an analytical framework for the assessment of the different sustainable development dimensions, which extend beyond the time frame of the 2030 SDG targets. The assessment is based on literature on mitigation options that are considered relevant for 1.5°C. The assessed strength of the SDG interactions is based on the qualitative and quantitative assessment of individual mitigation options listed in Table 5.2. For each mitigation option, the strength of the SDG-connection as well as the associated confidence of the underlying literature (shades of green and red) was assessed. The strength of positive connections (synergies) and negative connections (trade-offs) across all individual options within a sector (see Table 5.2) are aggregated into sectoral potentials for the whole mitigation portfolio. The (white) areas outside the bars, which indicate no interactions, have *low confidence* due to the uncertainty and limited number of studies exploring indirect effects. The strength of the connection considers only the effect of mitigation and does not include benefits of avoided impacts. SDG 13 (climate action) is not listed because mitigation is being considered in terms of interactions with SDGs and not vice versa. The bars denote the strength of the connection, and do not consider the strength of the impact on the SDGs. The energy demand sector comprises behavioural responses, fuel switching and efficiency options in the transport, industry and building sector as well as carbon capture options in the industry sector. Options assessed in the energy supply sector comprise biomass and non-biomass renewables, nuclear, carbon capture and storage (CCS) with bioenergy, and CCS with fossil fuels. Options in the land sector comprise agricultural and forest options, sustainable diets and reduced food waste, soil sequestration, livestock and manure management, reduced deforestation, afforestation and reforestation, and responsible sourcing. In addition to this figure, options in the ocean sector are discussed in the underlying report. {5.4, Table 5.2, Figure 5.2}

Information about the net impacts of mitigation on sustainable development in 1.5°C pathways is available only for a limited number of SDGs and mitigation options. Only a limited number of studies have assessed the benefits of avoided climate change impacts of 1.5°C pathways for the SDGs, and the co-effects of adaptation for mitigation and the SDGs. The assessment of the indicative mitigation potentials in Figure SPM.4 is a step further from AR5 towards a more comprehensive and integrated assessment in the future.

D.4.3 1.5°C and 2°C modelled pathways often rely on the deployment of large-scale land-related measures like afforestation and bioenergy supply, which, if poorly managed, can compete with food production and hence raise food security concerns (*high confidence*). The impacts of carbon dioxide removal (CDR) options on SDGs depend on the type of options and the scale of deployment (*high confidence*). If poorly implemented, CDR options such as BECCS and AFOLU options would lead to trade-offs. Context-relevant design and implementation requires considering people's needs, biodiversity, and other sustainable development dimensions (*very high confidence*). (Figure SPM.4) {5.4.1.3, Cross-Chapter Box 7 in Chapter 3}

D.4.4 Mitigation consistent with 1.5°C pathways creates risks for sustainable development in regions with high dependency on fossil fuels for revenue and employment generation (*high confidence*). Policies that promote diversification of the economy and the energy sector can address the associated challenges (*high confidence*). {5.4.1.2, Box 5.2}

D.4.5 Redistributive policies across sectors and populations that shield the poor and vulnerable can resolve trade-offs for a range of SDGs, particularly hunger, poverty and energy access. Investment needs for such complementary policies are only a small fraction of the overall mitigation investments in 1.5°C pathways. (*high confidence*) {2.4.3, 5.4.2, Figure 5.5}

D.5 Limiting the risks from global warming of 1.5°C in the context of sustainable development and poverty eradication implies system transitions that can be enabled by an increase of adaptation and mitigation investments, policy instruments, the acceleration of technological innovation and behaviour changes (*high confidence*). {2.3, 2.4, 2.5, 3.2, 4.2, 4.4, 4.5, 5.2, 5.5, 5.6}

D.5.1 Directing finance towards investment in infrastructure for mitigation and adaptation could provide additional resources. This could involve the mobilization of private funds by institutional investors, asset managers and development or investment banks, as well as the provision of public funds. Government policies that lower the risk of low-emission and adaptation investments can facilitate the mobilization of private funds and enhance the effectiveness of other public policies. Studies indicate a number of challenges, including access to finance and mobilization of funds. (*high confidence*) {2.5.1, 2.5.2, 4.4.5}

D.5.2 Adaptation finance consistent with global warming of 1.5°C is difficult to quantify and compare with 2°C. Knowledge gaps include insufficient data to calculate specific climate resilience-enhancing investments from the provision of currently underinvested basic infrastructure. Estimates of the costs of adaptation might be lower at global warming of 1.5°C than for 2°C. Adaptation needs have typically been supported by public sector sources such as national and subnational government budgets, and in developing countries together with support from development assistance, multilateral development banks, and United Nations Framework Convention on Climate Change channels (*medium confidence*). More recently there is a growing understanding of the scale and increase in non-governmental organizations and private funding in some regions (*medium confidence*). Barriers include the scale of adaptation financing, limited capacity and access to adaptation finance (*medium confidence*). {4.4.5, 4.6}

D.5.3 Global model pathways limiting global warming to 1.5°C are projected to involve the annual average investment needs in the energy system of around 2.4 trillion USD2010 between 2016 and 2035, representing about 2.5% of the world GDP (*medium confidence*). {4.4.5, Box 4.8}

D.5.4 Policy tools can help mobilize incremental resources, including through shifting global investments and savings and through market and non-market based instruments as well as accompanying measures to secure the equity of the transition, acknowledging the challenges related with implementation, including those of energy costs, depreciation of assets and impacts on international competition, and utilizing the opportunities to maximize co-benefits (*high confidence*). {1.3.3, 2.3.4, 2.3.5, 2.5.1, 2.5.2, Cross-Chapter Box 8 in Chapter 3, Cross-Chapter Box 11 in Chapter 4, 4.4.5, 5.5.2}

D.5.5 The systems transitions consistent with adapting to and limiting global warming to 1.5°C include the widespread adoption of new and possibly disruptive technologies and practices and enhanced climate-driven innovation. These imply enhanced technological innovation capabilities, including in industry and finance. Both national innovation policies and international cooperation can contribute to the development, commercialization and widespread adoption of mitigation and adaptation technologies. Innovation policies may be more effective when they combine public support for research and development with policy mixes that provide incentives for technology diffusion. (*high confidence*) {4.4.4, 4.4.5}.

D.5.6 Education, information, and community approaches, including those that are informed by indigenous knowledge and local knowledge, can accelerate the wide-scale behaviour changes consistent with adapting to and limiting global warming to 1.5°C. These approaches are more effective when combined with other policies and tailored to the motivations, capabilities and resources of specific actors and contexts (*high confidence*). Public acceptability can enable or inhibit the implementation of policies and measures to limit global warming to 1.5°C and to adapt to the consequences. Public acceptability depends on the individual's evaluation of expected policy consequences, the perceived fairness of the distribution of these consequences, and perceived fairness of decision procedures (*high confidence*). {1.1, 1.5, 4.3.5, 4.4.1, 4.4.3, Box 4.3, 5.5.3, 5.6.5}

D.6 Sustainable development supports, and often enables, the fundamental societal and systems transitions and transformations that help limit global warming to 1.5°C. Such changes facilitate the pursuit of climate-resilient development pathways that achieve ambitious mitigation and adaptation in conjunction with poverty eradication and efforts to reduce inequalities (*high confiden*ce). {Box 1.1, 1.4.3, Figure 5.1, 5.5.3, Box 5.3}

D.6.1 Social justice and equity are core aspects of climate-resilient development pathways that aim to limit global warming to 1.5°C as they address challenges and inevitable trade-offs, widen opportunities, and ensure that options, visions, and values are deliberated, between and within countries and communities, without making the poor and disadvantaged worse off (*high confidence*). {5.5.2, 5.5.3, Box 5.3, Figure 5.1, Figure 5.6, Cross-Chapter Boxes 12 and 13 in Chapter 5}

D.6.2 The potential for climate-resilient development pathways differs between and within regions and nations, due to different development contexts and systemic vulnerabilities (*very high confidence*). Efforts along such pathways to date have been limited (*medium confidence*) and enhanced efforts would involve strengthened and timely action from all countries and non-state actors (*high confidence*). {5.5.1, 5.5.3, Figure 5.1}

D.6.3 Pathways that are consistent with sustainable development show fewer mitigation and adaptation challenges and are associated with lower mitigation costs. The large majority of modelling studies could not construct pathways characterized by lack of international cooperation, inequality and poverty that were able to limit global warming to 1.5°C. (*high confidence*) {2.3.1, 2.5.1, 2.5.3, 5.5.2}

D.7 Strengthening the capacities for climate action of national and sub-national authorities, civil society, the private sector, indigenous peoples and local communities can support the implementation of ambitious actions implied by limiting global warming to 1.5°C (*high confidence*). International cooperation can provide an enabling environment for this to be achieved in all countries and for all people, in the context of sustainable development. International cooperation is a critical enabler for developing countries and vulnerable regions (*high confidence*). {1.4, 2.3, 2.5, 4.2, 4.4, 4.5, 5.3, 5.4, 5.5, 5.6, 5, Box 4.1, Box 4.2, Box 4.7, Box 5.3, Cross-Chapter Box 9 in Chapter 4, Cross-Chapter Box 13 in Chapter 5}

D.7.1 Partnerships involving non-state public and private actors, institutional investors, the banking system, civil society and scientific institutions would facilitate actions and responses consistent with limiting global warming to 1.5°C (*very high confidence*). {1.4, 4.4.1, 4.2.2, 4.4.3, 4.4.5, 4.5.3, 5.4.1, 5.6.2, Box 5.3}.

D.7.2 Cooperation on strengthened accountable multilevel governance that includes non-state actors such as industry, civil society and scientific institutions, coordinated sectoral and cross-sectoral policies at various governance levels, gender-sensitive policies, finance including innovative financing, and cooperation on technology development and transfer can ensure participation, transparency, capacity building and learning among different players (*high confidence*). {2.5.1, 2.5.2, 4.2.2, 4.4.1, 4.4.2, 4.4.3, 4.4.4, 4.4.5, 4.5.3, Cross-Chapter Box 9 in Chapter 4, 5.3.1, 5.5.3, Cross-Chapter Box 13 in Chapter 5, 5.6.1, 5.6.3}

D.7.3 International cooperation is a critical enabler for developing countries and vulnerable regions to strengthen their action for the implementation of 1.5°C-consistent climate responses, including through enhancing access to finance and technology and enhancing domestic capacities, taking into account national and local circumstances and needs (*high confidence*). {2.3.1, 2.5.1, 4.4.1, 4.4.2, 4.4.4, 4.4.5, 5.4.1 5.5.3, 5.6.1, Box 4.1, Box 4.2, Box 4.7}.

D.7.4 Collective efforts at all levels, in ways that reflect different circumstances and capabilities, in the pursuit of limiting global warming to 1.5°C, taking into account equity as well as effectiveness, can facilitate strengthening the global response to climate change, achieving sustainable development and eradicating poverty (*high confidence*). {1.4.2, 2.3.1, 2.5.1, 2.5.2, 2.5.3, 4.2.2, 4.4.1, 4.4.2, 4.4.3, 4.4.4, 4.4.5, 4.5.3, 5.3.1, 5.4.1, 5.5.3, 5.6.1, 5.6.2, 5.6.3}

SPM

Box SPM.1: Core Concepts Central to this Special Report

Global mean surface temperature (GMST): Estimated global average of near-surface air temperatures over land and sea ice, and sea surface temperatures over ice-free ocean regions, with changes normally expressed as departures from a value over a specified reference period. When estimating changes in GMST, near-surface air temperature over both land and oceans are also used.[19] {1.2.1.1}

Pre-industrial: The multi-century period prior to the onset of large-scale industrial activity around 1750. The reference period 1850–1900 is used to approximate pre-industrial GMST. {1.2.1.2}

Global warming: The estimated increase in GMST averaged over a 30-year period, or the 30-year period centred on a particular year or decade, expressed relative to pre-industrial levels unless otherwise specified. For 30-year periods that span past and future years, the current multi-decadal warming trend is assumed to continue. {1.2.1}

Net zero CO_2 emissions: Net zero carbon dioxide (CO_2) emissions are achieved when anthropogenic CO_2 emissions are balanced globally by anthropogenic CO_2 removals over a specified period.

Carbon dioxide removal (CDR): Anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage, but excludes natural CO_2 uptake not directly caused by human activities.

Total carbon budget: Estimated cumulative net global anthropogenic CO_2 emissions from the pre-industrial period to the time that anthropogenic CO_2 emissions reach net zero that would result, at some probability, in limiting global warming to a given level, accounting for the impact of other anthropogenic emissions. {2.2.2}

Remaining carbon budget: Estimated cumulative net global anthropogenic CO_2 emissions from a given start date to the time that anthropogenic CO_2 emissions reach net zero that would result, at some probability, in limiting global warming to a given level, accounting for the impact of other anthropogenic emissions. {2.2.2}

Temperature overshoot: The temporary exceedance of a specified level of global warming.

Emission pathways: In this Summary for Policymakers, the modelled trajectories of global anthropogenic emissions over the 21st century are termed emission pathways. Emission pathways are classified by their temperature trajectory over the 21st century: pathways giving at least 50% probability based on current knowledge of limiting global warming to below 1.5°C are classified as 'no overshoot'; those limiting warming to below 1.6°C and returning to 1.5°C by 2100 are classified as '1.5°C limited-overshoot'; while those exceeding 1.6°C but still returning to 1.5°C by 2100 are classified as 'higher-overshoot'.

Impacts: Effects of climate change on human and natural systems. Impacts can have beneficial or adverse outcomes for livelihoods, health and well-being, ecosystems and species, services, infrastructure, and economic, social and cultural assets.

Risk: The potential for adverse consequences from a climate-related hazard for human and natural systems, resulting from the interactions between the hazard and the vulnerability and exposure of the affected system. Risk integrates the likelihood of exposure to a hazard and the magnitude of its impact. Risk also can describe the potential for adverse consequences of adaptation or mitigation responses to climate change.

Climate-resilient development pathways (CRDPs): Trajectories that strengthen sustainable development at multiple scales and efforts to eradicate poverty through equitable societal and systems transitions and transformations while reducing the threat of climate change through ambitious mitigation, adaptation and climate resilience.

19 Past IPCC reports, reflecting the literature, have used a variety of approximately equivalent metrics of GMST change.

2

Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development

Coordinating Lead Authors:
Joeri Rogelj (Austria/Belgium), Drew Shindell (USA), Kejun Jiang (China)

Lead Authors:
Solomone Fifita (Fiji), Piers Forster (UK), Veronika Ginzburg (Russia), Collins Handa (Kenya), Haroon Kheshgi (USA), Shigeki Kobayashi (Japan), Elmar Kriegler (Germany), Luis Mundaca (Sweden/Chile), Roland Séférian (France), Maria Virginia Vilariño (Argentina)

Contributing Authors:
Katherine Calvin (USA), Joana Correia de Oliveira de Portugal Pereira (UK/Portugal), Oreane Edelenbosch (Netherlands/Italy), Johannes Emmerling (Italy/Germany), Sabine Fuss (Germany), Thomas Gasser (Austria/France), Nathan Gillett (Canada), Chenmin He (China), Edgar Hertwich (USA/Austria), Lena Höglund-Isaksson (Austria/Sweden), Daniel Huppmann (Austria), Gunnar Luderer (Germany), Anil Markandya (Spain/UK), David L. McCollum (USA/Austria), Malte Meinshausen (Australia/Germany), Richard Millar (UK), Alexander Popp (Germany), Pallav Purohit (Austria/India), Keywan Riahi (Austria), Aurélien Ribes (France), Harry Saunders (Canada/USA), Christina Schädel (USA/Switzerland), Chris Smith (UK), Pete Smith (UK), Evelina Trutnevyte (Switzerland/Lithuania), Yang Xiu (China), Wenji Zhou (Austria/China), Kirsten Zickfeld (Canada/Germany)

Chapter Scientists:
Daniel Huppmann (Austria), Chris Smith (UK)

Review Editors:
Greg Flato (Canada), Jan Fuglestvedt (Norway), Rachid Mrabet (Morocco), Roberto Schaeffer (Brazil)

This chapter should be cited as:
Rogelj, J., D. Shindell, K. Jiang, S. Fifita, P. Forster, V. Ginzburg, C. Handa, H. Kheshgi, S. Kobayashi, E. Kriegler, L. Mundaca, R. Séférian, and M.V. Vilariño, 2018: Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. In Press.

Table of Contents

Executive Summary

This chapter assesses mitigation pathways consistent with limiting warming to 1.5°C above pre-industrial levels. In doing so, it explores the following key questions: What role do CO_2 and non-CO_2 emissions play? {2.2, 2.3, 2.4, 2.6} To what extent do 1.5°C pathways involve overshooting and returning below 1.5°C during the 21st century? {2.2, 2.3} What are the implications for transitions in energy, land use and sustainable development? {2.3, 2.4, 2.5} How do policy frameworks affect the ability to limit warming to 1.5°C? {2.3, 2.5} What are the associated knowledge gaps? {2.6}

The assessed pathways describe integrated, quantitative evolutions of all emissions over the 21st century associated with global energy and land use and the world economy. The assessment is contingent upon available integrated assessment literature and model assumptions, and is complemented by other studies with different scope, for example, those focusing on individual sectors. In recent years, integrated mitigation studies have improved the characterizations of mitigation pathways. However, limitations remain, as climate damages, avoided impacts, or societal co-benefits of the modelled transformations remain largely unaccounted for, while concurrent rapid technological changes, behavioural aspects, and uncertainties about input data present continuous challenges. (*high confidence*) {2.1.3, 2.3, 2.5.1, 2.6, Technical Annex 2}

The Chances of Limiting Warming to 1.5°C and the Requirements for Urgent Action

Pathways consistent with 1.5°C of warming above pre-industrial levels can be identified under a range of assumptions about economic growth, technology developments and lifestyles. However, lack of global cooperation, lack of governance of the required energy and land transformation, and increases in resource-intensive consumption are key impediments to achieving 1.5°C pathways. Governance challenges have been related to scenarios with high inequality and high population growth in the 1.5°C pathway literature. {2.3.1, 2.3.2, 2.5}

Under emissions in line with current pledges under the Paris Agreement (known as Nationally Determined Contributions, or NDCs), global warming is expected to surpass 1.5°C above pre-industrial levels, even if these pledges are supplemented with very challenging increases in the scale and ambition of mitigation after 2030 (*high confidence*). This increased action would need to achieve net zero CO_2 emissions in less than 15 years. Even if this is achieved, temperatures would only be expected to remain below the 1.5°C threshold if the actual geophysical response ends up being towards the low end of the currently estimated uncertainty range. Transition challenges as well as identified trade-offs can be reduced if global emissions peak before 2030 and marked emissions reductions compared to today are already achieved by 2030. {2.2, 2.3.5, Cross-Chapter Box 11 in Chapter 4}

Limiting warming to 1.5°C depends on greenhouse gas (GHG) emissions over the next decades, where lower GHG emissions in 2030 lead to a higher chance of keeping peak warming to 1.5°C (*high confidence*). Available pathways that aim for no or limited (less than 0.1°C) overshoot of 1.5°C keep GHG emissions in 2030 to 25–30 GtCO2e yr^{-1} in 2030 (interquartile range). This contrasts with median estimates for current unconditional NDCs of 52–58 GtCO_2e yr^{-1} in 2030. Pathways that aim for limiting warming to 1.5°C by 2100 after a temporary temperature overshoot rely on large-scale deployment of carbon dioxide removal (CDR) measures, which are uncertain and entail clear risks. In model pathways with no or limited overshoot of 1.5°C, global net anthropogenic CO_2 emissions decline by about 45% from 2010 levels by 2030 (40–60% interquartile range), reaching net zero around 2050 (2045–2055 interquartile range). For limiting global warming to below 2°C with at least 66% probability CO_2 emissions are projected to decline by about 25% by 2030 in most pathways (10–30% interquartile range) and reach net zero around 2070 (2065–2080 interquartile range).[1] {2.2, 2.3.3, 2.3.5, 2.5.3, Cross-Chapter Boxes 6 in Chapter 3 and 9 in Chapter 4, 4.3.7}

Limiting warming to 1.5°C implies reaching net zero CO_2 emissions globally around 2050 and concurrent deep reductions in emissions of non-CO_2 forcers, particularly methane (*high confidence*). Such mitigation pathways are characterized by energy-demand reductions, decarbonization of electricity and other fuels, electrification of energy end use, deep reductions in agricultural emissions, and some form of CDR with carbon storage on land or sequestration in geological reservoirs. Low energy demand and low demand for land- and GHG-intensive consumption goods facilitate limiting warming to as close as possible to 1.5°C. {2.2.2, 2.3.1, 2.3.5, 2.5.1, Cross-Chapter Box 9 in Chapter 4}.

In comparison to a 2°C limit, the transformations required to limit warming to 1.5°C are qualitatively similar but more pronounced and rapid over the next decades (*high confidence*). 1.5°C implies very ambitious, internationally cooperative policy environments that transform both supply and demand *(high confidence).* {2.3, 2.4, 2.5}

Policies reflecting a high price on emissions are necessary in models to achieve cost-effective 1.5°C pathways (*high confidence*). Other things being equal, modelling studies suggest the global average discounted marginal abatement costs for limiting warming to 1.5°C being about 3–4 times higher compared to 2°C over the 21st century, with large variations across models and socio-economic and policy assumptions. Carbon pricing can be imposed directly or implicitly by regulatory policies. Policy instruments, like technology policies or performance standards, can complement explicit carbon pricing in specific areas. {2.5.1, 2.5.2, 4.4.5}

Limiting warming to 1.5°C requires a marked shift in investment patterns (*medium confidence*). Additional annual average energy-related investments for the period 2016 to 2050 in pathways limiting warming to 1.5°C compared to pathways without new climate policies beyond those in place today (i.e., baseline) are estimated to be around

[1] Kyoto-GHG emissions in this statement are aggregated with GWP-100 values of the IPCC Second Assessment Report.

830 billion USD2010 (range of 150 billion to 1700 billion USD2010 across six models). Total energy-related investments increase by about 12% (range of 3% to 24%) in 1.5°C pathways relative to 2°C pathways. Average annual investment in low-carbon energy technologies and energy efficiency are upscaled by roughly a factor of six (range of factor of 4 to 10) by 2050 compared to 2015, overtaking fossil investments globally by around 2025 (*medium confidence*). Uncertainties and strategic mitigation portfolio choices affect the magnitude and focus of required investments. {2.5.2}

Future Emissions in 1.5°C Pathways

Mitigation requirements can be quantified using carbon budget approaches that relate cumulative CO_2 emissions to global mean temperature increase. Robust physical understanding underpins this relationship, but uncertainties become increasingly relevant as a specific temperature limit is approached. These uncertainties relate to the transient climate response to cumulative carbon emissions (TCRE), non-CO_2 emissions, radiative forcing and response, potential additional Earth system feedbacks (such as permafrost thawing), and historical emissions and temperature. {2.2.2, 2.6.1}

Cumulative CO_2 emissions are kept within a budget by reducing global annual CO_2 emissions to net zero. This assessment suggests a remaining budget of about 420 $GtCO_2$ for a two-thirds chance of limiting warming to 1.5°C, and of about 580 $GtCO_2$ for an even chance (*medium confidence*). The remaining carbon budget is defined here as cumulative CO_2 emissions from the start of 2018 until the time of net zero global emissions for global warming defined as a change in global near-surface air temperatures. Remaining budgets applicable to 2100 would be approximately 100 $GtCO_2$ lower than this to account for permafrost thawing and potential methane release from wetlands in the future, and more thereafter. These estimates come with an additional geophysical uncertainty of at least ±400 $GtCO_2$, related to non-CO_2 response and TCRE distribution. Uncertainties in the level of historic warming contribute ±250 $GtCO_2$. In addition, these estimates can vary by ±250 $GtCO_2$ depending on non-CO_2 mitigation strategies as found in available pathways. {2.2.2, 2.6.1}

Staying within a remaining carbon budget of 580 $GtCO_2$ implies that CO_2 emissions reach carbon neutrality in about 30 years, reduced to 20 years for a 420 $GtCO_2$ remaining carbon budget (*high confidence*). The ±400 $GtCO_2$ geophysical uncertainty range surrounding a carbon budget translates into a variation of this timing of carbon neutrality of roughly ±15–20 years. If emissions do not start declining in the next decade, the point of carbon neutrality would need to be reached at least two decades earlier to remain within the same carbon budget. {2.2.2, 2.3.5}

Non-CO_2 emissions contribute to peak warming and thus affect the remaining carbon budget. The evolution of methane and sulphur dioxide emissions strongly influences the chances of limiting warming to 1.5°C. In the near-term, a weakening of aerosol cooling would add to future warming, but can be tempered by reductions in methane emissions (*high confidence*). Uncertainty in radiative forcing estimates (particularly aerosol) affects carbon budgets and the certainty of pathway categorizations. Some non-CO_2 forcers are emitted alongside CO_2, particularly in the energy and transport sectors, and can be largely addressed through CO_2 mitigation. Others require specific measures, for example, to target agricultural nitrous oxide (N_2O) and methane (CH_4), some sources of black carbon, or hydrofluorocarbons (*high confidence*). In many cases, non-CO2 emissions reductions are similar in 2°C pathways, indicating reductions near their assumed maximum potential by integrated assessment models. Emissions of N_2O and NH_3 increase in some pathways with strongly increased bioenergy demand. {2.2.2, 2.3.1, 2.4.2, 2.5.3}

The Role of Carbon Dioxide Removal (CDR)

All analysed pathways limiting warming to 1.5°C with no or limited overshoot use CDR to some extent to neutralize emissions from sources for which no mitigation measures have been identified and, in most cases, also to achieve net negative emissions to return global warming to 1.5°C following a peak (*high confidence*). The longer the delay in reducing CO_2 emissions towards zero, the larger the likelihood of exceeding 1.5°C, and the heavier the implied reliance on net negative emissions after mid-century to return warming to 1.5°C (*high confidence*). The faster reduction of net CO_2 emissions in 1.5°C compared to 2°C pathways is predominantly achieved by measures that result in less CO_2 being produced and emitted, and only to a smaller degree through additional CDR. Limitations on the speed, scale and societal acceptability of CDR deployment also limit the conceivable extent of temperature overshoot. Limits to our understanding of how the carbon cycle responds to net negative emissions increase the uncertainty about the effectiveness of CDR to decline temperatures after a peak. {2.2, 2.3, 2.6, 4.3.7}

CDR deployed at scale is unproven, and reliance on such technology is a major risk in the ability to limit warming to 1.5°C. CDR is needed less in pathways with particularly strong emphasis on energy efficiency and low demand. The scale and type of CDR deployment varies widely across 1.5°C pathways, with different consequences for achieving sustainable development objectives (*high confidence*). Some pathways rely more on bioenergy with carbon capture and storage (BECCS), while others rely more on afforestation, which are the two CDR methods most often included in integrated pathways. Trade-offs with other sustainability objectives occur predominantly through increased land, energy, water and investment demand. Bioenergy use is substantial in 1.5°C pathways with or without BECCS due to its multiple roles in decarbonizing energy use. {2.3.1, 2.5.3, 2.6.3, 4.3.7}

Properties of Energy and Land Transitions in 1.5°C Pathways

The share of primary energy from renewables increases while coal usage decreases across pathways limiting warming to 1.5°C with no or limited overshoot (*high confidence*). By 2050, renewables (including bioenergy, hydro, wind, and solar, with direct-equivalence method) supply a share of 52–67% (interquartile range) of primary energy in 1.5°C pathways with no or limited overshoot; while the share from coal decreases to 1–7% (interquartile range), with a large fraction of this coal use combined with carbon capture and storage (CCS). From 2020 to 2050 the primary energy supplied by oil declines in most pathways (–39 to –77% interquartile range). Natural gas changes by –13% to –62% (interquartile range), but some pathways show a marked increase albeit with widespread deployment of CCS. The overall deployment of CCS varies widely across 1.5°C pathways with no or limited overshoot, with cumulative CO_2 stored through 2050 ranging from zero up to 300 $GtCO_2$ (minimum–maximum range), of which zero up to 140 $GtCO_2$ is stored from biomass. Primary energy supplied by bioenergy ranges from 40–310 EJ yr^{-1} in 2050 (minimum-maximum range), and nuclear from 3–66 EJ yr^{-1} (minimum–maximum range). These ranges reflect both uncertainties in technological development and strategic mitigation portfolio choices. {2.4.2}

1.5°C pathways with no or limited overshoot include a rapid decline in the carbon intensity of electricity and an increase in electrification of energy end use (*high confidence*). By 2050, the carbon intensity of electricity decreases to –92 to +11 $gCO_2\ MJ^{-1}$ (minimum–maximum range) from about 140 $gCO_2\ MJ^{-1}$ in 2020, and electricity covers 34–71% (minimum–maximum range) of final energy across 1.5°C pathways with no or limited overshoot from about 20% in 2020. By 2050, the share of electricity supplied by renewables increases to 59–97% (minimum-maximum range) across 1.5°C pathways with no or limited overshoot. Pathways with higher chances of holding warming to below 1.5°C generally show a faster decline in the carbon intensity of electricity by 2030 than pathways that temporarily overshoot 1.5°C. {2.4.1, 2.4.2, 2.4.3}

Transitions in global and regional land use are found in all pathways limiting global warming to 1.5°C with no or limited overshoot, but their scale depends on the pursued mitigation portfolio (*high confidence*). Pathways that limit global warming to 1.5°C with no or limited overshoot project a 4 million km^2 reduction to a 2.5 million km2 increase of non-pasture agricultural land for food and feed crops and a 0.5–11 million km^2 reduction of pasture land, to be converted into 0-6 million km^2 of agricultural land for energy crops and a 2 million km^2 reduction to 9.5 million km^2 increase in forests by 2050 relative to 2010 (*medium confidence*). Land-use transitions of similar magnitude can be observed in modelled 2°C pathways (*medium confidence*). Such large transitions pose profound challenges for sustainable management of the various demands on land for human settlements, food, livestock feed, fibre, bioenergy, carbon storage, biodiversity and other ecosystem services (*high confidence*). {2.3.4, 2.4.4}

Demand-Side Mitigation and Behavioural Changes

Demand-side measures are key elements of 1.5°C pathways. Lifestyle choices lowering energy demand and the land- and GHG-intensity of food consumption can further support achievement of 1.5°C pathways (*high confidence*). By 2030 and 2050, all end-use sectors (including building, transport, and industry) show marked energy demand reductions in modelled 1.5°C pathways, comparable and beyond those projected in 2°C pathways. Sectoral models support the scale of these reductions. {2.3.4, 2.4.3, 2.5.1}

Links between 1.5°C Pathways and Sustainable Development

Choices about mitigation portfolios for limiting warming to 1.5°C can positively or negatively impact the achievement of other societal objectives, such as sustainable development (*high confidence*). In particular, demand-side and efficiency measures, and lifestyle choices that limit energy, resource, and GHG-intensive food demand support sustainable development (*medium confidence*). Limiting warming to 1.5°C can be achieved synergistically with poverty alleviation and improved energy security and can provide large public health benefits through improved air quality, preventing millions of premature deaths. However, specific mitigation measures, such as bioenergy, may result in trade-offs that require consideration. {2.5.1, 2.5.2, 2.5.3}

2.1 Introduction to Mitigation Pathways and the Sustainable Development Context

This chapter assesses the literature on mitigation pathways to limit or return global mean warming to 1.5°C (relative to the pre-industrial base period 1850–1900). Key questions addressed are: What types of mitigation pathways have been developed that could be consistent with 1.5°C? What changes in emissions, energy and land use do they entail? What do they imply for climate policy and implementation, and what impacts do they have on sustainable development? In terms of feasibility (see Cross-Chapter Box 3 in Chapter 1), this chapter focuses on geophysical dimensions and technological and economic enabling factors. Social and institutional dimensions as well as additional aspects of technical feasibility are covered in Chapter 4.

Mitigation pathways are typically designed to reach a predefined climate target alone. Minimization of mitigation expenditures, but not climate-related damages or sustainable development impacts, is often the basis for these pathways to the desired climate target (see Cross-Chapter Box 5 in this chapter for additional discussion). However, there are interactions between mitigation and multiple other sustainable development goals (see Sections 1.1 and 5.4) that provide both challenges and opportunities for climate action. Hence there are substantial efforts to evaluate the effects of the various mitigation pathways on sustainable development, focusing in particular on aspects for which integrated assessment models (IAMs) provide relevant information (e.g., land-use changes and biodiversity, food security, and air quality). More broadly, there are efforts to incorporate climate change mitigation as one of multiple objectives that, in general, reflect societal concerns more completely and could potentially provide benefits at lower costs than simultaneous single-objective policies (e.g., Clarke et al., 2014). For example, with carefully selected policies, universal energy access can be achieved while simultaneously reducing air pollution and mitigating climate change (McCollum et al., 2011; Riahi et al., 2012; IEA, 2017d). This chapter thus presents both the pathways and an initial discussion of their context within sustainable development objectives (Section 2.5), with the latter, along with equity and ethical issues, discussed in more detail in Chapter 5.

As described in Cross-Chapter Box 1 in Chapter 1, scenarios are comprehensive, plausible, integrated descriptions of possible futures based on specified, internally consistent underlying assumptions, with pathways often used to describe the clear temporal evolution of specific scenario aspects or goal-oriented scenarios. We include both these usages of 'pathways' here.

2.1.1 Mitigation Pathways Consistent with 1.5°C

Emissions scenarios need to cover all sectors and regions over the 21st century to be associated with a climate change projection out to 2100. Assumptions regarding future trends in population, consumption of goods and services (including food), economic growth, behaviour, technology, policies and institutions are all required to generate scenarios (Section 2.3.1). These societal choices must then be linked to the drivers of climate change, including emissions of well-mixed greenhouse gases and aerosol and ozone precursors as well as land-use and land-cover changes. Deliberate solar radiation modification is not included in these scenarios (see Cross-Chapter Box 10 in Chapter 4).

Plausible developments need to be anticipated in many facets of the key sectors of energy and land use. Within energy, these scenarios consider energy resources like biofuels, energy supply and conversion technologies, energy consumption, and supply and end-use efficiency. Within land use, agricultural productivity, food demand, terrestrial carbon management, and biofuel production are all considered. Climate policies are also considered, including carbon pricing and technology policies such as research and development funding and subsidies. The scenarios incorporate regional differentiation in sectoral and policy development. The climate changes resulting from such scenarios are derived using models that typically incorporate physical understanding of the carbon cycle and climate response derived from complex geophysical models evaluated against observations (Sections 2.2 and 2.6).

The temperature response to a given emission pathway (see glossary) is uncertain and therefore quantified in terms of a probabilistic outcome. Chapter 1 assesses the climate objectives of the Paris Agreement in terms of human-induced warming, thus excluding potential impacts of natural forcing such as volcanic eruptions or solar output changes or unforced internal variability. Temperature responses in this chapter are assessed using simple geophysically based models that evaluate the anthropogenic component of future temperature change and do not incorporate internal natural variations and are thus fit for purpose in the context of this assessment (Section 2.2.1). Hence a scenario that is consistent with 1.5°C may in fact lead to either a higher or lower temperature change, but within quantified and generally well-understood bounds (see also Chapter 1, Section 1.2.3). Consistency with avoiding a human-induced temperature change limit must therefore also be defined probabilistically, with likelihood values selected based on risk-avoidance preferences. Responses beyond global mean temperature are not typically evaluated in such models and are assessed in Chapter 3.

2.1.2 The Use of Scenarios

Variations in scenario assumptions and design define to a large degree which questions can be addressed with a specific scenario set, for example, the exploration of implications of delayed climate mitigation action. In this assessment, the following classes of 1.5°C- and 2°C-consistent scenarios are of particular interest to the topics addressed in this chapter: (i) scenarios with the same climate target over the 21st century but varying socio-economic assumptions (Sections 2.3 and 2.4), (ii) pairs of scenarios with similar socio-economic assumptions but with forcing targets aimed at 1.5°C and 2°C (Section 2.3), and (iii) scenarios that follow the Nationally Determined Contributions or NDCs[2] until 2030 with much more stringent mitigation action thereafter (Section 2.3.5).

[2] Current pledges include those from the United States although they have stated their intention to withdraw in the future.

Characteristics of these pathways, such as emissions reduction rates, time of peaking, and low-carbon energy deployment rates, can be assessed as being consistent with 1.5°C. However, they cannot be assessed as 'requirements' for 1.5°C, unless a targeted analysis is available that specifically asked whether there could be other 1.5°C-consistent pathways without the characteristics in question. AR5 already assessed such targeted analyses, for example, asking which technologies are important in order to keep open the possibility of limiting warming to 2°C (Clarke et al., 2014). By now, several such targeted analyses are also available for questions related to 1.5°C (Luderer et al., 2013; Rogelj et al., 2013b; Bauer et al., 2018; Strefler et al., 2018b; van Vuuren et al., 2018). This assessment distinguishes between 'consistent' and the much stronger concept of required characteristics of 1.5°C pathways wherever possible.

Ultimately, society will adjust the choices it makes as new information becomes available and technical learning progresses, and these adjustments can be in either direction. Earlier scenario studies have shown, however, that deeper emissions reductions in the near term hedge against the uncertainty of both climate response and future technology availability (Luderer et al., 2013; Rogelj et al., 2013b; Clarke et al., 2014). Not knowing what adaptations might be put in place in the future, and due to limited studies, this chapter examines prospective rather than iteratively adaptive mitigation pathways (Cross-Chapter Box 1 in Chapter 1). Societal choices illustrated by scenarios may also influence what futures are envisioned as possible or desirable and hence whether those come into being (Beck and Mahony, 2017).

2.1.3 New Scenario Information since AR5

In this chapter, we extend the AR5 mitigation pathway assessment based on new scenario literature. Updates in understanding of climate sensitivity, transient climate response, radiative forcing, and the cumulative carbon budget consistent with 1.5°C are discussed in Sections 2.2.

Mitigation pathways developed with detailed process-based integrated assessment models (IAMs) covering all sectors and regions over the 21st century describe an internally consistent and calibrated (to historical trends) way to get from current developments to meeting long-term climate targets like 1.5°C (Clarke et al., 2014). The overwhelming majority of available 1.5°C pathways were generated by such IAMs, and these pathways can be directly linked to climate outcomes and their consistency with the 1.5°C goal evaluated. The AR5 similarly relied upon such studies, which were mainly discussed in Chapter 6 of Working Group III (WGIII) (Clarke et al., 2014).

Since the AR5, several new, integrated multimodel studies have appeared in the literature that explore specific characteristics of scenarios more stringent than the lowest scenario category assessed in AR5 that was assessed to limit warming below 2°C with greater than 66% likelihood (Rogelj et al., 2015b, 2018; Akimoto et al., 2017; Marcucci et al., 2017; Su et al., 2017; Bauer et al., 2018; Bertram et al., 2018; Grubler et al., 2018; Holz et al., 2018b; Kriegler et al., 2018a; Liu et al., 2018; Luderer et al., 2018; Strefler et al., 2018a; van Vuuren et al., 2018; Vrontisi et al., 2018; Zhang et al., 2018). Those scenarios explore 1.5°C-consistent pathways from multiple perspectives (see Supplementary Material 2.SM.1.3), examining sensitivity to assumptions regarding:

- socio-economic drivers and developments including energy and food demand as, for example, characterized by the Shared Socio-Economic Pathways (SSPs; Cross-Chapter Box 1 in Chapter 1)
- near-term climate policies describing different levels of strengthening the NDCs
- the use of bioenergy and the availability and desirability of carbon dioxide removal (CDR) technologies

A large number of these scenarios were collected in a scenario database established for the assessment of this Special Report (Supplementary Material 2.SM.1.3). Mitigation pathways were classified by four factors: consistency with a temperature increase limit (as defined by Chapter 1), whether they temporarily overshoot that limit, the extent of this potential overshoot, and the likelihood of falling within these bounds.

Specifically, they were put into classes that either kept surface temperature increases below a given threshold throughout the 21st century or returned to a value below 1.5°C above pre-industrial levels at some point before 2100 after temporarily exceeding that level earlier – referred to as an overshoot (OS). Both groups were further separated based on the probability of being below the threshold and the degree of overshoot, respectively (Table 2.1). Pathways are uniquely classified, with 1.5°C-related classes given higher priority than 2°C classes in cases where a pathway would be applicable to either class.

The probability assessment used in the scenario classification is based on simulations using two reduced-complexity carbon cycle, atmospheric composition, and climate models: the 'Model for the Assessment of Greenhouse Gas-Induced Climate Change' (MAGICC) (Meinshausen et al., 2011a), and the 'Finite Amplitude Impulse Response' (FAIRv1.3) model (Smith et al., 2018). For the purpose of this report, and to facilitate comparison with AR5, the range of the key carbon cycle and climate parameters for MAGICC and its setup are identical to those used in AR5 WGIII (Clarke et al., 2014). For each mitigation pathway, MAGICC and FAIR simulations provide probabilistic estimates of atmospheric concentrations, radiative forcing and global temperature outcomes until 2100. However, the classification uses MAGICC probabilities directly for traceability with AR5 and because this model is more established in the literature. Nevertheless, the overall uncertainty assessment is based on results from both models, which are considered in the context of the latest radiative forcing estimates and observed temperatures (Etminan et al., 2016; Smith et al., 2018) (Section 2.2 and Supplementary Material 2.SM.1.1). The comparison of these lines of evidence shows *high agreement* in the relative temperature response of pathways, with *medium agreement* on the precise absolute magnitude of warming, introducing a level of imprecision in these attributes. Consideration of the combined evidence here leads to *medium confidence* in the overall geophysical characteristics of the pathways reported here.

In addition to the characteristics of the above-mentioned classes, four illustrative pathway archetypes have been selected and are used throughout this chapter to highlight specific features of and variations across 1.5°C pathways. These are chosen in particular to illustrate the spectrum of CO_2 emissions reduction patterns consistent with 1.5°C,

Table 2.1 | Classification of pathways that this chapter draws upon, along with the number of available pathways in each class. The definition of each class is based on probabilities derived from the MAGICC model in a setup identical to AR5 WGIII (Clarke et al., 2014), as detailed in Supplementary Material 2.SM.1.4.

Pathway group	Pathway Class	Pathway Selection Criteria and Description	Number of Scenarios	Number of Scenarios
1.5°C or 1.5°C-consistent**	Below-1.5°C	Pathways limiting peak warming to below 1.5°C during the entire 21st century with 50–66% likelihood*	9	90
	1.5°C-low-OS	Pathways limiting median warming to below 1.5°C in 2100 and with a 50–67% probability of temporarily overshooting that level earlier, generally implying less than 0.1°C higher peak warming than Below-1.5°C pathways	44	
	1.5°C-high-OS	Pathways limiting median warming to below 1.5°C in 2100 and with a greater than 67% probability of temporarily overshooting that level earlier, generally implying 0.1–0.4°C higher peak warming than Below-1.5°C pathways	37	
2°C or 2°C-consistent	Lower-2°C	Pathways limiting peak warming to below 2°C during the entire 21st century with greater than 66% likelihood	74	132
	Higher-2°C	Pathways assessed to keep peak warming to below 2°C during the entire 21st century with 50–66% likelihood	58	

* No pathways were available that achieve a greater than 66% probability of limiting warming below 1.5°C during the entire 21st century based on the MAGICC model projections.

** This chapter uses the term 1.5°C-consistent pathways to refer to pathways with no overshoot, with limited (low) overshoot, and with high overshoot. However, the Summary for Policymakers focusses on pathways with no or limited (low) overshoot.

ranging from very rapid and deep near-term decreases, facilitated by efficiency and demand-side measures that lead to limited CDR requirements, to relatively slower but still rapid emissions reductions that lead to a temperature overshoot and necessitate large CDR deployment later in the century (Section 2.3).

2.1.4 Utility of Integrated Assessment Models (IAMs) in the Context of this Report

IAMs lie at the basis of the assessment of mitigation pathways in this chapter, as much of the quantitative global scenario literature is derived with such models. IAMs combine insights from various disciplines in a single framework, resulting in a dynamic description of the coupled energy–economy–land-climate system that cover the largest sources of anthropogenic greenhouse gas (GHG) emissions from different sectors. Many of the IAMs that contributed mitigation scenarios to this assessment include a process-based description of the land system in addition to the energy system (e.g., Popp et al., 2017), and several have been extended to cover air pollutants (Rao et al., 2017) and water use (Hejazi et al., 2014; Fricko et al., 2016; Mouratiadou et al., 2016). Such integrated pathways hence allow the exploration of the whole-system transformation, as well as the interactions, synergies, and trade-offs between sectors, and, increasingly, questions beyond climate mitigation (von Stechow et al., 2015). The models do not, however, fully account for all constraints that could affect realization of pathways (see Chapter 4).

Section 2.3 assesses the overall characteristics of 1.5°C pathways based on fully integrated pathways, while Sections 2.4 and 2.5 describe underlying sectoral transformations, including insights from sector-specific assessment models and pathways that are not derived from IAMs. Such models provide detail in their domain of application and make exogenous assumptions about cross-sectoral or global factors. They often focus on a specific sector, such as the energy (Bruckner et al., 2014; IEA, 2017a; Jacobson, 2017; OECD/IEA and IRENA, 2017), buildings (Lucon et al., 2014) or transport (Sims et al., 2014) sector, or a specific country or region (Giannakidis et al., 2018). Sector-specific pathways are assessed in relation to integrated pathways because they cannot be directly linked to 1.5°C by themselves if they do not extend to 2100 or do not include all GHGs or aerosols from all sectors.

AR5 found sectoral 2°C decarbonization strategies from IAMs to be consistent with sector-specific studies (Clarke et al., 2014). A growing body of literature on 100%-renewable energy scenarios has emerged (e.g., see Creutzig et al., 2017; Jacobson et al., 2017), which goes beyond the wide range of IAM projections of renewable energy shares in 1.5°C and 2°C pathways. While the representation of renewable energy resource potentials, technology costs and system integration in IAMs has been updated since AR5, leading to higher renewable energy deployments in many cases (Luderer et al., 2017; Pietzcker et al., 2017), none of the IAM projections identify 100% renewable energy solutions for the global energy system as part of cost-effective mitigation pathways (Section 2.4.2). Bottom-up studies find higher mitigation potentials in the industry, buildings, and transport sectors in 2030 than realized in selected 2°C pathways from IAMs (UNEP 2017), indicating the possibility to strengthen sectoral decarbonization strategies until 2030 beyond the integrated 1.5°C pathways assessed in this chapter (Luderer et al., 2018).

Detailed, process-based IAMs are a diverse set of models ranging from partial equilibrium energy–land models to computable general equilibrium models of the global economy, from myopic to perfect foresight models, and from models with to models without endogenous technological change (Supplementary Material 2.SM.1.2). The IAMs used in this chapter have limited to no coverage of climate impacts. They typically use GHG pricing mechanisms to induce emissions reductions and associated changes in energy and land uses consistent with the imposed climate goal. The scenarios generated by these models are defined by the choice of climate goals and assumptions about near-term climate policy developments. They are also shaped by assumptions about mitigation potentials and technologies as well as baseline developments such as, for example, those represented by different Shared Socio-Economic Pathways (SSPs), especially those pertaining to energy and food demand (Riahi et al., 2017). See Section 2.3.1 for discussion of these assumptions. Since the AR5, the scenario literature has greatly expanded the exploration of these dimensions. This includes low-demand scenarios (Grubler et al., 2018; van Vuuren et al., 2018), scenarios taking into account a larger set of sustainable development goals (Bertram et al., 2018), scenarios with restricted availability of CDR technologies (Bauer et al., 2018; Grubler et al., 2018; Holz et al., 2018b; Kriegler et al., 2018a; Strefler et al., 2018b; van Vuuren et al., 2018), scenarios with near-term action dominated by regulatory policies (Kriegler et al., 2018a) and scenario variations across the SSPs (Riahi et al., 2017; Rogelj et al., 2018). IAM results depend upon multiple underlying assumptions, for example, the extent to which global markets and economies are assumed to operate frictionless and policies are cost-optimized, assumptions about technological progress and availability and costs of mitigation and CDR measures, assumptions about underlying socio-economic developments and future energy, food and materials demand, and assumptions about the geographic and temporal pattern of future regulatory and carbon pricing policies (see Supplementary Material 2.SM.1.2 for additional discussion on IAMs and their limitations).

2.2 Geophysical Relationships and Constraints

Emissions pathways can be characterized by various geophysical characteristics, such as radiative forcing (Masui et al., 2011; Riahi et al., 2011; Thomson et al., 2011; van Vuuren et al., 2011b), atmospheric concentrations (van Vuuren et al., 2007, 2011a; Clarke et al., 2014) or associated temperature outcomes (Meinshausen et al., 2009; Rogelj et al., 2011; Luderer et al., 2013). These attributes can be used to derive geophysical relationships for specific pathway classes, such as cumulative CO_2 emissions compatible with a specific level of warming, also known as 'carbon budgets' (Meinshausen et al., 2009; Rogelj et al., 2011; Stocker et al., 2013; Friedlingstein et al., 2014a), the consistent contributions of non-CO_2 GHGs and aerosols to the remaining carbon budget (Bowerman et al., 2011; Rogelj et al., 2015a, 2016b), or to temperature outcomes (Lamarque et al., 2011; Bowerman et al., 2013; Rogelj et al., 2014b). This section assesses geophysical relationships for both CO_2 and non-CO_2 emissions (see glossary).

2.2.1 Geophysical Characteristics of Mitigation Pathways

This section employs the pathway classification introduced in Section 2.1, with geophysical characteristics derived from simulations with the MAGICC reduced-complexity carbon cycle and climate model and supported by simulations with the FAIR reduced-complexity model (Section 2.1). Within a specific category and between models, there remains a large degree of variance. Most pathways exhibit a temperature overshoot which has been highlighted in several studies focusing on stringent mitigation pathways (Huntingford and Lowe, 2007; Wigley et al., 2007; Nohara et al., 2015; Rogelj et al., 2015d; Zickfeld and Herrington, 2015; Schleussner et al., 2016; Xu and Ramanathan, 2017). Only very few of the scenarios collected in the database for this report hold the average future warming projected by MAGICC below 1.5°C during the entire 21st century (Table 2.1, Figure 2.1). Most 1.5°C-consistent pathways available in the database overshoot 1.5°C around mid-century before peaking and then reducing temperatures so as to return below that level in 2100. However, because of numerous geophysical uncertainties and model dependencies (Section 2.2.1.1, Supplementary Material 2.SM.1.1), absolute temperature characteristics of the various pathway categories are more difficult to distinguish than relative features (Figure 2.1, Supplementary Material 2.SM.1.1), and actual probabilities of overshoot are imprecise. However, all lines of evidence available for temperature projections indicate a probability greater than 50% of overshooting 1.5°C by mid-century in all but the most stringent pathways currently available (Supplementary Material 2.SM.1.1, 2.SM.1.4).

Most 1.5°C-consistent pathways exhibit a peak in temperature by mid-century whereas 2°C-consistent pathways generally peak after 2050 (Supplementary Material 2.SM.1.4). The peak in median temperature in the various pathway categories occurs about ten years before reaching net zero CO_2 emissions due to strongly reduced annual CO_2 emissions and deep reductions in CH_4 emissions (Section 2.3.3). The two reduced-complexity climate models used in this assessment suggest that virtually all available 1.5°C-consistent pathways peak and then decline global mean temperature, but with varying rates of temperature decline after the peak (Figure 2.1). The estimated decadal rates of temperature change by the end of the century are smaller than the amplitude of the climate variability as assessed in AR5 (1 standard deviation of about ±0.1°C), which hence complicates the detection of a global peak and decline of warming in observations on time scales of one to two decades (Bindoff et al., 2013). In comparison, many pathways limiting warming to 2°C or higher by 2100 still have noticeable increasing trends at the end of the century, and thus imply continued warming.

By 2100, the difference between 1.5°C- and 2°C-consistent pathways becomes clearer compared to mid-century, not only for the temperature response (Figure 2.1) but also for atmospheric CO_2 concentrations. In 2100, the median CO_2 concentration in 1.5°C-consistent pathways is below 2016 levels (Le Quéré et al., 2018), whereas it remains higher by about 5–10% compared to 2016 in the 2°C-consistent pathways.

2.2.1.1 Geophysical uncertainties: non-CO_2 forcing agents

Impacts of non-CO_2 climate forcers on temperature outcomes are particularly important when evaluating stringent mitigation pathways (Weyant et al., 2006; Shindell et al., 2012; Rogelj et al., 2014b, 2015a; Samset et al., 2018). However, many uncertainties affect the role of non-CO_2 climate forcers in stringent mitigation pathways.

A first uncertainty arises from the magnitude of the radiative forcing attributed to non-CO_2 climate forcers. Figure 2.2 illustrates how, for one representative 1.5°C-consistent pathway (SSP2-1.9) (Fricko et al., 2017; Rogelj et al., 2018), the effective radiative forcings as estimated by MAGICC and FAIR can differ (see Supplementary Material 2.SM1.1 for further details). This large spread in non-CO_2 effective radiative forcings leads to considerable uncertainty in the predicted temperature response. This uncertainty ultimately affects the assessed temperature outcomes for pathway classes used in this chapter (Section 2.1) and also affects the carbon budget (Section 2.2.2). Figure 2.2 highlights

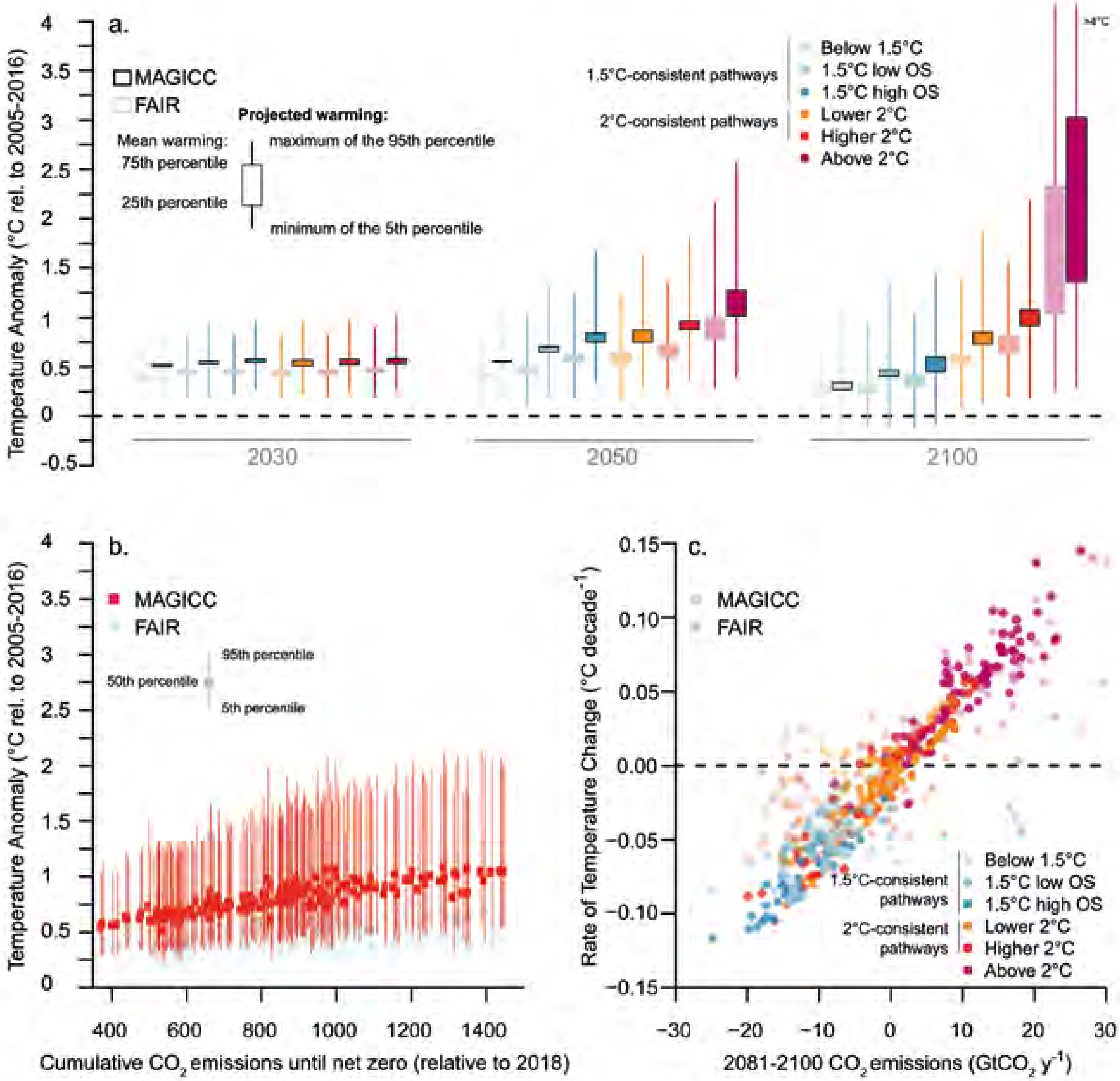


Figure 2.1 | Pathways classification overview. (a) Average global mean temperature increase relative to 2010 as projected by FAIR and MAGICC in 2030, 2050 and 2100; (b) response of peak warming to cumulative CO_2 emissions until net zero by MAGICC (red) and FAIR (blue); (c) decadal rate of average global mean temperature change from 2081 to 2100 as a function of the annual CO_2 emissions averaged over the same period as given by FAIR (transparent squares) and MAGICC (filled circles). In panel (a), horizontal lines at 0.63°C and 1.13°C are indicative of the 1.5°C and 2°C warming thresholds with the respect to 1850–1900, taking into account the assessed historical warming of 0.87°C ±0.12°C between the 1850–1900 and 2006–2015 periods (Chapter 1, Section 1.2.1). In panel (a), vertical lines illustrate both the physical and the scenario uncertainty as captured by MAGICC and FAIR and show the minimal warming of the 5th percentile of projected warming and the maximal warming of the 95th percentile of projected warming per scenario class. Boxes show the interquartile range of mean warming across scenarios, and thus represent scenario uncertainty only.

the important role of methane emissions reduction in this scenario, in agreement with the recent literature focussing on stringent mitigation pathways (Shindell et al., 2012; Rogelj et al., 2014b, 2015a; Stohl et al., 2015; Collins et al., 2018).

For mitigation pathways that aim at halting and reversing radiative forcing increase during this century, the aerosol radiative forcing is a considerable source of uncertainty (Figure 2.2) (Samset et al., 2018; Smith et al., 2018). Indeed, reductions in SO_2 (and NO_x) emissions largely associated with fossil-fuel burning are expected to reduce the cooling effects of both aerosol radiative interactions and aerosol cloud interactions, leading to warming (Myhre et al., 2013; Samset et al., 2018). A multimodel analysis (Myhre et al., 2017) and a study based on observational constraints (Malavelle et al., 2017) largely support the AR5 best estimate and uncertainty range of aerosol forcing. The partitioning of total aerosol radiative forcing between aerosol precursor emissions is important (Ghan et al., 2013; Jones et al., 2018; Smith et al., 2018) as this affects the estimate of the mitigation potential from different sectors that have aerosol precursor emission sources. The total aerosol effective radiative forcing change in stringent mitigation pathways is expected to be dominated by the effects from the phase-out of SO_2, although the magnitude of this aerosol-warming effect depends on how much of the present-day aerosol cooling is attributable to SO_2, particularly the cooling associated with aerosol–cloud interaction (Figure 2.2). Regional differences in the linearity of aerosol–cloud interactions (Carslaw et al., 2013; Kretzschmar et al., 2017) make it difficult to separate the role of individual precursors. Precursors that are not fully mitigated will continue to affect the Earth system. If, for example, the role of nitrate aerosol cooling is at the strongest end of the assessed IPCC AR5 uncertainty range, future temperature increases may be more modest if ammonia emissions continue to rise (Hauglustaine et al., 2014).

Figure 2.2 shows that there are substantial differences in the evolution of estimated effective radiative forcing of non-CO_2 forcers between MAGICC and FAIR. These forcing differences result in MAGICC simulating a larger warming trend in the near term compared to both the FAIR model and the recent observed trends of 0.2°C per decade reported in Chapter 1 (Figure 2.1, Supplementary Material 2.SM.1.1.1, Chapter 1, Section 1.2.1.3). The aerosol effective forcing is stronger in MAGICC compared to either FAIR or the AR5 best estimate, though it is still well within the AR5 uncertainty range (Supplementary Material 2.SM.1.1.1). A recent revision (Etminan et al., 2016) increases the methane forcing by 25%. This revision is used in the FAIR but not in the AR5 setup of MAGICC that is applied here. Other structural differences exist in how the two models relate emissions to concentrations that contribute to differences in forcing (see Supplementary Material 2.SM.1.1.1).

Non-CO_2 climate forcers exhibit a greater geographical variation in radiative forcings than CO_2, which leads to important uncertainties in the temperature response (Myhre et al., 2013). This uncertainty increases the relative uncertainty of the temperature pathways associated with low emission scenarios compared to high emission scenarios (Clarke et al., 2014). It is also important to note that geographical patterns of temperature change and other climate responses, especially those related to precipitation, depend significantly on the forcing mechanism (Myhre et al., 2013; Shindell et al., 2015; Marvel et al., 2016; Samset et al., 2016) (see also Chapter 3, Section 3.6.2.2).

2.2.1.2 Geophysical uncertainties: climate and Earth system feedbacks

Climate sensitivity uncertainty impacts future projections as well as carbon-budget estimates (Schneider et al., 2017). AR5 assessed the equilibrium climate sensitivity (ECS) to be *likely* in the 1.5°–4.5°C range, *extremely unlikely* less than 1°C and *very unlikely* greater than 6°C. The lower bound of this estimate is lower than the range of CMIP5 models (Collins et al., 2013). The evidence for the 1.5°C lower bound on ECS in AR5 was based on analysis of energy-budget changes over the historical period. Work since AR5 has suggested that the climate sensitivity inferred from such changes has been lower than the 2 × CO_2 climate sensitivity for known reasons (Forster, 2016; Gregory and Andrews, 2016; Rugenstein et al., 2016; Armour, 2017; Ceppi and Gregory, 2017; Knutti et al., 2017; Proistosescu and Huybers, 2017). Both a revised interpretation of historical estimates and other lines of evidence based on analysis of climate models with the best representation of today's climate (Sherwood et al., 2014; Zhai et al., 2015; Tan et al., 2016; Brown and Caldeira, 2017; Knutti

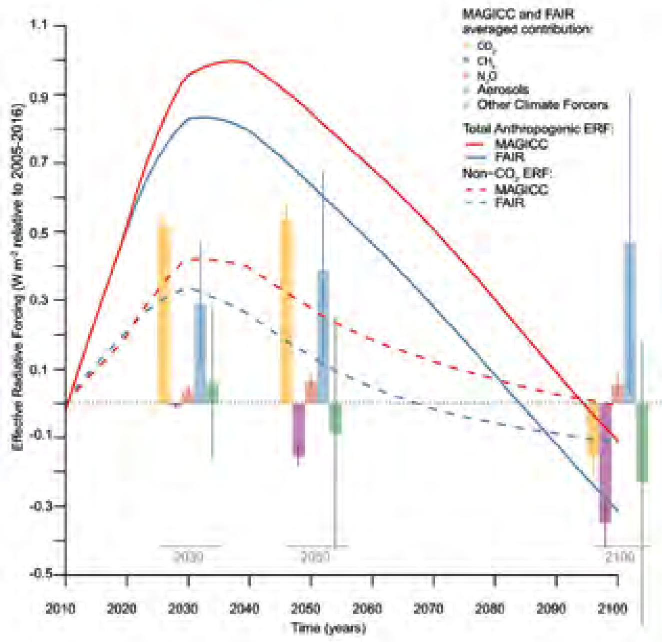


Figure 2.2 | Changes and uncertainties in effective radiative forcings (ERF) for one 1.5°C-consistent pathway (SSP2-19) as estimated by MAGICC and FAIR. The lines are indicative of the total effective radiative forcing from all anthropogenic sources (solid lines) and for non-CO^2 agents only (dashed lines), as represented by MAGICC (red) and FAIR (blue) relative to 2010, respectively. Vertical bars show the mean radiative forcing as predicted by MAGICC and FAIR of relevant non-CO_2 agents for year 2030, 2050 and 2100. The vertical lines give the uncertainty (1 standard deviation) of the ERFs for the represented species.

et al., 2017) suggest that the lower bound of ECS could be revised upwards, which would decrease the chances of limiting warming below 1.5°C in assessed pathways. However, such a reassessment has been challenged (Lewis and Curry, 2018), albeit from a single line of evidence. Nevertheless, it is premature to make a major revision to the lower bound. The evidence for a possible revision of the upper bound on ECS is less clear, with cases argued from different lines of evidence for both decreasing (Lewis and Curry, 2015, 2018; Cox et al., 2018) and increasing (Brown and Caldeira, 2017) the bound presented in the literature. The tools used in this chapter employ ECS ranges consistent with the AR5 assessment. The MAGICC ECS distribution has not been selected to explicitly reflect this but is nevertheless consistent (Rogelj et al., 2014a). The FAIR model used here to estimate carbon budgets explicitly constructs log-normal distributions of ECS and transient climate response based on a multi-parameter fit to the AR5 assessed ranges of climate sensitivity and individual historic effective radiative forcings (Smith et al., 2018) (Supplementary Material 2.SM.1.1.1).

Several feedbacks of the Earth system, involving the carbon cycle, non-CO_2 GHGs and/or aerosols, may also impact the future dynamics of the coupled carbon–climate system's response to anthropogenic emissions. These feedbacks are caused by the effects of nutrient limitation (Duce et al., 2008; Mahowald et al., 2017), ozone exposure (de Vries et al., 2017), fire emissions (Narayan et al., 2007) and changes associated with natural aerosols (Cadule et al., 2009; Scott et al., 2018). Among these Earth system feedbacks, the importance of the permafrost feedback's influence has been highlighted in recent studies. Combined evidence from both models (MacDougall et al., 2015; Burke et al., 2017; Lowe and Bernie, 2018) and field studies (like Schädel et al., 2014; Schuur et al., 2015) shows *high agreement* that permafrost thawing will release both CO_2 and CH_4 as the Earth warms, amplifying global warming. This thawing could also release N_2O (Voigt et al., 2017a, b). Field, laboratory and modelling studies estimate that the vulnerable fraction in permafrost is about 5–15% of the permafrost soil carbon (~5300–5600 $GtCO_2$ in Schuur et al., 2015) and that carbon emissions are expected to occur beyond 2100 because of system inertia and the large proportion of slowly decomposing carbon in permafrost (Schädel et al., 2014). Published model studies suggest that a large part of the carbon release to the atmosphere is in the form of CO_2 (Schädel et al., 2016), while the amount of CH4 released by permafrost thawing is estimated to be much smaller than that CO_2. Cumulative CH_4 release by 2100 under RCP2.6 ranges from 0.13 to 0.45 Gt of methane (Burke et al., 2012; Schneider von Deimling et al., 2012, 2015), with fluxes being the highest in the middle of the century because of maximum thermokarst lake extent by mid-century (Schneider von Deimling et al., 2015).

The reduced complexity climate models employed in this assessment do not take into account permafrost or non-CO_2 Earth system feedbacks, although the MAGICC model has a permafrost module that can be enabled. Taking the current climate and Earth system feedbacks understanding together, there is a possibility that these models would underestimate the longer-term future temperature response to stringent emission pathways (Section 2.2.2).

2.2.2 The Remaining 1.5°C Carbon Budget

2.2.2.1 Carbon budget estimates

Since the AR5, several approaches have been proposed to estimate carbon budgets compatible with 1.5°C or 2°C. Most of these approaches indirectly rely on the approximate linear relationship between peak global mean temperature and cumulative emissions of carbon (the transient climate response to cumulative emissions of carbon, TCRE) (Collins et al., 2013; Friedlingstein et al., 2014a; Rogelj et al., 2016b), whereas others base their estimates on equilibrium climate sensitivity (Schneider et al., 2017). The AR5 employed two approaches to determine carbon budgets. Working Group I (WGI) computed carbon budgets from 2011 onwards for various levels of warming relative to the 1861–1880 period using RCP8.5 (Meinshausen et al., 2011b; Stocker et al., 2013), whereas WGIII estimated their budgets from a set of available pathways that were assessed to have a >50% probability to exceed 1.5°C by mid-century, and return to 1.5°C or below in 2100 with greater than 66% probability (Clarke et al., 2014). These differences made AR5 WGI and WGIII carbon budgets difficult to compare as they are calculated over different time periods, are derived from a different sets of multi-gas and aerosol emission scenarios, and use different concepts of carbon budgets (exceedance for WGI, avoidance for WGIII) (Rogelj et al., 2016b; Matthews et al., 2017).

Carbon budgets can be derived from CO_2-only experiments as well as from multi-gas and aerosol scenarios. Some published estimates of carbon budgets compatible with 1.5°C or 2°C refer to budgets for CO_2-induced warming only, and hence do not take into account the contribution of non-CO_2 climate forcers (Allen et al., 2009; Matthews et al., 2009; Zickfeld et al., 2009; IPCC, 2013a). However, because the projected changes in non-CO_2 climate forcers tend to amplify future warming, CO_2-only carbon budgets overestimate the total net cumulative carbon emissions compatible with 1.5°C or 2°C (Friedlingstein et al., 2014a; Rogelj et al., 2016b; Matthews et al., 2017; Mengis et al., 2018; Tokarska et al., 2018).

Since the AR5, many estimates of the remaining carbon budget for 1.5°C have been published (Friedlingstein et al., 2014a; MacDougall et al., 2015; Peters, 2016; Rogelj et al., 2016b, 2018; Matthews et al., 2017; Millar et al., 2017; Goodwin et al., 2018b; Kriegler et al., 2018b; Lowe and Bernie, 2018; Mengis et al., 2018; Millar and Friedlingstein, 2018; Schurer et al., 2018; Séférian et al., 2018; Tokarska and Gillett, 2018; Tokarska et al., 2018). These estimates cover a wide range as a result of differences in the models used, and of methodological choices, as well as physical uncertainties. Some estimates are exclusively model-based while others are based on observations or on a combination of both. Remaining carbon budgets limiting warming below 1.5°C or 2°C that are derived from Earth system models of intermediate complexity (MacDougall et al., 2015; Goodwin et al., 2018a), IAMs (Luderer et al., 2018; Rogelj et al., 2018), or are based on Earth-system model results (Lowe and Bernie, 2018; Séférian et al., 2018; Tokarska and Gillett, 2018) give remaining carbon budgets of the same order of magnitude as the IPCC AR5 Synthesis Report (SYR) estimates (IPCC, 2014a). This is unsurprising as similar sets of models were used for the AR5 (IPCC, 2013b). The range of variation across models stems mainly from either the inclusion or exclusion of specific Earth system feedbacks (MacDougall et al., 2015; Burke et al., 2017; Lowe and Bernie, 2018) or different budget definitions (Rogelj et al., 2018).

In contrast to the model-only estimates discussed above and employed in the AR5, this report additionally uses observations to inform its evaluation of the remaining carbon budget. Table 2.2 shows that the assessed range of remaining carbon budgets consistent with 1.5°C or 2°C is larger than the AR5 SYR estimate and is part way towards estimates constrained by recent observations (Millar et al., 2017; Goodwin et al., 2018a; Tokarska and Gillett, 2018). Figure 2.3 illustrates that the change since AR5 is, in very large part, due to the application of a more recent observed baseline to the historic temperature change and cumulative emissions; here adopting the baseline period of 2006–2015 (see Chapter 1, Section 1.2.1). AR5 SYR Figures SPM.10 and 2.3 already illustrated the discrepancy between models and observations, but did not apply this as a correction to the carbon budget because they were being used to illustrate the overall linear relationship between warming and cumulative carbon emissions in the CMIP5 models since 1870, and were not specifically designed to quantify residual carbon budgets relative to the present for ambitious temperature goals. The AR5 SYR estimate was also dependent on a subset of Earth system models illustrated in Figure 2.3 of this report. Although, as outlined below and in Table 2.2, considerably uncertainties remain, there is *high agreement* across various lines of evidence assessed in this report that the remaining carbon budget for 1.5°C or 2°C would be larger than the estimates at the time of the AR5. However, the overall remaining budget for 2100 is assessed to be smaller than that derived from the recent observational-informed estimates, as Earth system feedbacks such as permafrost thawing reduce the budget applicable to centennial scales (see Section 2.2.2.2).

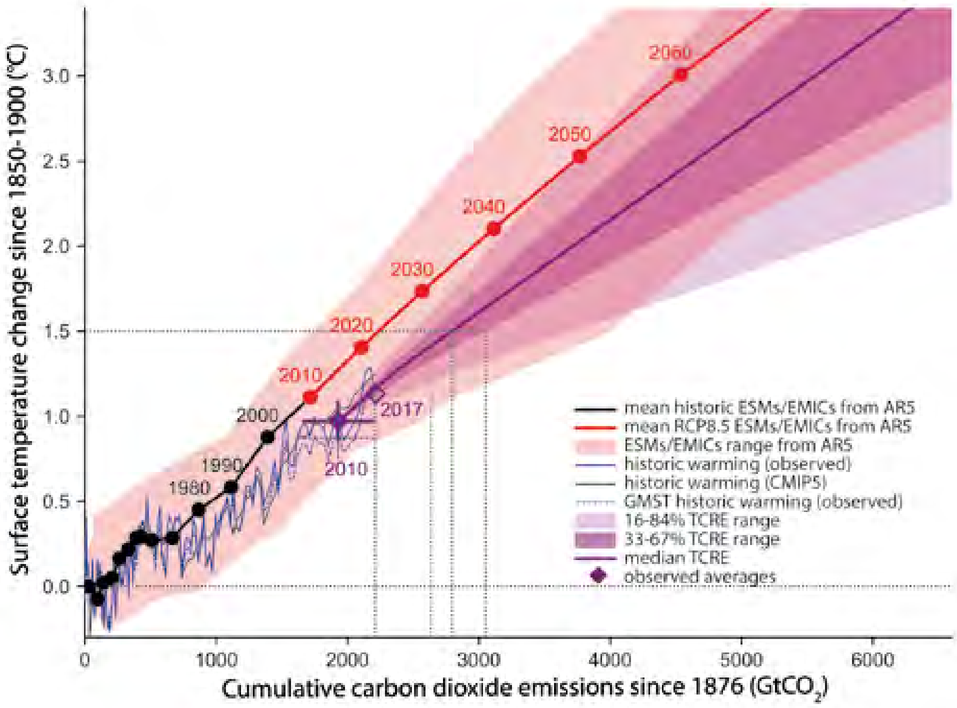


Figure 2.3 | Temperature changes from 1850–1900 versus cumulative CO_2 emissions since 1st January 1876. Solid lines with dots reproduce the globally averaged near-surface air temperature response to cumulative CO_2 emissions plus non-CO_2 forcers as assessed in Figure SPM10 of WGI AR5, except that points marked with years relate to a particular year, unlike in WGI AR5 Figure SPM.10, where each point relates to the mean over the previous decade. The AR5 data was derived from 15 Earth system models and 5 Earth system models of Intermediate Complexity for the historic observations (black) and RCP8.5 scenario (red), and the red shaded plume shows the range across the models as presented in the AR5. The purple shaded plume and the line are indicative of the temperature response to cumulative CO_2 emissions and non-CO_2 warming adopted in this report. The non-CO_2 warming contribution is averaged from the MAGICC and FAIR models, and the purple shaded range assumes the AR5 WGI TCRE distribution (Supplementary Material 2.SM.1.1.2). The 2010 observation of surface temperature change (0.97°C based on 2006–2015 mean compared to 1850–1900, Chapter 1, Section 1.2.1) and cumulative carbon dioxide emissions from 1876 to the end of 2010 of 1,930 $GtCO_2$ (Le Quéré et al., 2018) is shown as a filled purple diamond. The value for 2017 based on the latest cumulative carbon emissions up to the end of 2017 of 2,220 $GtCO_2$ (Version 1.3 accessed 22 May 2018) and a surface temperature anomaly of 1.1°C based on an assumed temperature increase of 0.2°C per decade is shown as a hollow purple diamond. The thin blue line shows annual observations, with CO_2 emissions from Le Quéré et al. (2018) and estimated globally averaged near-surface temperature from scaling the incomplete coverage and blended HadCRUT4 dataset in Chapter 1. The thin black line shows the CMIP5 multimodel mean estimate with CO_2 emissions also from (Le Quéré et al., 2018). The thin black line shows the GMST historic temperature trends from Chapter 1, which give lower temperature changes up to 2006–2015 of 0.87°C and would lead to a larger remaining carbon budget. The dotted black lines illustrate the remaining carbon budget estimates for 1.5°C given in Table 2.2. Note these remaining budgets exclude possible Earth system feedbacks that could reduce the budget, such as CO_2 and CH_4 release from permafrost thawing and tropical wetlands (see Section 2.2.2.2).

2.2.2.2 CO_2 and non-CO_2 contributions to the remaining carbon budget

A remaining carbon budget can be estimated from calculating the amount of CO_2 emissions consistent (given a certain value of TCRE) with an allowable additional amount of warming. Here, the allowable warming is the 1.5°C warming threshold minus the current warming taken as the 2006–2015 average, with a further amount removed to account for the estimated non-CO_2 temperature contribution to the remaining warming (Peters, 2016; Rogelj et al., 2016b). This assessment uses the TCRE range from AR5 WGI (Collins et al., 2013) supported by estimates of non-CO_2 contributions that are based on published methods and integrated pathways (Friedlingstein et al., 2014a; Allen et al., 2016, 2018; Peters, 2016; Smith et al., 2018). Table 2.2 and Figure 2.3 show the assessed remaining carbon budgets and key uncertainties for a set of additional warming levels relative to the 2006–2015 period (see Supplementary Material 2.SM.1.1.2 for details). With an assessed historical warming of 0.87°C ± 0.12°C from 1850–1900 to 2006–2015 (Chapter 1, Section 1.2.1), 0.63°C of additional warming would be approximately consistent with a global mean temperature increase of 1.5°C relative to pre-industrial levels. For this level of additional warming, remaining carbon budgets have been estimated (Table 2.2, Supplementary Material 2.SM.1.1.2).

The remaining carbon budget calculation presented in the Table 2.2 and illustrated in Figure 2.3 does not consider additional Earth system feedbacks such as permafrost thawing. These are uncertain but estimated to reduce the remaining carbon budget by an order of magnitude of about 100 $GtCO_2$ and more thereafter. Accounting for such feedbacks would make the carbon budget more applicable for 2100 temperature targets, but would also increase uncertainty (Table 2.2 and see below). Excluding such feedbacks, the assessed range for the remaining carbon budget is estimated to be 840, 580, and 420 $GtCO_2$ for the 33rd, 50th and, 67th percentile of TCRE, respectively, with a median non-CO_2 warming contribution and starting from 1 January 2018 onward. Consistent with the approach used in the IPCC Fifth Assessment Report (IPCC, 2013b), the latter estimates use global near-surface air temperatures both over the ocean and over land to estimate global surface temperature change since pre-industrial. The global warming from the pre-industrial period until the 2006–2015 reference period is estimated to amount to 0.97°C with an uncertainty range of about ±0.1°C (see Chapter 1, Section 1.2.1). Three methodological improvements lead to these estimates of the remaining carbon budget being about 300 $GtCO_2$ larger than those reported in Table 2.2 of the IPCC AR5 SYR (IPCC, 2014a) (*medium confidence*). The AR5 used 15 Earth System Models (ESM) and 5 Earth-system Models of Intermediate Complexity (EMIC) to derive an estimate of the remaining carbon budget. Their approach hence made implicit assumptions about the level of warming to date, the future contribution of non-CO_2 emissions, and the temperature response to CO_2 (TCRE). In this report, each of these aspects are considered explicitly. When estimating global warming until the 2006–2015 reference period as a blend of near-surface air temperature over land and sea-ice regions, and sea-surface temperature over open ocean, by averaging the four global mean surface temperature time series listed in Chapter 1 Section 1.2.1, the global warming would amount to 0.87°C ±0.1°C. Using the latter estimate of historical warming and projecting global warming using global near-surface air temperatures from model projections leads to remaining carbon budgets for limiting global warming to 1.5°C of 1080, 770, and 570 $GtCO_2$ for the 33rd, 50th, and 67th percentile of TCRE, respectively. Note that future research and ongoing observations over the next years will provide a better indication as to how the 2006–2015 base period compares with the long-term trends and might affect the budget estimates. Similarly, improved understanding in Earth system feedbacks would result in a better quantification of their impacts on remaining carbon budgets for 1.5°C and 2°C.

After TCRE uncertainty, a major additional source of uncertainty is the magnitude of non-CO_2 forcing and its contribution to the temperature change between the present day and the time of peak warming. Integrated emissions pathways can be used to ensure consistency between CO_2 and non-CO_2 emissions (Bowerman et al., 2013; Collins et al., 2013; Clarke et al., 2014; Rogelj et al., 2014b, 2015a; Tokarska et al., 2018). Friedlingstein et al. (2014a) used pathways with limited to no climate mitigation to find a variation due to non-CO_2 contributions of about ±33% for a 2°C carbon budget. Rogelj et al. (2016b) showed no particular bias in non-CO_2 radiative forcing or warming at the time of exceedance of 2°C or at peak warming between scenarios with increasing emissions and strongly mitigated scenarios (consistent with Stocker et al., 2013). However, clear differences of the non-CO_2 warming contribution at the time of deriving a 2°C-consistent carbon budget were reported for the four RCPs. Although the spread in non-CO_2 forcing across scenarios can be smaller in absolute terms at lower levels of cumulative emissions, it can be larger in relative terms compared to the remaining carbon budget (Stocker et al., 2013; Friedlingstein et al., 2014a; Rogelj et al., 2016b). Tokarska and Gillett (2018) find no statistically significant differences in 1.5°C-consistent cumulative emissions budgets when calculated for different RCPs from consistent sets of CMIP5 simulations.

The mitigation pathways assessed in this report indicate that emissions of non-CO_2 forcers contribute an average additional warming of around 0.15°C relative to 2006–2015 at the time of net zero CO_2 emissions, reducing the remaining carbon budget by roughly 320 $GtCO_2$. This arises from a weakening of aerosol cooling and continued emissions of non-CO_2 GHGs (Sections 2.2.1, 2.3.3). This non-CO_2 contribution at the time of net zero CO_2 emissions varies by about ±0.1°C across scenarios, resulting in a carbon budget uncertainty of about ±250 $GtCO_2$, and takes into account marked reductions in methane emissions (Section 2.3.3). If these reductions are not achieved, remaining carbon budgets are further reduced. Uncertainties in the non-CO_2 forcing and temperature response are asymmetric and can influence the remaining carbon budget by −400 to +200 $GtCO_2$, with the uncertainty in aerosol radiative forcing being the largest contributing factor (Table 2.2). The MAGICC and FAIR models in their respective parameter setups and model versions used to assess the non-CO_2 warming contribution give noticeable different non-CO_2 effective radiative forcing and warming for the same scenarios while both being within plausible ranges of future response (Figure 2.2 and Supplementary Material 2.SM.1.1, 2.SM.1.2). For this assessment, it is premature to assess the accuracy of their results, so it is assumed that both are equally representative of possible futures. Their non-CO_2 warming estimates are therefore averaged for the carbon budget assessment and their differences used to guide the uncertainty assessment of the role of non-CO_2 forcers. Nevertheless, the findings are robust enough to give *high confidence* that the changing emissions of non-CO_2 forcers (particularly the reduction in cooling aerosol precursors) cause additional near-term warming and reduce the remaining carbon budget compared to the CO_2-only budget.

TCRE uncertainty directly impacts carbon budget estimates (Peters, 2016; Matthews et al., 2017; Millar and Friedlingstein, 2018). Based on multiple lines of evidence, AR5 WGI assessed a *likely* range for TCRE of 0.2°–0.7°C per 1000 $GtCO_2$ (Collins et al., 2013). The TCRE of the CMIP5 Earth system models ranges from 0.23°C to 0.66°C per 1000 $GtCO_2$ (Gillett et al., 2013). At the same time, studies using observational constraints find best estimates of TCRE of 0.35°–0.41°C per 1000 $GtCO_2$ (Matthews et al., 2009; Gillett et al., 2013; Tachiiri et al., 2015; Millar and Friedlingstein, 2018). This assessment continues to use the assessed AR5 TCRE range under the working assumption that TCRE is normally distributed (Stocker et al., 2013). Observation-based estimates have reported log-normal distributions of TCRE (Millar and Friedlingstein, 2018). Assuming a log-normal instead of normal distribution of the assessed AR5 TCRE range would result in about a 200 $GtCO_2$ increase for the median budget estimates but only about half at the 67th percentile, while historical temperature uncertainty and uncertainty in recent emissions contribute ±150 and ±50 $GtCO_2$ to the uncertainty, respectively (Table 2.2).

Calculating carbon budgets from the TCRE requires the assumption that the instantaneous warming in response to cumulative CO_2 emissions equals the long-term warming or, equivalently, that the residual warming after CO_2 emissions cease is negligible. The magnitude of this residual warming, referred to as the zero-emission commitment, ranges from slightly negative (i.e., a slight cooling) to slightly positive for CO_2 emissions up to present-day (Chapter 1, Section 1.2.4) (Lowe et al., 2009; Frölicher and Joos, 2010; Gillett et al., 2011; Matthews and Zickfeld, 2012). The delayed temperature change from a pulse CO_2 emission introduces uncertainties in emission budgets, which have not been quantified in the literature for budgets consistent with limiting warming to 1.5°C. As a consequence, this uncertainty does not affect our carbon budget estimates directly but it is included as an additional factor in the assessed Earth system feedback uncertainty (as detailed below) of roughly 100 $GtCO_2$ on decadal time scales presented in Table 2.2.

Remaining carbon budgets are further influenced by Earth system feedbacks not accounted for in CMIP5 models, such as the permafrost carbon feedback (Friedlingstein et al., 2014b; MacDougall et al., 2015; Burke et al., 2017; Lowe and Bernie, 2018), and their influence on the TCRE. Lowe and Bernie (2018) used a simple climate sensitivity scaling approach to estimate that Earth system feedbacks (such as CO_2 released by permafrost thawing or methane released by wetlands) could reduce carbon budgets for 1.5°C and 2°C by roughly 100 $GtCO_2$ on centennial time scales. Their findings are based on an older understanding of Earth system feedbacks (Arneth et al., 2010). This estimate is broadly supported by more recent analysis of individual feedbacks. Schädel et al. (2014) suggest an upper bound of 24.4 PgC (90 $GtCO_2$) emitted from carbon release from permafrost over the next forty years for a RCP4.5 scenario. Burke et al. (2017) use a single model to estimate permafrost emissions between 0.3 and 0.6 $GtCO_2$ y^{-1} from the point of 1.5°C stabilization, which would reduce the budget by around 20 $GtCO_2$ by 2100. Comyn-Platt et al. (2018) include carbon and methane emissions from permafrost and wetlands and suggest the 1.5°C remaining carbon budget is reduced by 116 $GtCO_2$. Additionally, Mahowald et al. (2017) find there is possibility of 0.5–1.5 $GtCO_2$ y^{-1} being released from aerosol-biogeochemistry changes if aerosol emissions cease. In summary, these additional Earth system feedbacks taken together are assessed to reduce the remaining carbon budget applicable to 2100 by an order of magnitude of 100 $GtCO_2$, compared to the budgets based on the assumption of a constant TCRE presented in Table 2.2 (*limited evidence, medium agreement*), leading to overall *medium confidence* in their assessed impact. After 2100, the impact of additional Earth system feedbacks is expected to further reduce the remaining carbon budget (*medium confidence*).

The uncertainties presented in Table 2.2 cannot be formally combined, but current understanding of the assessed geophysical uncertainties suggests at least a ±50% possible variation for remaining carbon budgets for 1.5°C-consistent pathways. By the end of 2017, anthropogenic CO_2 emissions since the pre-industrial period are estimated to have amounted to approximately 2200 ±320 $GtCO_2$ (*medium confidence*) (Le Quéré et al., 2018). When put in the context of year-2017 CO_2 emissions (about 42 $GtCO_2$ yr^{-1}, ±3 $GtCO_2$ yr^{-1}, *high confidence*) (Le Quéré et al., 2018), a remaining carbon budget of 580 $GtCO_2$ (420 $GtCO_2$) suggests meeting net zero global CO_2 emissions in about 30 years (20 years) following a linear decline starting from 2018 (rounded to the nearest five years), with a variation of ±15–20 years due to the geophysical uncertainties mentioned above (*high confidence*).

The remaining carbon budgets assessed in this section are consistent with limiting peak warming to the indicated levels of additional warming. However, if these budgets are exceeded and the use of CDR (see Sections 2.3 and 2.4) is envisaged to return cumulative CO_2 emissions to within the carbon budget at a later point in time, additional uncertainties apply because the TCRE is different under increasing and decreasing atmospheric CO_2 concentrations due to ocean thermal and carbon cycle inertia (Herrington and Zickfeld, 2014; Krasting et al., 2014; Zickfeld et al., 2016). This asymmetrical behaviour makes carbon budgets path-dependent in the case of a budget and/or temperature overshoot (MacDougall et al., 2015). Although potentially large for scenarios with large overshoot (MacDougall et al., 2015), this path-dependence of carbon budgets has not been well quantified for 1.5°C- and 2°C-consistent scenarios and as such remains an important knowledge gap. This assessment does not explicitly account for path dependence but takes it into consideration for its overall confidence assessment.

This assessment finds a larger remaining budget from the 2006–2015 base period than the 1.5°C and 2°C remaining budgets inferred from AR5 from the start of 2011, which were approximately 1000 $GtCO_2$ for the 2°C (66% of model simulations) and approximately 400 $GtCO_2$ for the 1.5°C budget (66% of model simulations). In contrast, this assessment finds approximately 1600 $GtCO_2$ for the 2°C (66th TCRE percentile) and approximately 860 $GtCO_2$ for the 1.5°C budget (66th TCRE percentile) from 2011. However, these budgets are not directly equivalent as AR5 reported budgets for fractions of CMIP5 simulations and other lines of evidence, while this report uses the assessed range of TCRE and an assessment of the non-CO_2 contribution at net zero CO_2 emissions to provide remaining carbon budget estimates at various percentiles of TCRE. Furthermore, AR5 did not specify remaining budgets to carbon neutrality as we do here, but budgets until the time the temperature limit of interest was reached, assuming negligible zero emission commitment and taking into account the non-CO_2 forcing at that point in time.

In summary, although robust physical understanding underpins the carbon budget concept, relative uncertainties become larger as a specific temperature limit is approached. For the budget, applicable to the mid-century, the main uncertainties relate to the TCRE, non-CO_2 emissions, radiative forcing and response. For 2100, uncertain Earth system feedbacks such as permafrost thawing would further reduce the available budget. The remaining budget is also conditional upon the choice of baseline, which is affected by uncertainties in both historical emissions, and in deriving the estimate of globally averaged human-induced warming. As a result, only *medium confidence* can be assigned to the assessed remaining budget values for 1.5°C and 2.0°C and their uncertainty.

Table 2.2 | The assessed remaining carbon budget and its uncertainties. Shaded blue horizontal bands illustrate the uncertainty in historical temperature increase from the 1850–1900 base period until the 2006–2015 period as estimated from global near-surface air temperatures, which impacts the additional warming until a specific temperature limit like 1.5°C or 2°C relative to the 1850–1900 period. Shaded grey cells indicate values for when historical temperature increase is estimated from a blend of near-surface air temperatures over land and sea ice regions and sea-surface temperatures over oceans.

Additional Warming since 2006–2015 [°C]*(1)	Approximate Warming since 1850–1900 [°C]*(1)	Remaining Carbon Budget (Excluding Additional Earth System Feedbacks*(5)) [$GtCO_2$ from 1.1.2018]*(2)			Key Uncertainties and Variations*(4)					
		Percentiles of TCRE *(3)			Earth System Feedbacks *(5)	Non-CO_2 scenario variation *(6)	Non-CO_2 forcing and response uncertainty	TCRE distribution uncertainty *(7)	Historical temperature uncertainty *(1)	Recent emissions uncertainty *(8)
		33rd	*50th*	*67th*	*[$GtCO_2$]*	*[$GtCO_2$]*	*[$GtCO_2$]*	*[$GtCO_2$]*	*[$GtCO_2$]*	*[$GtCO_2$]*
0.3		290	160	80						
0.4		530	350	230						
0.5		770	530	380						
0.53	**~1.5°C**	**840**	**580**	**420**	Budgets on the left are reduced by about –100 on centennial time scales	±250	–400 to +200	+100 to +200	±250	±20
0.6		1010	710	530						
0.63		1080	770	570						
0.7		1240	900	680						
0.78		1440	1040	800						
0.8		1480	1080	830						
0.9		1720	1260	980						
1		1960	1450	1130						
1.03	**~2°C**	2030	1500	1170						
1.1		2200	1630	1280						
1.13		2270	1690	1320						
1.2		2440	1820	1430						

Notes:

*(1) Chapter 1 has assessed historical warming between the 1850–1900 and 2006–2015 periods to be 0.87°C with a ±0.12°C *likely* (1-standard deviation) range, and global near-surface air temperature to be 0.97°C. The temperature changes from the 2006–2015 period are expressed in changes of global near-surface air temperature.

*(2) Historical CO_2 emissions since the middle of the 1850–1900 historical base period (mid-1875) are estimated at 1940 $GtCO_2$ (1640–2240 GtCO2, one standard deviation range) until end 2010. Since 1 January 2011, an additional 290 $GtCO_2$ (270–310 $GtCO_2$, one sigma range) has been emitted until the end of 2017 (Le Quéré et al., 2018).

*(3) TCRE: transient climate response to cumulative emissions of carbon, assessed by AR5 to fall *likely* between 0.8–2.5°C/1000 PgC (Collins et al., 2013), considering a normal distribution consistent with AR5 (Stocker et al., 2013). Values are rounded to the nearest 10 $GtCO_2$.

*(4) Focussing on the impact of various key uncertainties on median budgets for 0.53°C of additional warming.

*(5) Earth system feedbacks include CO_2 released by permafrost thawing or methane released by wetlands, see main text.

*(6) Variations due to different scenario assumptions related to the future evolution of non-CO_2 emissions.

*(7) The distribution of TCRE is not precisely defined. Here the influence of assuming a lognormal instead of a normal distribution shown.

*(8) Historical emissions uncertainty reflects the uncertainty in historical emissions since 1 January 2011.

2.3 Overview of 1.5°C Mitigation Pathways

Limiting global mean temperature increase at any level requires global CO_2 emissions to become net zero at some point in the future (Zickfeld et al., 2009; Collins et al., 2013). At the same time, limiting the residual warming of short-lived non-CO_2 emissions can be achieved by reducing their annual emissions as much as possible (Section 2.2, Cross-Chapter Box 2 in Chapter 1). This would require large-scale transformations of the global energy–agriculture–land-economy system, affecting the way in which energy is produced, agricultural systems are organized, and food, energy and materials are consumed (Clarke et al., 2014). This section assesses key properties of pathways consistent with limiting global mean temperature to 1.5°C relative to pre-industrial levels, including their underlying assumptions and variations.

Since the AR5, an extensive body of literature has appeared on integrated pathways consistent with 1.5°C (Section 2.1) (Rogelj et al., 2015b, 2018; Akimoto et al., 2017; Löffler et al., 2017; Marcucci et al., 2017; Su et al., 2017; Bauer et al., 2018; Bertram et al., 2018; Grubler et al., 2018; Holz et al., 2018b; Kriegler et al., 2018a; Liu et al., 2018; Luderer et al., 2018; Strefler et al., 2018a; van Vuuren et al., 2018; Vrontisi et al., 2018; Zhang et al., 2018). These pathways have global coverage and represent all GHG-emitting sectors and their interactions. Such integrated pathways allow the exploration of the whole-system transformation, and hence provide the context in which the detailed sectoral transformations assessed in Section 2.4 of this chapter are taking place.

The overwhelming majority of published integrated pathways have been developed by global IAMs that represent key societal systems and their interactions, like the energy system, agriculture and land use, and the economy (see Section 6.2 in Clarke et al., 2014). Very often these models also include interactions with a representation of the geophysical system, for example, by including spatially explicit land models or carbon cycle and climate models. The complex features of these subsystems are approximated and simplified in these models. IAMs are briefly introduced in Section 2.1 and important knowledge gaps identified in Section 2.6. An overview to the use, scope and limitations of IAMs is provided in Supplementary Material 2.SM.1.2.

The pathway literature is assessed in two ways in this section. First, various insights on specific questions reported by studies can be assessed to identify robust or divergent findings. Second, the combined body of scenarios can be assessed to identify salient features of pathways in line with a specific climate goal across a wide range of models. The latter can be achieved by assessing pathways available in the database to this assessment (Section 2.1, Supplementary Material 2.SM.1.2–4). The ensemble of scenarios available to this assessment is an ensemble of opportunity: it is a collection of scenarios from a diverse set of studies that was not developed with a common set of questions and a statistical analysis of outcomes in mind. This means that ranges can be useful to identify robust and sensitive features across available scenarios and contributing modelling frameworks, but do not lend themselves to a statistical interpretation. To understand the reasons underlying the ranges, an assessment of the underlying scenarios and studies is required. To this end, this section highlights illustrative pathway archetypes that help to clarify the variation in assessed ranges for 1.5°C-consistent pathways.

2.3.1 Range of Assumptions Underlying 1.5°C Pathways

Earlier assessments have highlighted that there is no single pathway to achieve a specific climate objective (e.g., Clarke et al., 2014). Pathways depend on the underlying development processes, and societal choices, which affect the drivers of projected future baseline emissions. Furthermore, societal choices also affect climate change solutions in pathways, like the technologies that are deployed, the scale at which they are deployed, or whether solutions are globally coordinated. A key finding is that 1.5°C-consistent pathways could be identified under a considerable range of assumptions in model studies despite the tightness of the 1.5°C emissions budget (Figures 2.4, 2.5) (Rogelj et al., 2018).

The AR5 provided an overview of how differences in model structure and assumptions can influence the outcome of transformation pathways (Section 6.2 in Clarke et al., 2014, as well as Table A.II.14 in Krey et al., 2014b) and this was further explored by the modelling community in recent years with regard to, e.g., socio-economic drivers (Kriegler et al., 2016; Marangoni et al., 2017; Riahi et al., 2017), technology assumptions (Bosetti et al., 2015; Creutzig et al., 2017; Pietzcker et al., 2017), and behavioural factors (van Sluisveld et al., 2016; McCollum et al., 2017).

2.3.1.1 Socio-economic drivers and the demand for energy and land in 1.5°C pathways

There is deep uncertainty about the ways humankind will use energy and land in the 21st century. These ways are intricately linked to future population levels, secular trends in economic growth and income convergence, behavioural change and technological progress. These dimensions have been recently explored in the context of the SSPs (Kriegler et al., 2012; O'Neill et al., 2014), which provide narratives (O'Neill et al., 2017) and quantifications (Crespo Cuaresma, 2017; Dellink et al., 2017; KC and Lutz, 2017; Leimbach et al., 2017; Riahi et al., 2017) of different world futures across which scenario dimensions are varied to explore differential challenges to adaptation and mitigation (Cross-Chapter Box 1 in Chapter 1). This framework is increasingly adopted by IAMs to systematically explore the impact of socio-economic assumptions on mitigation pathways (Riahi et al., 2017), including 1.5°C-consistent pathways (Rogelj et al., 2018). The narratives describe five worlds (SSP1–5) with different socio-economic predispositions to mitigate and adapt to climate change (Table 2.3). As a result, population and economic growth projections can vary strongly across integrated scenarios, including available 1.5°C-consistent pathways (Figure 2.4). For example, based on alternative future fertility, mortality, migration and educational assumptions, population projections vary between 8.5 and 10.0 billion people by 2050 and between 6.9 and 12.6 billion people by 2100 across the SSPs. An important factor for these differences is future female educational attainment, with higher attainment leading to lower fertility rates and therefore decreased population growth up to a level of 1 billion people by 2050 (Lutz and KC, 2011; Snopkowski et al., 2016; KC and Lutz, 2017). Consistent with population development, GDP per capita also varies strongly in SSP baselines, ranging from about 20 to more than 50 thousand USD2010 per capita in 2050 (in purchasing power parity values, PPP), in part driven by assumptions on human development, technological progress and development convergence between and within regions (Crespo Cuaresma, 2017; Dellink et al., 2017; Leimbach et al., 2017). Importantly, none of the GDP projections in the mitigation pathway literature assessed in this chapter included the feedback of climate damages on economic growth (Hsiang et al., 2017).

Baseline projections for energy-related GHG emissions are sensitive to economic growth assumptions, while baseline projections for land-use emissions are more directly affected by population growth (assuming unchanged land productivity and per capita demand for agricultural products) (Kriegler et al., 2016). SSP-based modelling studies of mitigation pathways have identified high challenges to mitigation for worlds with a focus on domestic issues and regional security combined with high population growth (SSP3), and for worlds with rapidly growing resource and fossil-fuel intensive consumption (SSP5) (Riahi et al., 2017). No model could identify a 2°C-consistent pathway for SSP3, and high mitigation costs were found for SSP5. This picture translates to 1.5°C-consistent pathways that have to remain within even tighter emissions constraints (Rogelj et al., 2018). No model found a 1.5°C-consistent pathway for SSP3 and some models could not identify 1.5°C-consistent pathways for SSP5 (2 of 4 models, compared to 1 of 4 models for 2°C-consistent pathways). The modelling analysis also found that the effective control of land-use emissions becomes even more critical in 1.5°C-consistent pathways. Due to high inequality levels in SSP4, land use can be less well managed. This caused 2 of 3 models to no longer find an SSP4-based 1.5°C-consistent pathway even though they identified SSP4-based 2°C-consistent pathways at relatively moderate mitigation costs (Riahi et al., 2017). Rogelj et al. (2018) further reported that all six participating models identified

Table 2.3 | Key Characteristics of the Five Shared Socio-Economic Pathways (SSPs) (O'Neill et al., 2017).

Socio-Economic Challenges to Mitigation	Socio-Economic Challenges to Adaptation		
	Low	**Medium**	**High**
High	**SSP5: Fossil-fuelled development** • low population • very high economic growth per capita • high human development • high technological progress • ample fossil fuel resources • very resource intensive lifestyles • high energy and food demand per capita • economic convergence and global cooperation		**SSP3: Regional rivalry** • high population • low economic growth per capita • low human development • low technological progress • resource-intensive lifestyles • resource-constrained energy and food demand per capita • focus on regional food and energy security • regionalization and lack of global cooperation
Medium		**SSP2: Middle of the road** • medium population • medium and uneven economic growth • medium and uneven human development • medium and uneven technological progress • resource-intensive lifestyles • medium and uneven energy and food demand per capita • limited global cooperation and economic convergence	
Low	**SSP1: Sustainable development** • low population • high economic growth per capita • high human development • high technological progress • environmentally oriented technological and behavioural change • resource-efficient lifestyles • low energy and food demand per capita • economic convergence and global cooperation		**SSP4: Inequality** • Medium to high population • Unequal low to medium economic growth per capita • Unequal low to medium human development • unequal technological progress: high in globalized high-tech sectors, slow in domestic sectors • unequal lifestyles and energy /food consumption: resource intensity depending on income • Globally connected elite, disconnected domestic work forces

1.5°C-consistent pathways in a sustainability oriented world (SSP1) and four of six models found 1.5°C-consistent pathways for middle-of-the-road developments (SSP2). These results show that 1.5°C-consistent pathways can be identified under a broad range of assumptions, but that lack of global cooperation (SSP3), high inequality (SSP4) and/or high population growth (SSP3) that limit the ability to control land use emissions, and rapidly growing resource-intensive consumption (SSP5) are key impediments.

Figure 2.4 compares the range of underlying socio-economic developments as well as energy and food demand in available 1.5°C-consistent pathways with the full set of published scenarios that were submitted to this assessment. While 1.5°C-consistent pathways broadly cover the full range of population and economic growth developments (except for the high population development in SSP3-based scenarios), they tend to cluster on the lower end for energy and food demand. They still encompass, however, a wide range of developments from decreasing to increasing demand levels relative to today. For the purpose of this assessment, a set of four illustrative 1.5°C-consistent pathway archetypes were selected to show the variety of underlying assumptions and characteristics (Figure 2.4). They comprise three 1.5°C-consistent pathways based on the SSPs (Rogelj et al., 2018): a sustainability oriented scenario (S1 based on SSP1) developed with the AIM model (Fujimori, 2017), a fossil-fuel intensive and high energy demand scenario (S5, based on SSP5) developed with the REMIND-MAgPIE model (Kriegler et al., 2017), and a middle-of-the-road scenario (S2, based on SSP2) developed with the MESSAGE-GLOBIOM model (Fricko et al., 2017). In addition, we include a scenario with low energy demand (LED) (Grubler et al., 2018), which reflects recent literature with a stronger focus on demand-side measures (Bertram et al., 2018; Grubler et al., 2018; Liu et al., 2018; van Vuuren et al., 2018). Pathways LED, S1, S2, and S5 are referred to as P1, P2, P3, and P4 in the Summary for Policymakers.

2.3.1.2 Mitigation options in 1.5°C pathways

In the context of 1.5°C pathways, the portfolio of mitigation options available to the model becomes an increasingly important factor. IAMs include a wide variety of mitigation options, as well as measures that achieve CDR from the atmosphere (Krey et al., 2014a, b) (see Chapter 4, Section 4.3 for a broad assessment of available mitigation measures). For the purpose of this assessment, we elicited technology availability in models that submitted scenarios to the database as summarized in Supplementary Material 2.SM.1.2, where a detailed picture of the technology variety underlying available 1.5°C-consistent pathways is provided. Modelling choices on whether a particular mitigation measure is included are influenced by an assessment of its global mitigation potential, the availability of data and literature describing

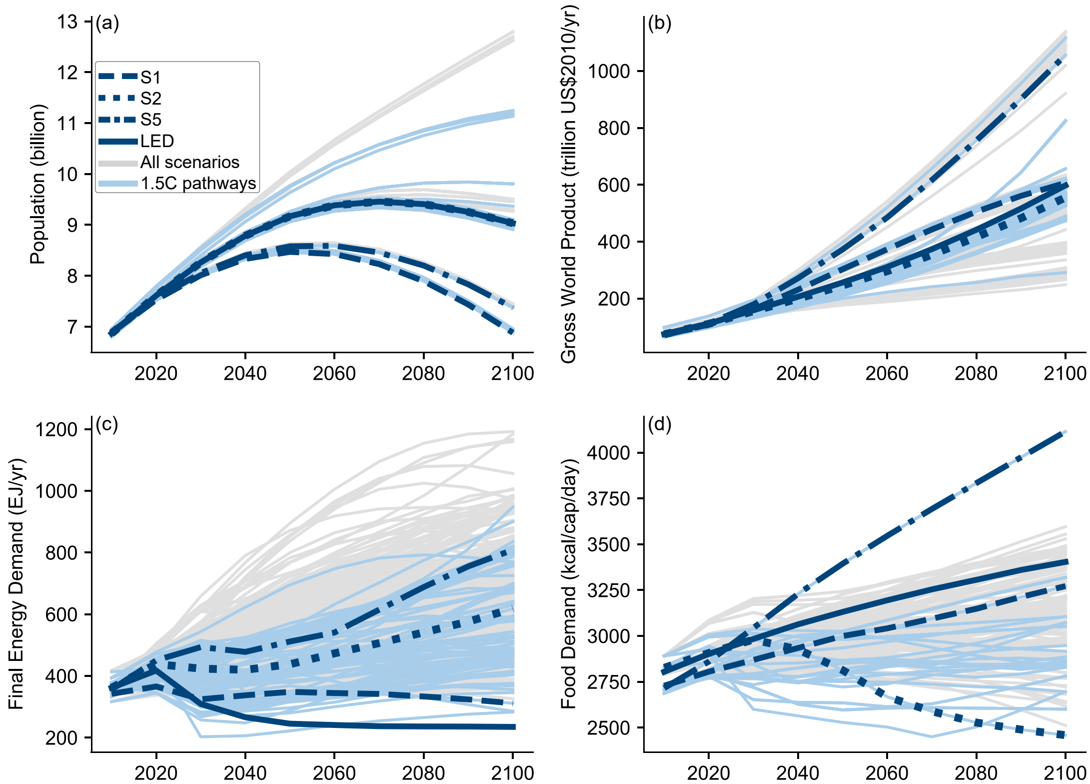


Figure 2.4 | Range of assumptions about socio-economic drivers and projections for energy and food demand in the pathways available to this assessment. 1.5°C-consistent pathways are blue, other pathways grey. Trajectories for the illustrative 1.5°C-consistent archetypes used in this Chapter (LED, S1, S2, S5; referred to as P1, P2, P3, and P4 in the Summary for Policymakers.) are highlighted. S1 is a sustainability oriented scenario, S2 is a middle-of-the-road scenario, and S5 is a fossil-fuel intensive and high energy demand scenario. LED is a scenario with particularly low energy demand. Population assumptions in S2 and LED are identical. Panels show (a) world population, (b) gross world product in purchasing power parity values, (c) final energy demand, and (d) food demand.

its techno-economic characteristics and future prospects, and the computational challenge of representing the measure, e.g., in terms of required spatio-temporal and process detail.

This elicitation (Supplementary Material 2.SM.1.2) confirms that IAMs cover most supply-side mitigation options on the process level, while many demand-side options are treated as part of underlying assumptions, which can be varied (Clarke et al., 2014). In recent years, there has been increasing attention on improving the modelling of integrating variable renewable energy into the power system (Creutzig et al., 2017; Luderer et al., 2017; Pietzcker et al., 2017) and of behavioural change and other factors influencing future demand for energy and food (van Sluisveld et al., 2016; McCollum et al., 2017; Weindl et al., 2017), including in the context of 1.5°C-consistent pathways (Grubler et al., 2018; van Vuuren et al., 2018). The literature on the many diverse CDR options only recently started to develop strongly (Minx et al., 2017) (see Chapter 4, Section 4.3.7 for a detailed assessment), and hence these options are only partially included in IAM analyses. IAMs mostly incorporate afforestation and bioenergy with carbon capture and storage (BECCS) and only in few cases also include direct air capture with CCS (DACCS) (Chen and Tavoni, 2013; Marcucci et al., 2017; Strefler et al., 2018b).

Several studies have either directly or indirectly explored the dependence of 1.5°C-consistent pathways on specific (sets of) mitigation and CDR technologies (Bauer et al., 2018; Grubler et al., 2018; Holz et al., 2018b; Kriegler et al., 2018a; Liu et al., 2018; Rogelj et al., 2018; Strefler et al., 2018b; van Vuuren et al., 2018). However, there are a few potentially disruptive technologies that are typically not yet well covered in IAMs and that have the potential to alter the shape of mitigation pathways beyond the ranges in the IAM-based literature. Those are also included in Supplementary Material 2.SM.1.2. The configuration of carbon-neutral energy systems projected in mitigation pathways can vary widely, but they all share a substantial reliance on bioenergy under the assumption of effective land-use emissions control. There are other configurations with less reliance on bioenergy that are not yet comprehensively covered by global mitigation pathway modelling. One approach is to dramatically reduce and electrify energy demand for transportation and manufacturing to levels that make residual non-electric fuel use negligible or replaceable by limited amounts of electrolytic hydrogen. Such an approach is presented in a first-of-its kind low-energy-demand scenario (Grubler et al., 2018) which is part of this assessment. Other approaches rely less on energy demand reductions, but employ cheap renewable electricity to push the boundaries of electrification in the industry and transport sectors (Breyer et al., 2017; Jacobson, 2017). In addition, these approaches deploy renewable-based Power-2-X (read: Power to "x") technologies to substitute residual fossil-fuel use (Brynolf et al., 2018). An important element of carbon-neutral Power-2-X applications is the combination of hydrogen generated from renewable electricity and CO_2 captured from the atmosphere (Zeman and Keith, 2008). Alternatively, algae are considered as a bioenergy source with more limited implications for land use and agricultural systems than energy crops (Williams and Laurens, 2010; Walsh et al., 2016; Greene et al., 2017).

Furthermore, a range of measures could radically reduce agricultural and land-use emissions and are not yet well-covered in IAM modelling. This includes plant-based proteins (Joshi and Kumar, 2015) and cultured meat (Post, 2012) with the potential to substitute for livestock products at much lower GHG footprints (Tuomisto and Teixeira de Mattos, 2011). Large-scale use of synthetic or algae-based proteins for animal feed could free pasture land for other uses (Madeira et al., 2017; Pikaar et al., 2018). Novel technologies such as methanogen inhibitors and vaccines (Wedlock et al., 2013; Hristov et al., 2015; Herrero et al., 2016; Subharat et al., 2016) as well as synthetic and biological nitrification inhibitors (Subbarao et al., 2013; Di and Cameron, 2016) could substantially reduce future non-CO_2 emissions from agriculture if commercialized successfully. Enhancing carbon sequestration in soils (Paustian et al., 2016; Frank et al., 2017; Zomer et al., 2017) can provide the dual benefit of CDR and improved soil quality. A range of conservation, restoration and land management options can also increase terrestrial carbon uptake (Griscom et al., 2017). In addition, the literature discusses CDR measures to permanently sequester atmospheric carbon in rocks (mineralization and enhanced weathering, see Chapter 4, Section 4.3.7) as well as carbon capture and usage in long-lived products like plastics and carbon fibres (Mazzotti et al., 2005; Hartmann et al., 2013). Progress in the understanding of the technical viability, economics and sustainability of these ways to achieve and maintain carbon neutral energy and land use can affect the characteristics, costs and feasibility of 1.5°C-consistent pathways significantly.

2.3.1.3 Policy assumptions in 1.5°C pathways

Besides assumptions related to socio-economic drivers and mitigation technology, scenarios are also subject to assumptions about the mitigation policies that can be put in place. Mitigation policies can either be applied immediately in scenarios or follow staged or delayed approaches. Policies can span many sectors (e.g., economy-wide carbon pricing), or policies can be applicable to specific sectors only (like the energy sector) with other sectors (e.g., the agricultural or the land-use sector) treated differently. These variations can have an important impact on the ability of models to generate scenarios compatible with stringent climate targets like 1.5°C (Luderer et al., 2013; Rogelj et al., 2013b; Bertram et al., 2015b; Kriegler et al., 2018a; Michaelowa et al., 2018). In the scenario ensemble available to this assessment, several variations of near-term mitigation policy implementation can be found: immediate and cross-sectoral global cooperation from 2020 onward towards a global climate objective, a phase-in of globally coordinated mitigation policy from 2020 to 2040, and a more short-term oriented and regionally diverse global mitigation policy, following NDCs until 2030 (Kriegler et al., 2018a; Luderer et al., 2018; McCollum et al., 2018; Rogelj et al., 2018; Strefler et al., 2018b). For example, the above-mentioned SSP quantifications assume regionally scattered mitigation policies until 2020, and vary in global convergence thereafter (Kriegler et al., 2014a; Riahi et al., 2017). The impact of near-term policy choices on 1.5°C-consistent pathways is discussed in Section 2.3.5. The literature has also explored 1.5°C-consistent pathways that build on a portfolio of policy approaches until 2030, including the combination of regulatory policies and carbon pricing (Kriegler et al., 2018a), and a variety of ancillary policies to safeguard other sustainable development goals (Bertram et al., 2018; van Vuuren et al., 2018). A further discussion of policy implications of 1.5°C-consistent pathways is provided in Section 2.5.1, while a general discussion of policies and options to strengthen action are subject of Chapter 4, Section 4.4.

2.3.2 Key Characteristics of 1.5°C Pathways

1.5°C-consistent pathways are characterized by a rapid phase out of CO_2 emissions and deep emissions reductions in other GHGs and climate forcers (Section 2.2.2 and 2.3.3). This is achieved by broad transformations in the energy; industry; transport; buildings; and agriculture, forestry and other land-use (AFOLU) sectors (Section 2.4) (Bauer et al., 2018; Grubler et al., 2018; Holz et al., 2018b; Kriegler et al., 2018b; Liu et al., 2018; Luderer et al., 2018; Rogelj et al., 2018; van Vuuren et al., 2018; Zhang et al., 2018). Here we assess 1.5°C-consistent pathways with and without overshoot during the 21st century. One study also explores pathways overshooting 1.5°C for longer than the 21st century (Akimoto et al., 2017), but these are not considered 1.5°C-consistent pathways in this report (Chapter 1, Section 1.1.3). This subsection summarizes robust and varying properties of 1.5°C-consistent pathways regarding system transformations, emission reductions and overshoot. It aims to provide an introduction to the detailed assessment of the emissions evolution (Section 2.3.3), CDR deployment (Section 2.3.4), energy (Section 2.4.1, 2.4.2), industry (2.4.3.1), buildings (2.4.3.2), transport (2.4.3.3) and land-use transformations (Section 2.4.4) in 1.5°C-consistent pathways. Throughout Sections 2.3 and 2.4, pathway properties are highlighted with four 1.5°C-consistent pathway archetypes (LED, S1, S2, S5; referred to as P1, P2, P3, and P4 in the Summary for Policymakers) covering a wide range of different socio-economic and technology assumptions (Figure 2.5, Section 2.3.1).

2.3.2.1 Variation in system transformations underlying 1.5°C pathways

Be it for the energy, transport, buildings, industry, or AFOLU sector, the literature shows that multiple options and choices are available in each of these sectors to pursue stringent emissions reductions (Section 2.3.1.2, Supplementary Material 2.SM.1.2, Chapter 4, Section 4.3). Because the overall emissions total under a pathway is limited by a geophysical carbon budget (Section 2.2.2), choices in one sector affect the efforts that are required from others (Clarke et al., 2014). A robust feature of 1.5°C-consistent pathways, as highlighted by the set of pathway archetypes in Figure 2.5, is a virtually full decarbonization of the power sector around mid-century, a feature shared with 2°C-consistent pathways. The additional emissions reductions in 1.5°C-consistent compared to 2°C-consistent pathways come predominantly from the transport and industry sectors (Luderer et al., 2018). Emissions can be apportioned differently across sectors, for example, by focussing on reducing the overall amount of CO_2 produced in the energy end-use sectors, and using limited contributions of CDR by the AFOLU sector (afforestation and reforestation, S1 and LED pathways in Figure 2.5) (Grubler et al., 2018; Holz et al., 2018b; van Vuuren et al., 2018), or by being more lenient about the amount of CO_2 that continues to be produced in the above-mentioned end-use sectors (both by 2030 and mid-century) and strongly relying on technological CDR options

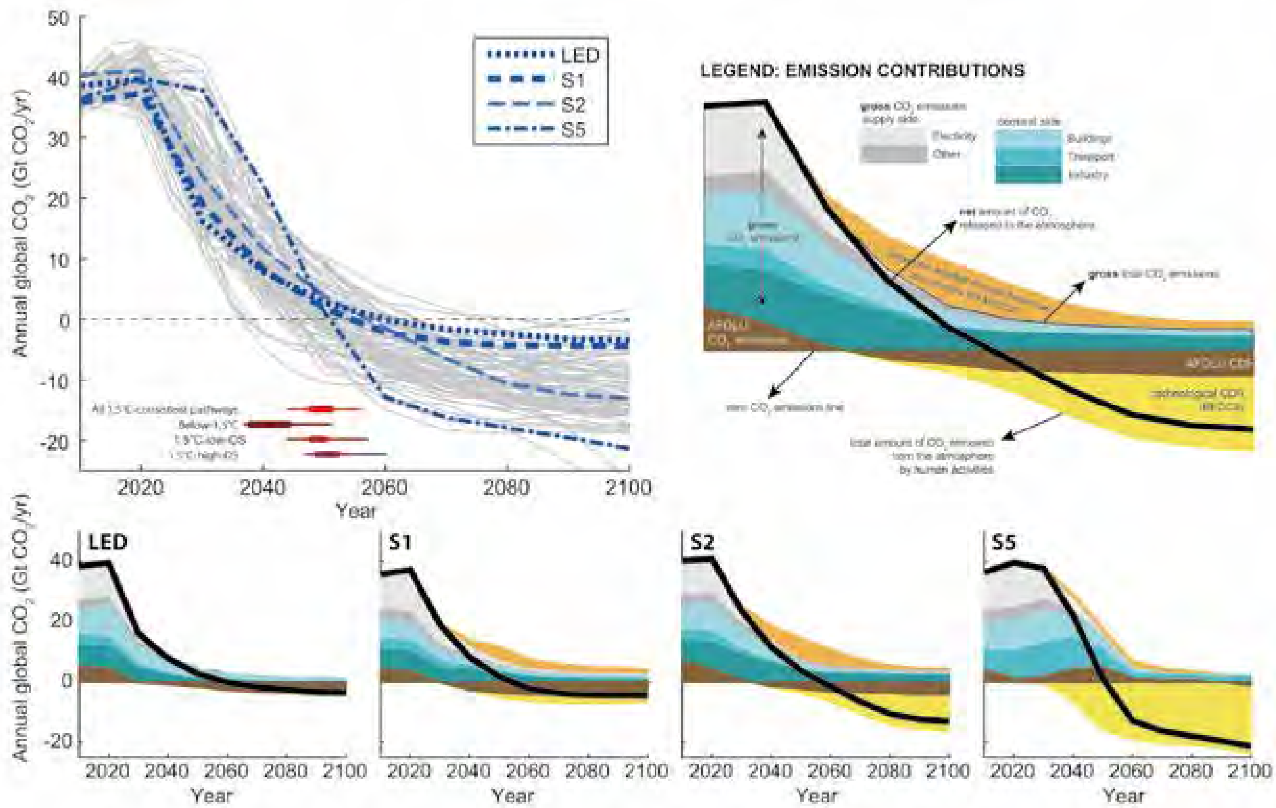


Figure 2.5 | Evolution and break down of global anthropogenic CO_2 emissions until 2100. The top-left panel shows global net CO_2 emissions in Below-1.5°C, 1.5°C-low-overshoot (OS), and 1.5°C-high-OS pathways, with the four illustrative 1.5°C-consistent pathway archetypes of this chapter highlighted. Ranges at the bottom of the top-left panel show the 10th–90th percentile range (thin line) and interquartile range (thick line) of the time that global CO_2 emissions reach net zero per pathway class, and for all pathways classes combined. The top-right panel provides a schematic legend explaining all CO_2 emissions contributions to global CO_2 emissions. The bottom row shows how various CO_2 contributions are deployed and used in the four illustrative pathway archetypes (LED, S1, S2, S5, referred to as P1, P2, P3, and P4 in the Summary for Policymakers) used in this chapter (see Section 2.3.1.1). Note that the S5 scenario reports the building and industry sector emissions jointly. Green-blue areas hence show emissions from the transport sector and the joint building and industry demand sector, respectively.

like BECCS (S2 and S5 pathways in Figure 2.5) (Luderer et al., 2018; Rogelj et al., 2018). Major drivers of these differences are assumptions about energy and food demand and the stringency of near-term climate policy (see the difference between early action in the scenarios S1, LED and more moderate action until 2030 in the scenarios S2, S5). Furthermore, the carbon budget in each of these pathways depends also on the non-CO_2 mitigation measures implemented in each of them, particularly for agricultural emissions (Sections 2.2.2, 2.3.3) (Gernaat et al., 2015). Those pathways differ not only in terms of their deployment of mitigation and CDR measures (Sections 2.3.4 and 2.4), but also in terms of the resulting temperature overshoot (Figure 2.1). Furthermore, they have very different implications for the achievement of sustainable development objectives, as further discussed in Section 2.5.3.

2.3.2.2 Pathways keeping warming below 1.5°C or temporarily overshooting it

This subsection explores the conditions that would need to be fulfilled to stay below 1.5°C warming without overshoot. As discussed in Section 2.2.2, to keep warming below 1.5°C with a two-in-three (one-in-two) chance, the cumulative amount of CO_2 emissions from 2018 onwards need to remain below a carbon budget of 420 (580) $GtCO_2$; accounting for the effects of additional Earth system feedbacks until 2100 reduces this estimate by 100 $GtCO_2$. Based on the current state of knowledge, exceeding this remaining carbon budget at some point in time would give a one-in-three (one-in-two) chance that the 1.5°C limit is overshot (Table 2.2). For comparison, around 290 ± 20 (1 standard deviation range) $GtCO_2$ have been emitted in the years 2011–2017, with annual CO_2 emissions in 2017 around 42 ± 3 $GtCO_2$ yr^{-1} (Jackson et al., 2017; Le Quéré et al., 2018). Committed fossil-fuel emissions from existing fossil-fuel infrastructure as of 2010 have been estimated at around 500 ± 200 $GtCO_2$ (with about 200 $GtCO_2$ already emitted through 2017) (Davis and Caldeira, 2010). Coal-fired power plants contribute the largest part. Committed emissions from existing coal-fired power plants built through the end of 2016 are estimated to add up to roughly 200 $GtCO_2$, and a further 100–150 $GtCO_2$ from coal-fired power plants under construction or planned (González-Eguino et al., 2017; Edenhofer et al., 2018). However, there has been a marked slowdown of planned coal-power projects in recent years, and some estimates indicate that the committed emissions from coal plants that are under construction or planned have halved since 2015 (Shearer et al., 2018). Despite these uncertainties, the committed fossil-fuel emissions are assessed to already amount to more than two thirds (half) of the remaining carbon budget.

An important question is to what extent the nationally determined contributions (NDCs) under the Paris Agreement are aligned with the remaining carbon budget. It was estimated that the NDCs, if successfully implemented, imply a total of 400–560 $GtCO_2$ emissions over the 2018–2030 period (considering both conditional and unconditional NDCs) (Rogelj et al., 2016a). Thus, following an NDC trajectory would already exhaust 95–130% (70–95%) of the remaining two-in-three (one-in-two) 1.5°C carbon budget (unadjusted for additional Earth system feedbacks) by 2030. This would leave no time (0–9 years) to bring down global emissions from NDC levels of around 40 $GtCO_2$ yr^{-1} in 2030 (Fawcett et al., 2015; Rogelj et al., 2016a) to net zero (further discussion in Section 2.3.5).

Most 1.5°C-consistent pathways show more stringent emissions reductions by 2030 than implied by the NDCs (Section 2.3.5) The lower end of those pathways reach down to below 20 $GtCO_2$ yr^{-1} in 2030 (Section 2.3.3, Table 2.4), less than half of what is implied by the NDCs. Whether such pathways will be able to limit warming to 1.5°C without overshoot will depend on whether cumulative net CO_2 emissions over the 21st century can be kept below the remaining carbon budget at any time. Net global CO_2 emissions are derived from the gross amount of CO_2 that humans annually emit into the atmosphere reduced by the amount of anthropogenic CDR in each year. New research has looked more closely at the amount and the drivers of gross CO_2 emissions from fossil-fuel combustion and industrial processes (FFI) in deep mitigation pathways (Luderer et al., 2018), and found that the larger part of remaining CO_2 emissions come from direct fossil-fuel use in the transport and industry sectors, while residual energy supply sector emissions (mostly from the power sector) are limited by a rapid approach to net zero CO_2 emissions until mid-century. The 1.5°C pathways with no or limited (<0.1°C) overshoot that were reported in the scenario database project remaining FFI CO_2 emissions of 610–1260 $GtCO_2$ over the period 2018–2100 (5th–95th percentile range; median: 880 $GtCO_2$). Kriegler et al. (2018b) conducted a sensitivity analysis that explores the four central options for reducing fossil-fuel emissions: lowering energy demand, electrifying energy services, decarbonizing the power sector and decarbonizing non-electric fuel use in energy end-use sectors. By exploring these options to their extremes, they found a lowest value of 500 $GtCO_2$ (2018–2100) gross fossil-fuel CO_2 emissions for the hypothetical case of aligning the strongest assumptions for all four mitigation options. The two lines of evidence and the fact that available 1.5°C pathways cover a wide range of assumptions (Section 2.3.1) give a robust indication of a lower limit of about 500 $GtCO_2$ remaining fossil-fuel and industry CO_2 emissions in the 21st century.

To compare these numbers with the remaining carbon budget, CO_2 emissions from agriculture, forestry and other land use (AFOLU) need to be taken into account. In many of the 1.5°C-consistent pathways, AFOLU CO_2 emissions reach zero at or before mid-century and then turn to negative values (Table 2.4). This means human changes to the land lead to atmospheric carbon being stored in plants and soils. This needs to be distinguished from the natural CO_2 uptake by land, which is not accounted for in the anthropogenic AFOLU CO_2 emissions reported in the pathways. Given the difference in estimating the 'anthropogenic' sink between countries and the global integrated assessment and carbon modelling community (Grassi et al., 2017), the AFOLU CO_2 estimates included here are not necessarily directly comparable with countries' estimates at global level. The cumulated amount of AFOLU CO_2 emissions until the time they reach zero combine with the fossil-fuel and industry CO_2 emissions to give a total amount of gross emissions of 650–1270 $GtCO_2$ for the period 2018–2100 (5th–95th percentile; median 950 $GtCO_2$) in 1.5°C pathways with no or limited overshoot. The lower end of the range is close to what emerges from a scenario of transformative change that halves CO_2 emissions every decade from 2020 to 2050 (Rockström et al., 2017). All these estimates are above the remaining carbon budget for a one-in-two chance of limiting warming below 1.5°C without overshoot, including the low end of the hypothetical sensitivity analysis of Kriegler et al. (2018b), who assumes 75 Gt AFOLU CO_2 emissions adding to a total of 575 $GtCO_2$ gross CO_2 emissions. As almost no cases have been identified that keep gross CO_2 emissions within the remaining carbon budget for a one-in-two chance of limiting warming to 1.5°C, and based on current understanding of the geophysical response and its uncertainties, the available evidence indicates that avoiding overshoot of 1.5°C will require some type of CDR in a broad sense, e.g., via net negative AFOLU CO_2 emissions (*medium confidence*). (Table 2.2).

Net CO_2 emissions can fall below gross CO_2 emissions, if CDR is brought into the mix. Studies have looked at mitigation and CDR in combination to identify strategies for limiting warming to 1.5°C (Sanderson et al., 2016; Ricke et al., 2017). CDR, which may include net negative AFOLU CO_2 emissions, is deployed by all 1.5°C-consistent pathways available to this assessment, but the scale of deployment and choice of CDR measures varies widely (Section 2.3.4). Furthermore, no CDR technology has been deployed at scale yet, and all come with concerns about their potential (Fuss et al., 2018), feasibility (Nemet et al., 2018) and/or sustainability (Smith et al., 2015; Fuss et al., 2018) (see Sections 2.3.4, 4.3.2 and 4.3.7 and Cross-Chapter Box 7 in Chapter 3 for further discussion). CDR can have two very different functions in 1.5°C-consistent pathways. If deployed in the first half of the century, before net zero CO_2 emissions are reached, it neutralizes some of the remaining CO_2 emissions year by year and thus slows the accumulation of CO_2 in the atmosphere. In this first function it can be used to remain within the carbon budget and avoid overshoot. If CDR is deployed in the second half of the century after carbon neutrality has been established, it can still be used to neutralize some residual emissions from other sectors, but also to create net negative emissions that actively draw down the cumulative amount of CO_2 emissions to return below a 1.5°C warming level. In the second function, CDR enables temporary overshoot. The literature points to strong limitations to upscaling CDR (limiting its first abovementioned function) and to sustainability constraints (limiting both abovementioned functions) (Fuss et al., 2018; Minx et al., 2018; Nemet et al., 2018). Large uncertainty hence exists about what amount of CDR could actually be available before mid-century. Kriegler et al. (2018b) explore a case limiting CDR to 100 $GtCO_2$ until 2050, and the 1.5°C pathways with no or limited overshoot available in the report's database project 40–260 $GtCO_2$ CDR until the point of carbon neutrality (5th to 95th percentile; median 110 $GtCO_2$). Because gross CO_2 emissions in most cases exceed the remaining carbon budget by several hundred $GtCO_2$ and given the limits to CDR deployment until 2050, most of the 1.5°C-consistent pathways available to this assessment are overshoot pathways. However, the scenario database also contains nine non-overshoot pathways that remain below 1.5°C throughout the 21st century (Table 2.1).

2.3.3 Emissions Evolution in 1.5°C Pathways

This section assesses the salient temporal evolutions of climate forcers over the 21st century. It uses the classification of 1.5°C pathways presented in Section 2.1, which includes a Below-1.5°C class, as well as other classes with varying levels of projected overshoot (1.5°C-low-OS and 1.5°C-high-OS). First, aggregate-GHG benchmarks for 2030 are assessed. Subsequent sections assess long-lived climate forcers (LLCF) and short-lived climate forcers (SLCF) separately because they contribute in different ways to near-term, peak and long-term warming (Section 2.2, Cross-Chapter Box 2 in Chapter 1).

Estimates of aggregated GHG emissions in line with specific policy choices are often compared to near-term benchmark values from mitigation pathways to explore their consistency with long-term climate goals (Clarke et al., 2014; UNEP, 2016, 2017; UNFCCC, 2016). Benchmark emissions or estimates of peak years derived from IAMs provide guidelines or milestones that are consistent with achieving a given temperature level. While they do not set mitigation requirements in a strict sense, exceeding these levels in a given year almost invariably increases the mitigation challenges afterwards by increasing the rates of change and increasing the reliance on speculative technologies, including the possibility that its implementation becomes unachievable (see Cross-Chapter Box 3 in Chapter 1 for a discussion of feasibility concepts) (Luderer et al., 2013; Rogelj et al., 2013b; Clarke et al., 2014; Fawcett et al., 2015; Riahi et al., 2015; Kriegler et al., 2018a). These trade-offs are particularly pronounced in 1.5°C pathways and are discussed in Section 2.3.5. This section assesses Kyoto-GHG emissions in 2030 expressed in CO_2 equivalent (CO_2e) emissions using 100-year global warming potentials.[3]

Appropriate benchmark values of aggregated GHG emissions depend on a variety of factors. First and foremost, they are determined by the desired likelihood to keep warming below 1.5°C and the extent to which projected temporary overshoot is to be avoided (Sections 2.2, 2.3.2, and 2.3.5). For instance, median aggregated 2030 GHG emissions are about 10 $GtCO_2e\ yr^{-1}$ lower in 1.5°C-low-OS compared to 1.5°C-high-OS pathways, with respective interquartile ranges of 26–31 and 36–49 $GtCO_2e\ yr^{-1}$ (Table 2.4). These ranges correspond to about 25–30 and 35–48 $GtCO_2e\ yr^{-1}$ in 2030, respectively, when aggregated with 100-year Global Warming Potentials from the IPCC Second Assessment Report. The limited evidence available for pathways aiming to limit warming below 1.5°C without overshoot or with limited amounts of CDR (Grubler et al., 2018; Holz et al., 2018b; van Vuuren et al., 2018) indicates that under these conditions consistent emissions in 2030 would fall at the lower end and below the above mentioned ranges. Due to the small number of 1.5°C pathways with no overshoot in the report's database (Table 2.4) and the potential for a downward bias in the selection of underlying scenario assumptions, the headline range for 1.5°C pathways with no or limited overshoot is also assessed to be of the order of 25–30 $GtCO_2e\ yr^{-1}$. Ranges for the 1.5°C-low-OS and Lower-2°C classes only overlap outside their interquartile ranges, highlighting the more accelerated reductions in 1.5°C-consistent compared to 2°C-consistent pathways.

Appropriate emissions benchmark values also depend on the acceptable or desired portfolio of mitigation measures, representing clearly identified trade-offs and choices (Sections 2.3.4, 2.4, and 2.5.3) (Luderer et al., 2013; Rogelj et al., 2013a; Clarke et al., 2014; Krey et al., 2014a; Strefler et al., 2018b). For example, lower 2030 GHG emissions correlate with a lower dependence on the future availability and desirability of CDR (Strefler et al., 2018b). On the other hand, pathways that assume or anticipate only limited deployment of CDR during the 21st century imply lower emissions benchmarks over the coming decades, which are achieved in models through further reducing CO_2 emissions in the coming decades. The pathway archetypes used in the chapter illustrate this further (Figure 2.6). Under middle-of-the-road assumptions of technological and socioeconomic development, pathway S2 suggests emission benchmarks of 34, 12 and –8 $GtCO_2e\ yr^{-1}$ in the years 2030, 2050, and 2100, respectively. In contrast, a pathway that further limits overshoot and aims at eliminating the reliance on negative emissions technologies like BECCS as well as CCS (here labelled as the LED pathway) shows deeper emissions reductions in 2030 to limit the cumulative amount of CO_2 until net zero global CO_2 emissions (carbon neutrality). The LED pathway here suggests emission benchmarks of 25, 9 and 2 $GtCO_2e\ yr^{-1}$ in the years 2030, 2050, and 2100, respectively. However, a pathway that allows and plans for the successful large-scale deployment of BECCS by and beyond 2050 (S5) shows a shift in the opposite direction. The variation within and between the abovementioned ranges of 2030 GHG benchmarks hence depends strongly on societal choices and preferences related to the acceptability and availability of certain technologies.

Overall these variations do not strongly affect estimates of the 1.5°C-consistent timing of global peaking of GHG emissions. Both Below-1.5°C and 1.5°C-low-OS pathways show minimum–maximum ranges in 2030 that do not overlap with 2020 ranges, indicating the global GHG emissions peaked before 2030 in these pathways. Also, 2020 and 2030 GHG emissions in 1.5°C-high-OS pathways only overlap outside their interquartile ranges.

Kyoto-GHG emission reductions are achieved by reductions in CO_2 and non-CO_2 GHGs. The AR5 identified two primary factors that influence the depth and timing of reductions in non-CO_2 Kyoto-GHG emissions: (i) the abatement potential and costs of reducing the emissions of these gases and (ii) the strategies that allow making trade-offs between them (Clarke et al., 2014). Many studies indicate low-cost, near-term mitigation options in some sectors for non-CO_2 gases compared to supply-side measures for CO_2 mitigation (Clarke et al., 2014). A large share of this potential is hence already exploited in mitigation pathways in line with 2°C. At the same time, by mid-century and beyond, estimates of further reductions of non-CO_2 Kyoto-GHGs – in particular CH_4 and N_2O – are hampered by the absence of mitigation

[3] In this chapter GWP-100 values from the IPCC Fourth Assessement Report are used because emissions of fluorinated gases in the integrated pathways have been reported in this metric to the database. At a global scale, switching between GWP-100 values of the Second, Fourth or Fifth IPCC Assessment Reports could result in variations in aggregated Kyoto-GHG emissions of about ±5% in 2030 (UNFCCC, 2016).

options in the current generation of IAMs, which are hence not able to reduce residual emissions of sources linked to livestock production and fertilizer use (Clarke et al., 2014; Gernaat et al., 2015) (Sections 2.3.1.2, 2.4.4, Supplementary Material 2.SM.1.2). Therefore, while net CO2 emissions are projected to be markedly lower in 1.5°C-consistent compared to 2°C-consistent pathways, this is much less the case for methane (CH_4) and nitrous-oxide (N_2O) (Figures 2.6–2.7). This results in reductions of CO_2 being projected to take up the largest share of emissions reductions when moving between 1.5°C-consistent and 2°C-consistent pathways (Rogelj et al., 2015b, 2018; Luderer et al., 2018). If additional non-CO_2 mitigation measures are identified and adequately included in IAMs, they are expected to further contribute to mitigation efforts by lowering the floor of residual non-CO_2 emissions. However, the magnitude of these potential contributions has not been assessed as part of this report.

As a result of the interplay between residual CO_2 and non-CO_2 emissions and CDR, global GHG emissions reach net zero levels at different times in different 1.5°C-consistent pathways. Interquartile ranges of the years in which 1.5°C-low-OS and 1.5°C-high-OS reach net zero GHG emissions range from 2060 to 2080 (Table 2.4). A seesaw characteristic can be found between near-term emissions reductions and the timing of net zero GHG emissions. This is because pathways with limited emissions reductions in the next one to two decades require net negative CO_2 emissions later on (see earlier). Most 1.5°C-high-OS pathways lead to net zero GHG emissions in approximately the third quarter of this century, because all of them rely on significant amounts of annual net negative CO_2 emissions in the second half of the century to decline temperatures after overshoot (Table 2.4). However, in pathways that aim at limiting overshoot as much as possible or more slowly decline temperatures after their peak, emissions reach the point of net zero GHG emissions slightly later or at times never. Early emissions reductions in this case reduce the requirement for net negative CO_2 emissions. Estimates of 2030 GHG emissions in line with the current NDCs overlap with the highest quartile of 1.5°C-high-OS pathways (Cross-Chapter Box 9 in Chapter 4).

2.3.3.1 Emissions of long-lived climate forcers

Climate effects of long-lived climate forcers (LLCFs) are dominated by CO_2, with smaller contributions of N_2O and some fluorinated gases (Myhre et al., 2013; Blanco et al., 2014). Overall net CO_2 emissions in pathways are the result of a combination of various anthropogenic contributions (Figure 2.5) (Clarke et al., 2014): (i) CO_2 produced by fossil-fuel combustion and industrial processes, (ii) CO_2 emissions or removals from the agriculture, forestry and other land use (AFOLU) sector, (iii) CO_2 capture and sequestration (CCS) from fossil fuels or industrial activities before it is released to the atmosphere, (iv) CO_2 removal by technological means, which in current pathways is mainly achieved by BECCS and AFOLU-related CDR, although other options could be conceivable (see Chapter 4, Section 4.3.7). Pathways apply these four contributions in different configurations (Figure 2.5) depending on societal choices and preferences related to the acceptability and availability of certain technologies, the timing and stringency of near-term climate policy, and the ability to limit the demand that drives baseline emissions (Marangoni et al., 2017; Riahi et al., 2017; Grubler et al., 2018; Rogelj et al., 2018; van Vuuren et al., 2018), and come with very different implication for sustainable development (Section 2.5.3).

All 1.5°C pathways see global CO_2 emissions embark on a steady decline to reach (near) net zero levels around 2050, with 1.5°C-low-OS pathways reaching net zero CO_2 emissions around 2045–2055 (Table 2.4; Figure 2.5). Near-term differences between the various pathway classes are apparent, however. For instance, Below-1.5°C and 1.5°C-low-OS pathways show a clear shift towards lower CO_2 emissions in 2030 relative to other 1.5°C and 2°C pathway classes, although in all 1.5°C classes reductions are clear (Figure 2.6). These lower near-term emissions levels are a direct consequence of the former two pathway classes limiting cumulative CO_2 emissions until carbon neutrality in order to aim for a higher probability of limiting peak warming to 1.5°C (Section 2.2.2 and 2.3.2.2). In some cases, 1.5°C-low-OS pathways achieve net zero CO_2 emissions one or two decades later, contingent on 2030 CO_2 emissions in the lower quartile of the literature range, that is, below about 18 $GtCO_2\ yr^{-1}$. Median year-2030 global CO_2 emissions are of the order of 5–10 $GtCO_2\ yr^{-1}$ lower in Below-1.5°C compared to 1.5°C-low-OS pathways, which are in turn lower than 1.5°C-high-OS pathways (Table 2.4). Below-1.5°C and 1.5°C-low-OS pathways combined show a decline in global net anthropogenic CO_2 emissions of about 45% from 2010 levels by 2030 (40–60% interquartile range). Lower-2°C pathways show CO_2 emissions declining by about 25% by 2030 in most pathways (10–30% interquartile range). The 1.5°C-high-OS pathways show emissions levels that are broadly similar to the 2°C-consistent pathways in 2030.

The development of CO_2 emissions in the second half of the century in 1.5°C pathways is characterized by the need to stay or return within a carbon budget. Figure 2.6 shows net CO_2 and N_2O emissions from various sources in 2050 and 2100 in 1.5°C pathways in the literature. Virtually all 1.5°C pathways obtain net negative CO_2 emissions at some point during the 21st century, but the extent to which net negative emissions are relied upon varies substantially (Figure 2.6, Table 2.4). This net withdrawal of CO_2 from the atmosphere compensates for residual long-lived non-CO_2 GHG emissions that also accumulate in the atmosphere (like N2O) or cancels some of the build-up of CO_2 due to earlier emissions to achieve increasingly higher likelihoods that warming stays or returns below 1.5°C (see Section 2.3.4 for a discussion of various uses of CDR). Even non-overshoot pathways that aim at achieving temperature stabilization would hence deploy a certain amount of net negative CO_2 emissions to offset any accumulating long-lived non-CO_2 GHGs. The 1.5°C overshoot pathways display significantly larger amounts of annual net negative CO_2 emissions in the second half of the century. The larger the overshoot the more net negative CO_2 emissions are required to return temperatures to 1.5°C by the end of the century (Table 2.4, Figure 2.1).

N_2O emissions decline to a much lesser extent than CO_2 in currently available 1.5°C pathways (Figure 2.6). Current IAMs have limited emissions-reduction potentials (Gernaat et al., 2015) (Sections 2.3.1.2, 2.4.4, Supplementary Material 2.SM.1.2), reflecting the difficulty of eliminating N_2O emission from agriculture (Bodirsky et al., 2014). Moreover, the reliance of some pathways on significant amounts of bioenergy after mid-century (Section 2.4.2) coupled to a substantial use of nitrogen fertilizer (Popp et al., 2017) also makes reducing N_2O emissions harder (for example, see pathway S5 in Figure 2.6). As

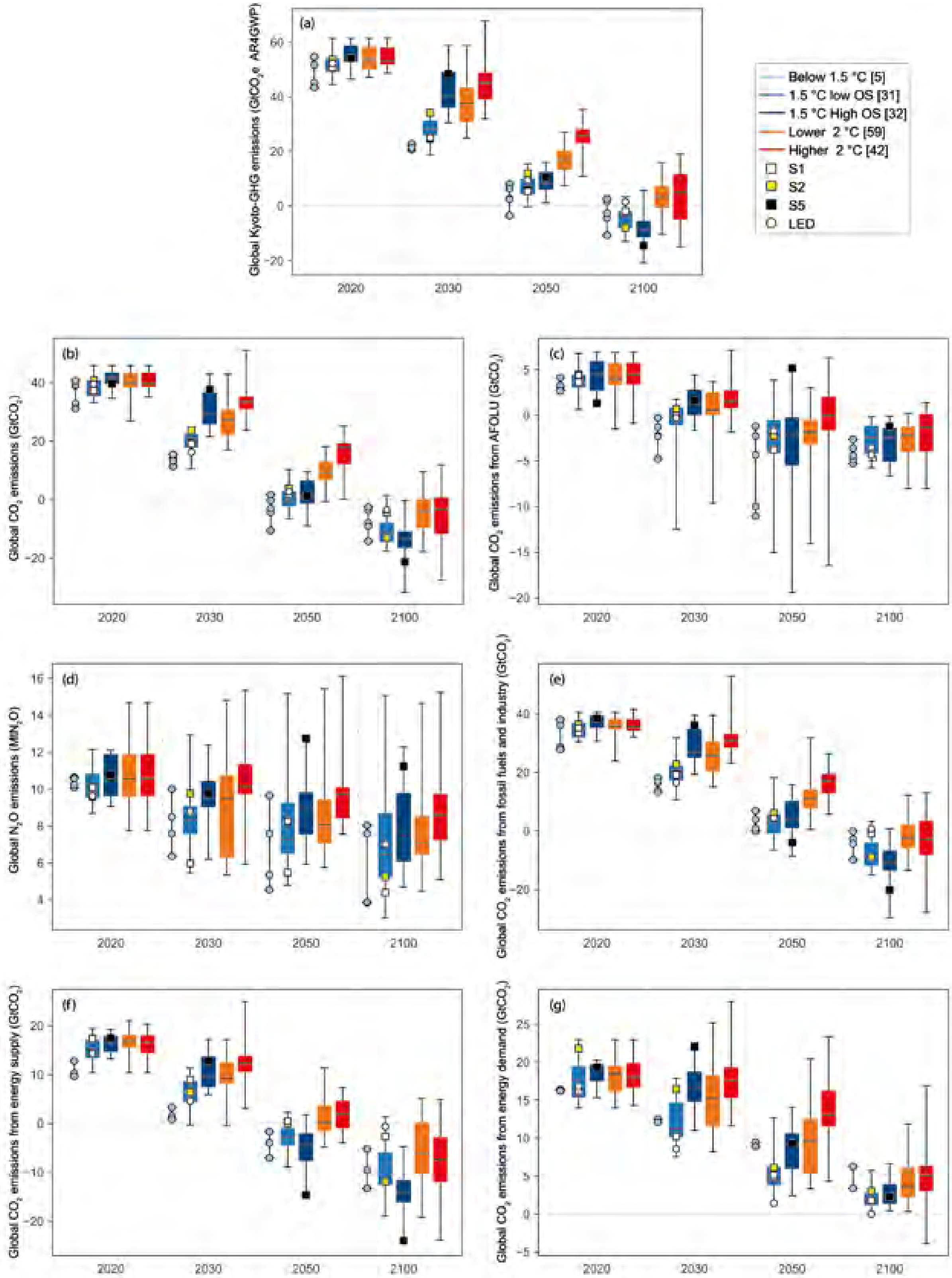


Figure 2.6 | Annual global emissions characteristics for 2020, 2030, 2050, 2100. Data are shown for (a) Kyoto-GHG emissions, and (b) global total CO_2 emissions, (c) CO_2 emissions from the agriculture, forestry and other land use (AFOLU) sector, (d) global N_2O emissions, and (e) CO_2 emissions from fossil fuel use and industrial processes. The latter is also split into (f) emissions from the energy supply sector (electricity sector and refineries) and (g) direct emissions from fossil-fuel use in energy demand sectors (industry, buildings, transport) (bottom row). Horizontal black lines show the median, boxes show the interquartile range, and whiskers the minimum–maximum range. Icons indicate the four pathway archetypes used in this chapter. In case less than seven data points are available in a class, the minimum–maximum range and single data points are shown. Kyoto-GHG, emissions in the top panel are aggregated with AR4 GWP-100 and contain CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6. NF_3 is typically not reported by IAMs. Scenarios with year-2010 Kyoto-GHG emissions outside the range assessed by IPCC AR5 WGIII assessed are excluded (IPCC, 2014b).

a result, sizeable residual N_2O emissions are currently projected to continue throughout the century, and measures to effectively mitigate them will be of continued relevance for 1.5°C societies. Finally, the reduction of nitrogen use and N_2O emissions from agriculture is already a present-day concern due to unsustainable levels of nitrogen pollution (Bodirsky et al., 2012). Section 2.4.4 provides a further assessment of the agricultural non-CO_2 emissions reduction potential.

2.3.3.2 Emissions of short-lived climate forcers and fluorinated gases

SLCFs include shorter-lived GHGs like CH_4 and some fluorinated gases as well as particles (aerosols), their precursors and ozone precursors. SLCFs are strongly mitigated in 1.5°C pathways, as is the case for 2°C pathways (Figure 2.7). SLCF emissions ranges of 1.5°C and 2°C pathway classes strongly overlap, indicating that the main incremental mitigation contribution between 1.5°C and 2°C pathways comes from CO_2 (Luderer et al., 2018; Rogelj et al., 2018). CO_2 and SLCF emissions reductions are connected in situations where SLCF and CO_2 are co-emitted by the same process, for example, with coal-fired power plants (Shindell and Faluvegi, 2010) or within the transport sector (Fuglestvedt et al., 2010). Many CO_2-targeted mitigation measures in industry, transport and agriculture (Sections 2.4.3–4) hence also reduce non-CO_2 forcing (Rogelj et al., 2014b; Shindell et al., 2016).

Despite the fact that methane has a strong warming effect (Myhre et al., 2013; Etminan et al., 2016), current 1.5°C-consistent pathways still project significant emissions of CH_4 by 2050, indicating only a limited CH_4 mitigation potential in IAM analyses (Gernaat et al., 2015) (Sections 2.3.1.2, 2.4.4, Table 2.SM.2). The AFOLU sector contributes an important share of the residual CH_4 emissions until mid-century, with its relative share increasing from slightly below 50% in 2010 to around 55–70% in 2030, and 60–80% in 2050 in 1.5°C-consistent pathways (interquartile range across 1.5°C-consistent pathways for projections). Many of the proposed measures to target CH_4 (Shindell et al., 2012; Stohl et al., 2015) are included in 1.5°C-consistent pathways (Figure 2.7), though not all (Sections 2.3.1.2, 2.4.4, Table 2.SM.2). A detailed assessment of measures to further reduce AFOLU CH_4 emissions has not been conducted.

Overall reductions of SLCFs can have effects of either sign on temperature depending on the balance between cooling and warming agents. The reduction in SO_2 emissions is the dominant single effect as it weakens the negative total aerosol forcing. This means that reducing all SLCF emissions to zero would result in a short-term warming, although this warming is *unlikely* to be more than 0.5°C (Section 2.2 and Figure 1.5 (Samset et al., 2018)). Because of this effect, suggestions have been proposed that target the warming agents only (referred to as short-lived climate pollutants or SLCPs instead of the more general short-lived climate forcers; e.g., Shindell et al., 2012), though aerosols are often emitted in varying mixtures of warming and cooling species (Bond et al., 2013). Black carbon (BC) emissions reach similar levels across 1.5°C-consistent and 2°C-consistent pathways available in the literature, with interquartile ranges of emissions reductions across pathways of 16–34% and 48–58% in 2030 and 2050, respectively, relative to 2010 (Figure 2.7). Recent studies have identified further reduction potentials for the near term, with global reductions of about 80% being suggested (Stohl et al., 2015; Klimont et al., 2017). Because the dominant sources of certain aerosol mixtures are emitted during the combustion of fossil fuels, the rapid phase-out of unabated fossil fuels to avoid CO_2 emissions would also result in removal of these either warming or cooling SLCF air-pollutant species. Furthermore, SLCFs are also reduced by efforts to reduce particulate air pollution. For example, year-2050 SO_2 emissions (precursors of sulphate aerosol) in 1.5°C-consistent pathways are about 75–85% lower than their 2010 levels. Some caveats apply, for example, if residential biomass use would be encouraged in industrialised countries in stringent mitigation pathways without appropriate pollution control measures, aerosol concentrations could also increase (Sand et al., 2015; Stohl et al., 2015).

Emissions of fluorinated gases (IPCC/TEAP, 2005; US EPA, 2013; Velders et al., 2015; Purohit and Höglund-Isaksson, 2017) in 1.5°C-consistent pathways are reduced by roughly 75–80% relative to 2010 levels (interquartile range across 1.5°C-consistent pathways) in 2050, with no clear differences between the classes. Although unabated hydrofluorocarbon (HFC) emissions have been projected to increase (Velders et al., 2015), the Kigali Amendment recently added HFCs to the basket of gases controlled under the Montreal Protocol (Höglund-Isaksson et al., 2017). As part of the larger group of fluorinated gases, HFCs are also assumed to decline in 1.5°C-consistent pathways. Projected reductions by 2050 of fluorinated gases under 1.5°C-consistent pathways are deeper than published estimates of what a full implementation of the Montreal Protocol including its Kigali Amendment would achieve (Höglund-Isaksson et al., 2017), which project roughly a halving of fluorinated gas emissions in 2050 compared to 2010. Assuming the application of technologies that are currently commercially available and at least to a limited extent already tested and implemented, potential fluorinated gas emissions reductions of more than 90% have been estimated (Höglund-Isaksson et al., 2017).

There is a general agreement across 1.5°C-consistent pathways that until 2030 forcing from the warming SLCFs is reduced less strongly than the net cooling forcing from aerosol effects, compared to 2010. As a result, the net forcing contributions from all SLCFs combined are projected to increase slightly by about 0.2–0.3 W m^{-2}, compared to 2010. Also, by the end of the century, about 0.1–0.3 W m^{-2} of SLCF forcing is generally currently projected to remain in 1.5°C-consistent scenarios (Figure 2.8). This is similar to developments in 2°C-consistent pathways (Rose et al., 2014b; Riahi et al., 2017), which show median forcing contributions from these forcing agents that are generally no more than 0.1 W m^{-2} higher. Nevertheless, there can be additional gains from targeted deeper reductions of CH_4 emissions and tropospheric ozone precursors, with some scenarios projecting less than 0.1 W m^{-2} forcing from SLCFs by 2100.

2.3.4 CDR in 1.5°C Pathways

Deep mitigation pathways assessed in AR5 showed significant deployment of CDR, in particular through BECCS (Clarke et al., 2014). This has led to increased debate about the necessity, feasibility and desirability of large-scale CDR deployment, sometimes also called 'negative emissions technologies' in the literature (Fuss et al., 2014; Anderson and Peters, 2016; Williamson, 2016; van Vuuren et al.,

Table 2.4 | Emissions in 2030, 2050 and 2100 in 1.5°C and 2°C scenario classes and absolute annual rates of change between 2010–2030, 2020–2030 and 2030–2050, respectively.

Values show median and interquartile range across available scenarios (25th and 75th percentile given in brackets). If fewer than seven scenarios are available (*), the minimum–maximum range is given instead. Kyoto-GHG emissions are aggregated with GWP-100 values from IPCC AR4. Emissions in 2010 for total net CO_2, CO_2 from fossil-fuel use and industry, and AFOLU CO_2 are estimated at 38.5, 33.4, and 5 $GtCO_2$ yr^{-1}, respectively (Le Quéré et al., 2018). Percentage reduction numbers included in headline statement C.1 in the Summary for Policymakers are computed relative to 2010 emissions in each individual pathway, and hence differ slightly from a case where reductions are computed relative to the historical 2010 emissions reported above. A difference is reported in estimating the 'anthropogenic' sink by countries or the global carbon modelling community (Grassi et al., 2017), and AFOLU CO_2 estimates reported here are thus not necessarily comparable with countries' estimates. Scenarios with year-2010 Kyoto-GHG emissions outside the range assessed by IPCC AR5 WGIII are excluded (IPCC, 2014b), as are scenario duplicates that would bias ranges towards a single study.

			Annual emissions/sequestration ($GtCO_2$ yr^{-1})			Absolute Annual Change ($GtCO_2/yr^{-1}$)			Timing of Global Zero
Name	**Category**	**#**	**2030**	**2050**	**2100**	**2010–2030**	**2020–2030**	**2030–2050**	**Year**
Total CO_2 (net)	**Below-1.5°C**	5*	13.4 (15.4, 11.4)	−3.0 (1.7, −10.6)	−8.0 (−2.6, −14.2)	−1.2 (−1.0, −1.3)	−2.5 (−1.8, −2.8)	−0.8 (−0.7, −1.2)	2044 (2037, 2054)
	1.5°C-low-OS	37	20.8 (22.2, 18.0)	−0.4 (2.7, −2.0)	−10.8 (−8.1, −14.3)	−0.8 (−0.7, −1.0)	−1.7 (−1.4, −2.3)	−1.0 (−0.8, −1.2)	2050 (2047, 2055)
	1.5°C with no or limited OS	42	20.3 (22.0, 15.9)	−0.5 (2.2, −2.8)	−10.2 (−7.6, −14.2)	−0.9 (−0.7, −1.1)	−1.8 (−1.5, −2.3)	−1.0 (−0.8, −1.2)	2050 (2046, 2055)
	1.5°C-high-OS	36	29.1 (36.4, 26.0)	1.0 (6.3, −1.2)	−13.8 (−11.1, −16.4)	−0.4 (0.0, −0.6)	−1.1 (−0.5, −1.5)	−1.3 (−1.1, −1.8)	2052 (2049, 2059)
	Lower-2°C	54	28.9 (33.7, 24.5)	9.9 (13.1, 6.5)	−5.1 (−2.6, −10.3)	−0.4 (−0.2, −0.6)	−1.1 (−0.8, −1.6)	−0.9 (−0.8, −1.2)	2070 (2063, 2079)
	Higher-2°C	54	33.5 (35.0, 31.0)	17.9 (19.1, 12.2)	−3.3 (0.6, −11.5)	−0.2 (−0.0, −0.4)	−0.7 (−0.5, −0.9)	−0.8 (−0.6, −1.0)	2085 (2070, post–2100)
CO_2 from fossil fuels and industry (gross)	**Below-1.5°C**	5*	18.0 (21.4, 13.8)	10.5 (20.9, 0.3)	8.3 (11.6, 0.1)	−0.7 (−0.6, −1)	−1.5 (−0.9, −2.2)	−0.4 (0, −0.7)	-
	1.5°C-low-OS	37	22.1 (24.4, 18.7)	10.3 (14.1, 7.8)	5.6 (8.1, 2.6)	−0.5 (−0.4, −0.6)	−1.3 (−0.9, −1.7)	−0.6 (−0.5, −0.7)	-
	1.5°C with no or limited OS	42	21.6 (24.2, 18.0)	10.3 (13.8, 7.7)	6.1 (8.4, 2.6)	−0.5 (−0.4, −0.7)	−1.3 (−0.9, −1.8)	−0.6 (−0.4, −0.7)	-
	1.5°C-high-OS	36	27.8 (37.1, 25.6)	13.1 (17.0, 11.6)	6.6 (8.8, 2.8)	−0.2 (0.2, −0.3)	−0.8 (−0.2, −1.1)	−0.7 (−0.6, −1.0)	-
	Lower-2°C	54	27.7 (31.5, 23.5)	15.4 (19.0, 11.1)	7.2 (10.4, 3.7)	−0.2 (−0.0, −0.4)	−0.8 (−0.5, −1.2)	−0.6 (−0.5, −0.8)	-
	Higher-2°C	54	31.3 (33.4, 28.7)	19.2 (22.6, 17.1)	8.1 (10.9, 5.0)	−0.1 (0.1, −0.2)	−0.5 (−0.2, −0.7)	−0.6 (−0.5, −0.7)	-
CO_2 from fossil fuels and industry (net)	**Below-1.5°C**	5*	16.4 (18.2, 13.5)	1.0 (7.0, 0)	−2.7 (0, −9.8)	−0.8 (−0.7, −1)	−1.8 (−1.2, −2.2)	−0.6 (−0.5, −0.9)	-
	1.5°C-low-OS	37	20.6 (22.2, 17.5)	3.2 (5.6, −0.6)	−8.5 (−4.1, −11.6)	−0.6 (−0.5, −0.7)	−1.4 (−1.1, −1.8)	−0.8 (−0.7, −1.1)	-
	1.5°C with no or limited OS	42	20.1 (22.1, 16.8)	3.0 (5.6, 0.0)	−8.3 (−3.5, −10.8)	−0.6 (−0.5, −0.8)	−1.4 (−1.1, −1.9)	−0.8 (−0.7, −1.1)	-
	1.5°C-high-OS	36	26.9 (34.7, 25.3)	4.2 (10.0, 1.2)	−10.7 (−6.9, −13.2)	−0.3 (0.1, −0.3)	−0.9 (−0.3, −1.2)	−1.2 (−0.9, −1.5)	-
	Lower-2°C	54	28.2 (31.0, 23.1)	11.8 (14.1, 6.2)	−3.1 (−0.7, −6.4)	−0.2 (−0.1, −0.4)	−0.8 (−0.5, −1.2)	−0.8 (−0.7, −1.0)	-
	Higher-2°C	54	31.0 (33.0, 28.7)	17.0 (19.3, 13.1)	−2.9 (3.3, −8.0)	−0.1 (0.1, −0.2)	−0.5 (−0.2, −0.7)	−0.7 (−0.5, −1.0)	-
CO_2 from AFOLU	**Below-1.5°C**	5*	−2.2 (−0.3, −4.8)	−4.4 (−1.2, −11.1)	−4.4 (−2.6, −5.3)	−0.3 (−0.2, −0.4)	−0.5 (−0.4, −0.8)	−0.1 (0, −0.4)	-
	1.5°C-low-OS	37	−0.1 (0.8, −1.0)	−2.3 (−0.6, −4.1)	−2.4 (−1.2, −4.2)	−0.2 (−0.2, −0.3)	−0.4 (−0.3, −0.5)	−0.1 (−0.1, −0.2)	-
	1.5°C with no or limited OS	42	−0.1 (0.7, −1.3)	−2.6 (−0.6, −4.5)	−2.6 (−1.3, −4.2)	−0.2 (−0.2, −0.3)	−0.4 (−0.3, −0.5)	−0.1 (−0.1, −0.2)	-
	1.5°C-high-OS	36	1.2 (2.7, 0.1)	−2.1 (−0.3, −5.4)	−2.4 (−1.5, −5.0)	−0.1 (−0.1, −0.3)	−0.2 (−0.1, −0.5)	−0.2 (−0.0, −0.3)	-
	Lower-2°C	54	1.4 (2.8, 0.3)	−1.4 (−0.5, −2.7)	−2.4 (−1.3, −4.2)	−0.2 (−0.1, −0.2)	−0.3 (−0.2, −0.4)	−0.1 (−0.1, −0.2)	-
	Higher-2°C	54	1.5 (2.7, 0.8)	−0.0 (1.9, −1.6)	−1.3 (0.1, −3.9)	−0.2 (−0.1, −0.2)	−0.2 (−0.1, −0.4)	−0.1 (−0.0, −0.1)	-
Bioenergy combined with carbon capture and storage (BECCS)	**Below-1.5°C**	5*	0.4 (1.1, 0)	3.4 (8.3, 0)	5.7 (13.4, 0)	0 (0.1, 0)	0 (0.1, 0)	0.2 (0.4, 0)	-
	1.5°C-low-OS	36	0.3 (1.1, 0.0)	4.6 (6.4, 3.8)	12.4 (15.6, 7.6)	0.0 (0.1, 0.0)	0.0 (0.1, 0.0)	0.2 (0.3, 0.2)	-
	1.5°C with no or limited OS	41	0.4 (1.0, 0.0)	4.5 (6.3, 3.4)	12.4 (15.0, 6.4)	0.0 (0.1, 0.0)	0.0 (0.1, 0.0)	0.2 (0.3, 0.2)	-
	1.5°C-high-OS	36	0.1 (0.4, 0.0)	6.8 (9.5, 3.7)	14.9 (16.3, 12.1)	0.0 (0.0, 0.0)	0.0 (0.0, 0.0)	0.3 (0.4, 0.2)	-
	Lower-2°C	54	0.1 (0.3, 0.0)	3.6 (4.6, 1.8)	9.5 (12.1, 6.9)	0.0 (0.0, 0.0)	0.0 (0.0, 0.0)	0.2 (0.2, 0.1)	-
	Higher-2°C	47	0.1 (0.2, 0.0)	3.0 (4.9, 1.6)	10.8 (15.3, 8.2) [46]	0.0 (0.0, 0.0)	0.0 (0.0, 0.0)	0.1 (0.2, 0.1)	-
Kyoto GHG (AR4) [$GtCO_2e$]	**Below-1.5°C**	5*	22.1 (22.8, 20.7)	2.7 (8.1, −3.5)	−2.6 (2.7, −10.7)	−1.4 (−1.3, −1.5)	−2.9 (−2.1, −3.3)	−0.9 (−0.7, −1.3)	2066 (2044, post–2100)
	1.5°C-low-OS	31	27.9 (31.1, 26.0)	7.0 (9.9, 4.5)	−3.8 (−2.1, −7.9)	−1.1 (−0.9, −1.2)	−2.3 (−1.8, −2.8)	−1.1 (−0.9, −1.2)	2068 (2061, 2080)
	1.5°C with no or limited OS	36	27.4 (30.9, 24.7)	6.5 (9.6, 4.2)	−3.7 (−1.8, −7.8)	−1.1 (−1.0, −1.3)	−2.4 (−1.9, −2.9)	−1.1 (−0.9, −1.2)	2067 (2061, 2084)
	1.5°C-high-OS	32	40.4 (48.9, 36.3)	8.4 (12.3, 6.2)	−8.5 (−5.7, −11.2)	−0.5 (−0.0, −0.7)	−1.3 (−0.6, −1.8)	−1.5 (−1.3, −2.1)	2063 (2058, 2067)
	Lower-2°C	46	39.6 (45.1, 35.7)	18.3 (20.4, 15.2)	2.1 (4.2, −2.4)	−0.5 (−0.1, −0.7)	−1.5 (−0.9, −2.2)	−1.1 (−0.9, −1.2)	post–2100 (2090 post–2100)
	Higher-2°C	42	45.3 (48.5, 39.3)	25.9 (27.9, 23.3)	5.2 (11.5, −4.8)	−0.2 (−0.0, −0.6)	−1.0 (−0.6, −1.2)	−1.0 (−0.7, −1.2)	post–2100 (2085 post–2100)

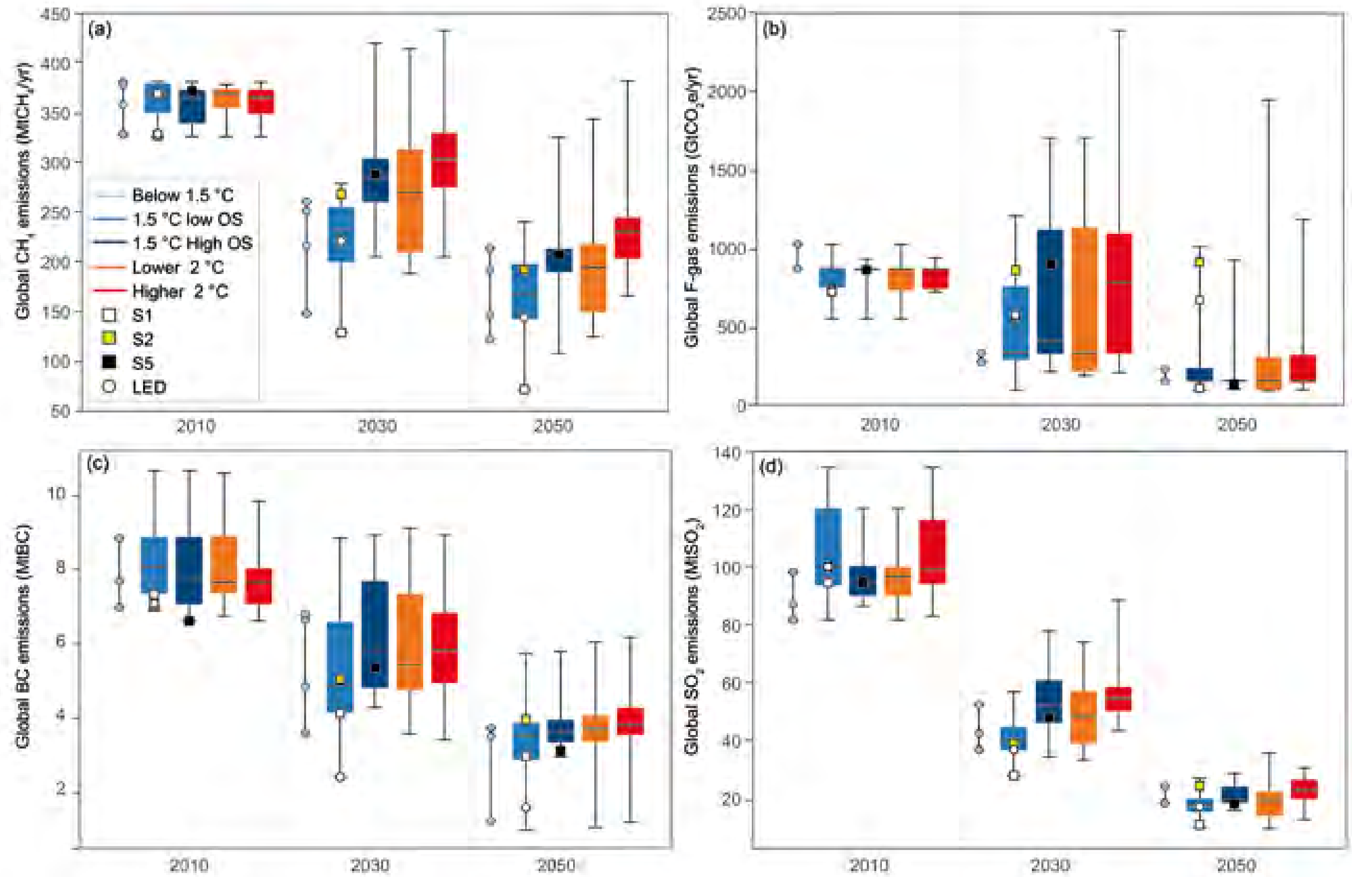


Figure 2.7 | Global characteristics of a selection of short-lived non-CO_2 emissions until mid-century for five pathway classes used in this chapter. Data are shown for (a) methane (CH_4), (b) fluorinated gases (F-gas), (c) black carbon (BC), and (d) sulphur dioxide (SO_2) emissions. Boxes with different colours refer to different scenario classes. Icons on top the ranges show four illustrative pathway archetypes that apply different mitigation strategies for limiting warming to 1.5°C. Boxes show the interquartile range, horizontal black lines the median, and whiskers the minimum–maximum range. F-gases are expressed in units of CO_2-equivalence computed with 100-year Global Warming Potentials reported in IPCC AR4.

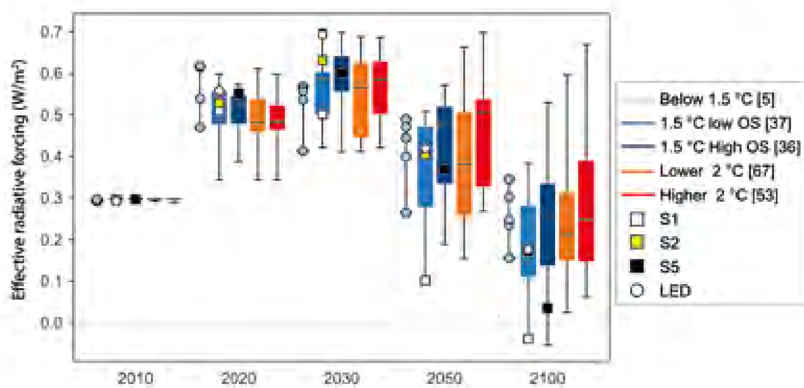


Figure 2.8 | Estimated aggregated effective radiative forcing of SLCFs for 1.5°C and 2°C pathway classes in 2010, 2020, 2030, 2050, and 2100, as estimated by the FAIR model (Smith et al., 2018). Aggregated short-lived climate forcer (SLCF) radiative forcing is estimated as the difference between total anthropogenic radiative forcing and the sum of CO_2 and N_2O radiative forcing over time, and is expressed relative to 1750. Symbols indicate the four pathways archetypes used in this chapter. Horizontal black lines indicate the median, boxes the interquartile range, and whiskers the minimum–maximum range per pathway class. Because very few pathways fall into the Below-1.5°C class, only the minimum–maximum is provided here.

2017a; Obersteiner et al., 2018). Most CDR technologies remain largely unproven to date and raise substantial concerns about adverse side-effects on environmental and social sustainability (Smith et al., 2015; Dooley and Kartha, 2018). A set of key questions emerge: how strongly do 1.5°C-consistent pathways rely on CDR deployment and what types of CDR measures are deployed at which scale? How does this vary across available 1.5°C-consistent pathways and on which factors does it depend? How does CDR deployment compare between 1.5°C- and 2°C-consistent pathways and how does it compare with the findings at the time of the AR5? How does CDR deployment in 1.5°C-consistent pathways relate to questions about availability, policy implementation and sustainable development implications that have been raised about CDR technologies? The first three questions are assessed in this section with the goal to provide an overview and assessment of CDR deployment in the 1.5°C pathway literature. The fourth question is only touched upon here and is addressed in greater depth in Chapter 4, Section 4.3.7, which assesses the rapidly growing literature on costs, potentials, availability and sustainability implications of individual CDR measures (Minx et al., 2017, 2018; Fuss et al., 2018; Nemet et al., 2018). In addition, Section 2.3.5 assesses the relationship between delayed mitigation action and increased CDR reliance. CDR deployment is intricately linked to the land-use transformation in 1.5°C-consistent pathways. This transformation is assessed in Section 2.4.4. Bioenergy and BECCS impacts on sustainable land management are further assessed in Chapter 3, Section 3.6.2 and Cross-Chapter Box 7 in Chapter 3. Ultimately, a comprehensive assessment of the land implication of land-based CDR measures will be provided in the IPCC AR6 Special Report on Climate Change and Land (SRCCL).

2.3.4.1 CDR technologies and deployment levels in 1.5°C pathways

A number of approaches to actively remove carbon-dioxide from the atmosphere are increasingly discussed in the literature (Minx et al., 2018) (see also Chapter 4, Section 4.3.7). Approaches under consideration include the enhancement of terrestrial and coastal carbon storage in plants and soils such as afforestation and reforestation (Canadell and Raupach, 2008), soil carbon enhancement (Paustian et al., 2016; Frank et al., 2017; Zomer et al., 2017), and other conservation, restoration, and management options for natural and managed land (Griscom et al., 2017) and coastal ecosystems (McLeod et al., 2011). Biochar sequestration (Woolf et al., 2010; Smith, 2016; Werner et al., 2018) provides an additional route for terrestrial carbon storage. Other approaches are concerned with storing atmospheric carbon dioxide in geological formations. They include the combination of biomass use for energy production with carbon capture and storage (BECCS) (Obersteiner et al., 2001; Keith and Rhodes, 2002; Gough and Upham, 2011) and direct air capture with storage (DACCS) using chemical solvents and sorbents (Zeman and Lackner, 2004; Keith et al., 2006; Socolow et al., 2011). Further approaches investigate the mineralization of atmospheric carbon dioxide (Mazzotti et al., 2005; Matter et al., 2016), including enhanced weathering of rocks (Schuiling and Krijgsman, 2006; Hartmann et al., 2013; Strefler et al., 2018a). A fourth group of approaches is concerned with the sequestration of carbon dioxide in the oceans, for example by means of ocean alkalinization (Kheshgi, 1995; Rau, 2011; Ilyina et al., 2013; Lenton et al., 2018). The costs, CDR potential and environmental side effects of several of these measures are increasingly investigated and compared in the literature, but large uncertainties remain, in particular concerning the feasibility and impact of large-scale deployment of CDR measures (The Royal Society, 2009; Smith et al., 2015; Psarras et al., 2017; Fuss et al., 2018) (see Chapter 4.3.7). There are also proposals to remove methane, nitrous oxide and halocarbons via photocatalysis from the atmosphere (Boucher and Folberth, 2010; de Richter et al., 2017), but a broader assessment of their effectiveness, cost and sustainability impacts is lacking to date.

Only some of these approaches have so far been considered in IAMs (see Section 2.3.1.2). The mitigation scenario literature up to AR5 mostly included BECCS and, to a more limited extent, afforestation and reforestation (Clarke et al., 2014). Since then, some 2°C- and 1.5°C-consistent pathways including additional CDR measures such as DACCS (Chen and Tavoni, 2013; Marcucci et al., 2017; Lehtilä and Koljonen, 2018; Strefler et al., 2018b) and soil carbon sequestration (Frank et al., 2017) have become available. Other, more speculative approaches, in particular ocean-based CDR and removal of non-CO_2 gases, have not yet been taken up by the literature on mitigation pathways. See Supplementary Material 2.SM.1.2 for an overview on the coverage of CDR measures in models which contributed pathways to this assessment. Chapter 4.3.7 assesses the potential, costs, and sustainability implications of the full range of CDR measures.

Integrated assessment modelling has not yet explored land conservation, restoration and management options to remove carbon dioxide from the atmosphere in sufficient depth, despite land management having a potentially considerable impact on the terrestrial carbon stock (Erb et al., 2018). Moreover, associated CDR measures have low technological requirements, and come with potential environmental and social co-benefits (Griscom et al., 2017). Despite the evolving capabilities of IAMs in accounting for a wider range of CDR measures, 1.5°C-consistent pathways assessed here continue to predominantly rely on BECCS and afforestation/reforestation (see Supplementary Material 2.SM.1.2). However, IAMs with spatially explicit land-use modelling include a full accounting of land-use change emissions comprising carbon stored in the terrestrial biosphere and soils. Net CDR in the AFOLU sector, including but not restricted to afforestation and reforestation, can thus in principle be inferred by comparing AFOLU CO_2 emissions between a baseline scenario and a 1.5°C-consistent pathway from the same model and study. However, baseline AFOLU CO_2 emissions can not only be reduced by CDR in the AFOLU sector but also by measures to reduce deforestation and preserve land carbon stocks. The pathway literature and pathway data available to this assessment do not yet allow separating the two contributions. As a conservative approximation, the additional net negative AFOLU CO_2 emissions below the baseline are taken as a proxy for AFOLU CDR in this assessment. Because this does not include CDR that was deployed before reaching net zero AFOLU CO_2 emissions, this approximation is a lower-bound for terrestrial CDR in the AFOLU sector (including all mitigation-policy-related factors that lead to net negative AFOLU CO_2 emissions).

The scale and type of CDR deployment in 1.5°C-consistent pathways varies widely (Figure 2.9 and 2.10). Overall CDR deployment over the 21st century is substantial in most of the pathways, and deployment levels cover a wide range, on the order of 100–1000 Gt CO_2 in 1.5°C pathways with no or limited overshoot (730 [260–1030] $GtCO_2$, for median and 5th–95th percentile range). Both BECCS (480 [0–1000] $GtCO_2$ in 1.5°C pathways with no or limited overshoot) and AFOLU CDR measures including afforestation and reforestation (210 [10-540] $GtCO_2$ in 1.5°C pathways with no or limited overshoot) can play a major role,[4] but for both cases pathways exist where they play no role at all. This shows the flexibility in substituting between individual CDR measures, once a portfolio of options becomes available. The high end of the CDR deployment range is populated by high overshoot pathways, as illustrated by pathway archetype S5 based on SSP5 (fossil-fuelled development, see Section 2.3.1.1) and characterized by very large BECCS deployment to return warming to 1.5°C by 2100 (Kriegler et al., 2017). In contrast, the low end is populated by a few pathways with no or limited overshoot that limit CDR to on the order of 100–200 $GtCO_2$ over the 21st century, coming entirely from terrestrial CDR measures with no or small use of BECCS. These are pathways with very low energy demand facilitating the rapid phase-out of fossil fuels and process emissions that exclude BECCS and CCS use (Grubler et al., 2018) and/or pathways with rapid shifts to sustainable food consumption freeing up sufficient land areas for afforestation and reforestation (Haberl et al., 2011; van Vuuren et al., 2018). Some pathways use neither BECCS nor afforestation but still rely on CDR through considerable net negative CO_2 emissions in the AFOLU sector around mid-century (Holz et al., 2018b). We conclude that the role of BECCS as a dominant CDR measure in deep mitigation pathways has been reduced since the time of the AR5. This is related to three factors: a larger variation of underlying assumptions about socio-economic drivers (Riahi et al., 2017; Rogelj et al., 2018) and associated energy (Grubler et al., 2018) and food demand (van Vuuren et al., 2018); the incorporation of a larger portfolio of mitigation and CDR options (Marcucci et al., 2017; Grubler et al., 2018; Lehtilä and Koljonen, 2018; Liu et al., 2018; van Vuuren et al., 2018); and targeted analysis of deployment limits for (specific) CDR measures (Holz et al., 2018b; Kriegler et al., 2018a; Strefler et al., 2018b), including the availability of bioenergy (Bauer et al., 2018), CCS (Krey et al., 2014a; Grubler et al., 2018) and afforestation (Popp et al., 2014b, 2017). As additional CDR measures are being built into IAMs, the prevalence of BECCS is expected to be further reduced.

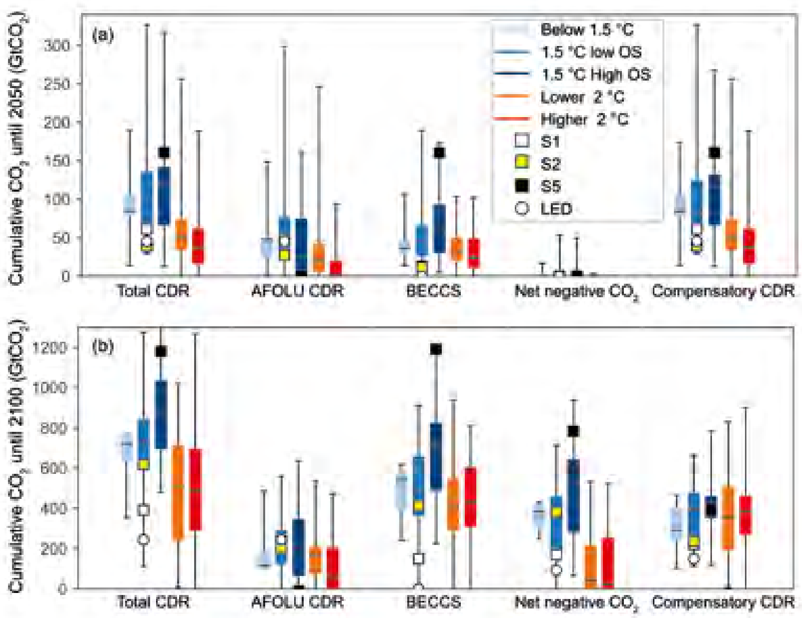


Figure 2.9 | Cumulative CDR deployment in 1.5°C-consistent pathways in the literature as reported in the database collected for this assessment until 2050 (panel a) and until 2100 (panel b). Total CDR comprises all forms of CDR, including AFOLU CDR and BECCS, and, in a few pathways, other CDR measures like DACCS. It does not include CCS combined with fossil fuels (which is not a CDR technology as it does not result in active removal of CO_2 from the atmosphere). AFOLU CDR has not been reported directly and is hence represented by means of a proxy: the additional amount of net negative CO_2 emissions in the AFOLU sector compared to a baseline scenario (see text for a discussion). 'Compensatory CO_2' depicts the cumulative amount of CDR that is used to neutralize concurrent residual CO_2 emissions. 'Net negative CO_2' describes the additional amount of CDR that is used to produce net negative CO_2 emissions, once residual CO_2 emissions are neutralized. The two quantities add up to total CDR for individual pathways (not for percentiles and medians, see Footnote 4).

As discussed in Section 2.3.2, CDR can be used in two ways in mitigation pathways: (i) to move more rapidly towards the point of carbon neutrality and maintain it afterwards in order to stabilize global mean temperature rise, and (ii) to produce net negative CO_2 emissions, drawing down anthropogenic CO_2 in the atmosphere in order to decline global mean temperature after an overshoot peak (Kriegler et al., 2018b; Obersteiner et al., 2018). Both uses are important in 1.5°C-consistent pathways (Figure 2.9 and 2.10). Because of the tighter remaining 1.5°C carbon budget, and because many pathways in the literature do not restrict exceeding this budget prior to 2100, the relative weight of the net negative emissions component of CDR increases compared to 2°C-consistent pathways. The amount of compensatory CDR remains roughly the same over the century. This is the net effect of stronger deployment of compensatory CDR until mid-century to accelerate the approach to carbon neutrality and less compensatory CDR in the second half of the century due to deeper mitigation of end-use sectors

[4] The median and percentiles of the sum of two quantities is in general not equal to the sum of the medians and percentiles, respectively, of the two quantitites.

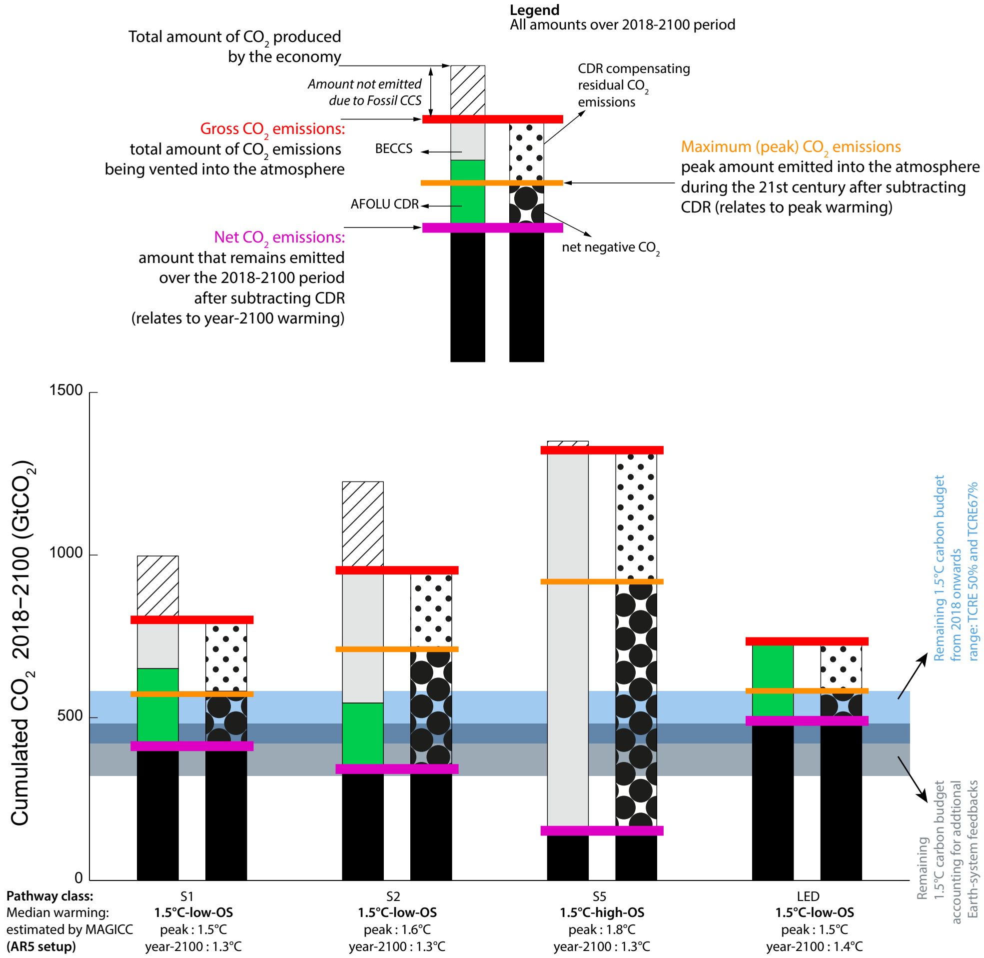


Figure 2.10 | Accounting of cumulative CO_2 emissions for the four 1.5°C-consistent pathway archetypes. See top panel for explanation of the bar plots. Total CDR is the difference between gross (red horizontal bar) and net (purple horizontal bar) cumulative CO_2 emissions over the period 2018–2100, and it is equal to the sum of the BECCS (grey) and AFOLU CDR (green) contributions. Cumulative net negative emissions are the difference between peak (orange horizontal bar) and net (purple) cumulative CO_2 emissions. The blue shaded area depicts the estimated range of the remaining carbon budget for a two-in-three to one-in-two chance of staying below1.5°C. The grey shaded area depicts the range when accounting for additional Earth system feedbacks.

in 1.5°C-consistent pathways (Luderer et al., 2018). Comparing median levels, end-of-century net cumulative CO_2 emissions are roughly 600 $GtCO_2$ smaller in 1.5°C compared to 2°C-consistent pathways, with approximately two thirds coming from further reductions of gross CO_2 emissions and the remaining third from increased CDR deployment. As a result, median levels of total CDR deployment in 1.5°C-consistent pathways are larger than in 2°C-consistent pathways (Figure 2.9), but with marked variations in each pathway class.

Ramp-up rates of individual CDR measures in 1.5°C-consistent pathways are provided in Table 2.4. BECCS deployment is still limited in 2030, but ramps up to median levels of 3 (Below-1.5°C), 5 (1.5°C-low-OS) and 7 $GtCO_2$ yr^{-1} (1.5°C-high-OS) in 2050, and to 6 (Below-1.5°C), 12 (1.5°C-low-OS) and 15 $GtCO_2$ yr^{-1} (1.5°C-high-OS) in 2100, respectively. In 1.5°C pathways with no or limited overshoot, this amounts to 0–1, 0–8, and 0–16 $GtCO_2$ yr^{-1} in 2030, 2050, and 2100, respectively (ranges refer to the union of the min-max range of the Below-1.5°C and the interquartile range of the 1.5°C-low-OS class; see Table 2.4). Net CDR in the AFOLU sector reaches slightly lower levels in 2050, and stays more constant until 2100. In 1.5°C pathways with no or limited overshoot, AFOLU CDR amounts to 0–5, 1–11, and 1–5 $GtCO_2$ yr^{-1} (see above for the definition of the ranges) in 2030, 2050, and 2100, respectively. In contrast to BECCS, AFOLU CDR is more strongly deployed in non-overshoot than overshoot pathways. This indicates differences in the timing of the two CDR approaches. Afforestation is scaled up until around mid-century, when the time of carbon neutrality is reached in 1.5°C-consistent pathways, while BECCS is projected to be used predominantly in the 2nd half of the century (Figure 2.5). This reflects the fact that afforestation is a readily available CDR technology, while BECCS is more costly and much less mature a technology. As a result, the two options contribute differently to compensating concurrent CO_2 emissions (until 2050) and to producing net negative CO_2 emissions (post-2050). BECCS deployment is particularly strong in pathways with high overshoots but can also feature in pathways with low overshoot (see Figure 2.5 and 2.10). Annual deployment levels until mid-century are not found to be significantly different between 2°C-consistent pathways and 1.5°C-consistent pathways with no or low overshoot. This suggests similar implementation challenges for ramping up BECCS deployment at the rates projected in the pathways (Honegger and Reiner, 2018; Nemet et al., 2018). The feasibility and sustainability of upscaling CDR at these rates is assessed in Chapter 4.3.7.

Concerns have been raised that building expectations about large-scale CDR deployment in the future can lead to an actual reduction of near-term mitigation efforts (Geden, 2015; Anderson and Peters, 2016; Dooley and Kartha, 2018). The pathway literature confirms that CDR availability influences the shape of mitigation pathways critically (Krey et al., 2014a; Holz et al., 2018b; Kriegler et al., 2018a; Strefler et al., 2018b). Deeper near-term emissions reductions are required to reach the 1.5°C–2°C target range if CDR availability is constrained. As a result, the least-cost benchmark pathways to derive GHG emissions gap estimates (UNEP, 2017) are dependent on assumptions about CDR availability. Using GHG benchmarks in climate policy makes implicit assumptions about CDR availability (Fuss et al., 2014; van Vuuren et al., 2017a). At the same time, the literature also shows that rapid and stringent mitigation as well as large-scale CDR deployment occur simultaneously in 1.5°C pathways due to the tight remaining carbon budget (Luderer et al., 2018). Thus, an emissions gap is identified even for high CDR availability (Strefler et al., 2018b), contradicting a wait-and-see approach. There are significant trade-offs between near-term action, overshoot and reliance on CDR deployment in the long-term which are assessed in Section 2.3.5.

Box 2.1 | Bioenergy and BECCS Deployment in Integrated Assessment Modelling

Bioenergy can be used in various parts of the energy sector of IAMs, including for electricity, liquid fuel, biogas, and hydrogen production. It is this flexibility that makes bioenergy and bioenergy technologies valuable for the decarbonization of energy use (Klein et al., 2014; Krey et al., 2014a; Rose et al., 2014a; Bauer et al., 2017, 2018). Most bioenergy technologies in IAMs are also available in combination with CCS (BECCS). Assumed capture rates differ between technologies, for example, about 90% for electricity and hydrogen production and about 40–50% for liquid fuel production. Decisions about bioenergy deployment in IAMs are based on economic considerations to stay within a carbon budget that is consistent with a long-term climate goal. IAMs consider both the value of bioenergy in the energy system and the value of BECCS in removing CO_2 from the atmosphere. Typically, if bioenergy is strongly limited, BECCS technologies with high capture rates are favoured. If bioenergy is plentiful IAMs tend to choose biofuel technologies with lower capture rates but high value for replacing fossil fuels in transport (Kriegler et al., 2013a; Bauer et al., 2018). Most bioenergy use in IAMs is combined with CCS if available (Rose et al., 2014a). If CCS is unavailable, bioenergy use remains largely unchanged or even increases due to the high value of bioenergy for the energy transformation (Bauer et al., 2018). As land impacts are tied to bioenergy use, the exclusion of BECCS from the mitigation portfolio will not automatically remove the trade-offs with food, water and other sustainability objectives due to the continued and potentially increased use of bioenergy.

IAMs assume bioenergy to be supplied mostly from second generation biomass feedstocks such as dedicated cellulosic crops (for example *Miscanthus* or poplar) as well as agricultural and forest residues. Detailed process IAMs include land-use models that capture competition for land for different uses (food, feed, fiber, bioenergy, carbon storage, biodiversity protection) under a range of dynamic factors including socio-economic drivers, productivity increases in crop and livestock systems, food demand, and land, environmental, biodiversity, and carbon policies. Assumptions about these factors can vary widely between different scenarios (Calvin et al., 2014; Popp et al., 2017; van Vuuren et al., 2018). IAMs capture a number of potential environmental impacts from bioenergy production, in particular indirect land-use change emissions from land conversion and nitrogen and water use for bioenergy production (Kraxner et al., 2013; Bodirsky et al., 2014; Bonsch et al., 2014; Obersteiner et al., 2016; Humpenöder et al., 2018). The impact of bioenergy production on soil degradation is an area of active IAM development and was not comprehensively accounted for in the mitigation pathways assessed in this report (but is, for example, in Frank et al., 2017). Whether bioenergy has large adverse impacts on environmental and societal goals depends in large parts on the governance of land use (Haberl et al., 2013; Erb et al., 2016b; Obersteiner et al., 2016; Humpenöder et al., 2018). Here IAMs often make idealized assumptions about effective land management, such as full protection of the land carbon stock by conservation measures and a global carbon price, respectively, but variations on these assumptions have also been explored (Calvin et al., 2014; Popp et al., 2014a).

2.3.4.2 Sustainability implications of CDR deployment in 1.5°C pathways

Strong concerns about the sustainability implications of large-scale CDR deployment in deep mitigation pathways have been raised in the literature (Williamson and Bodle, 2016; Boysen et al., 2017b; Dooley and Kartha, 2018; Heck et al., 2018), and a number of important knowledge gaps have been identified (Fuss et al., 2016). An assessment of the literature on implementation constraints and sustainable development implications of CDR measures is provided in Chapter 4, Section 4.3.7 and the Cross-chapter Box 7 in Chapter 3. An initial discussion of potential environmental side effects of CDR deployment in 1.5°C-consistent pathways is provided in this section. Chapter 4, Section 4.3.7 then contrasts CDR deployment in 1.5°C-consistent pathways with other branches of literature on limitations of CDR. Integrated modelling aims to explore a range of developments compatible with specific climate goals and often does not include the full set of broader environmental and societal concerns beyond climate change. This has given rise to the concept of sustainable development pathways (Cross-Chapter Box 1 in Chapter 1) (van Vuuren et al., 2015), and there is an increasing body of work to extend integrated modelling to cover a broader range of sustainable development goals (Section 2.6). However, only some of the available 1.5°C-consistent pathways were developed within a larger sustainable development context (Bertram et al., 2018; Grubler et al., 2018; Rogelj et al., 2018; van Vuuren et al., 2018). As discussed in Section 2.3.4.1, those pathways are characterized by low energy and/or food demand effectively limiting fossil-fuel substitution and alleviating land competition, respectively. They also include regulatory policies for deepening early action and ensuring environmental protection (Bertram et al., 2018). Overall sustainability implications of 1.5°C-consistent pathways are assessed in Section 2.5.3 and Chapter 5, Section 5.4.

Individual CDR measures have different characteristics and therefore would carry different risks for their sustainable deployment at scale (Smith et al., 2015). Terrestrial CDR measures, BECCS and enhanced weathering of rock powder distributed on agricultural lands require land. Those land-based measures could have substantial impacts on environmental services and ecosystems (Cross-Chapter Box 7 in Chapter 3) (Smith and Torn, 2013; Boysen et al., 2016; Heck et al., 2016; Krause et al., 2017). Measures like afforestation and bioenergy with and without CCS that directly compete with other land uses could have significant impacts on agricultural and food systems (Creutzig et al., 2012, 2015; Calvin et al., 2014; Popp et al., 2014b, 2017; Kreidenweis et al., 2016; Boysen et al., 2017a; Frank et al., 2017; Stevanović et al., 2017; Strapasson et al., 2017; Humpenöder et al., 2018). BECCS using dedicated bioenergy crops could substantially increase agricultural water demand (Bonsch et al., 2014; Séférian et al., 2018) and nitrogen fertilizer use (Bodirsky et al., 2014). DACCS and BECCS rely on CCS and would require safe storage space in geological formations, including management of leakage risks (Pawar et al., 2015) and induced seismicity (Nicol et al., 2013). Some approaches like DACCS have high energy demand (Socolow et al., 2011). Most of the CDR measures currently discussed could have significant impacts on either land, energy, water, or nutrients if deployed at scale (Smith et al., 2015). However, actual trade-offs depend on a multitude factors (Haberl et al., 2011; Erb et al., 2012; Humpenöder et al., 2018), including the modalities of CDR deployment (e.g., on marginal vs. productive land) (Bauer et al., 2018), socio-economic developments (Popp et al., 2017), dietary choices (Stehfest et al., 2009; Popp et al., 2010; van Sluisveld et al., 2016; Weindl et al., 2017; van Vuuren et al., 2018), yield increases, livestock productivity and other advances in agricultural technology (Havlik et al., 2013; Valin et al., 2013; Havlík et al., 2014; Weindl et al., 2015; Erb et al., 2016b), land policies (Schmitz et al., 2012; Calvin et al., 2014; Popp et al., 2014a), and governance of land use (Unruh, 2011; Buck, 2016; Honegger and Reiner, 2018).

Figure 2.11 shows the land requirements for BECCS and afforestation in the selected 1.5°C-consistent pathway archetypes, including the LED (Grubler et al., 2018) and S1 pathways (Fujimori, 2017; Rogelj et al., 2018) following a sustainable development paradigm. As discussed, these land-use patterns are heavily influenced by assumptions about, among other things, future population levels, crop yields, livestock production systems, and food and livestock demand, which all vary between the pathways (Popp et al., 2017) (Section 2.3.1.1). In pathways that allow for large-scale afforestation in addition to BECCS, land demand for afforestation can be larger than for BECCS (Humpenöder et al., 2014). This follows from the assumption in the modelled pathways that, unlike bioenergy crops, forests are not harvested to allow unabated carbon storage on the same patch of land. If wood harvest and subsequent processing or burial are taken into account, this finding can change. There are also synergies between the various uses of land, which are not reflected in the depicted pathways. Trees can grow on agricultural land (Zomer et al., 2016), and harvested wood can be used with BECCS and pyrolysis systems (Werner et al., 2018). The pathways show a very substantial land demand for the two CDR measures combined, up to the magnitude of the current global cropland area. This is achieved in IAMs in particular by a conversion of pasture land freed by intensification of livestock production systems, pasture intensification and/or demand changes (Weindl et al., 2017), and to a more limited extent, cropland for food production, as well as expansion into natural land. However, pursuing such large-scale changes in land use would pose significant food supply, environmental and governance challenges, concerning both land management and tenure (Unruh, 2011; Erb et al., 2012, 2016b; Haberl et al., 2013; Haberl, 2015; Buck, 2016), particularly if synergies between land uses, the relevance of dietary changes for reducing land demand, and co-benefits with other sustainable development objectives are not fully recognized. A general discussion of the land-use transformation in 1.5°C-consistent pathways is provided in Section 2.4.4.

An important consideration for CDR which moves carbon from the atmosphere to the geological, oceanic or terrestrial carbon pools is the permanence of carbon stored in these different pools (Matthews and Caldeira, 2008; NRC, 2015; Fuss et al., 2016; Jones et al., 2016) (see also Chapter 4, Section 4.3.7 for a discussion). Terrestrial carbon can be returned to the atmosphere on decadal time scales by a variety of mechanisms, such as soil degradation, forest pest outbreaks and forest fires, and therefore requires careful consideration of policy frameworks to manage carbon storage, for example, in forests (Gren and Aklilu, 2016). There are similar concerns about outgassing of CO_2 from ocean storage (Herzog et al., 2003), unless it is transformed to a substance that does not easily exchange with the atmosphere, for example, ocean alkalinity or buried marine biomass (Rau, 2011). Understanding of the assessment and management of the potential risk of CO_2 release from geological storage of CO_2 has improved since the IPCC Special Report on Carbon Dioxide Capture and Storage (IPCC, 2005) with experience and the development of management practices in geological storage projects, including risk management to prevent sustentative leakage (Pawar et al., 2015). Estimates of leakage risk have been updated to include scenarios of unregulated drilling and limited wellbore integrity (Choi et al., 2013) and find that about 70% of stored CO_2 would still be retained after 10,000 years in these circumstances (Alcalde et al., 2018). The literature on the potential environmental impacts from the leakage of CO_2 – and approaches to minimize these impacts should a leak occur – has also grown and is reviewed by Jones et al. (2015). To the extent that non-permanence of terrestrial and geological carbon storage is driven by socio-economic and political factors, there are parallels to questions of fossil-fuel reservoirs remaining in the ground (Scott et al., 2015).

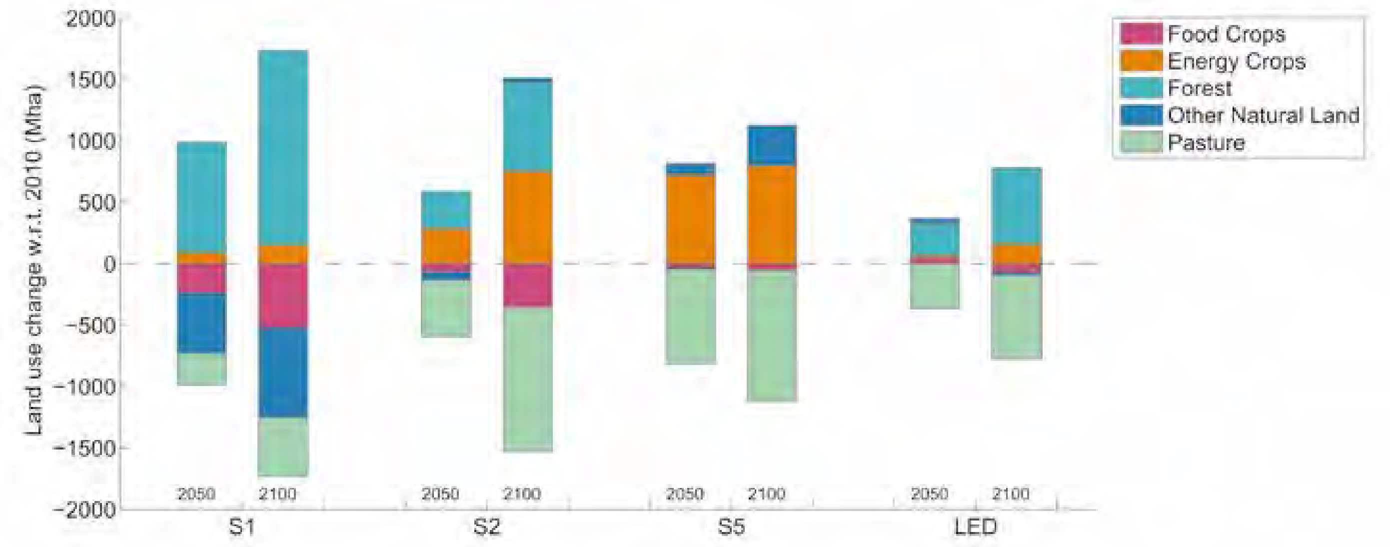


Figure 2.11 | Land-use changes in 2050 and 2100 in the illustrative 1.5°C-consistent pathway archetypes (Fricko et al., 2017; Fujimori, 2017; Kriegler et al., 2017; Grubler et al., 2018; Rogelj et al., 2018). Changes in land for food crops, energy crops, forest, pasture and other natural land are shown, compared to 2010.

2.3.5 Implications of Near-Term Action in 1.5°C Pathways

Less CO_2 emission reductions in the near term would require steeper and deeper reductions in the longer term in order to meet specific warming targets afterwards (Riahi et al., 2015; Luderer et al., 2016a). This is a direct consequence of the quasi-linear relationship between the total cumulative amount of CO_2 emitted into the atmosphere and global mean temperature rise (Matthews et al., 2009; Zickfeld et al., 2009; Collins et al., 2013; Knutti and Rogelj, 2015). Besides this clear geophysical trade-off over time, delaying GHG emissions reductions over the coming years also leads to economic and institutional lock-in into carbon-intensive infrastructure, that is, the continued investment in and use of carbon-intensive technologies that are difficult or costly to phase-out once deployed (Unruh and Carrillo-Hermosilla, 2006; Jakob et al., 2014; Erickson et al., 2015; Steckel et al., 2015; Seto et al., 2016; Michaelowa et al., 2018). Studies show that to meet stringent climate targets despite near-term delays in emissions reductions, models prematurely retire carbon-intensive infrastructure, in particular coal without CCS (Bertram et al., 2015a; Johnson et al., 2015). The AR5 reports that delaying mitigation action leads to substantially higher rates of emissions reductions afterwards, a larger reliance on CDR technologies in the long term, and higher transitional and long-term economic impacts (Clarke et al., 2014). The literature mainly focuses on delayed action until 2030 in the context of meeting a 2°C goal (den Elzen et al., 2010; van Vuuren and Riahi, 2011; Kriegler et al., 2013b; Luderer et al., 2013, 2016a; Rogelj et al., 2013b; Riahi et al., 2015; OECD/IEA and IRENA, 2017). However, because of the smaller carbon budget consistent with limiting warming to 1.5°C and the absence of a clearly declining long-term trend in global emissions to date, these general insights apply equally, or even more so, to the more stringent mitigation context of 1.5°C-consistent pathways. This is further supported by estimates of committed emissions due to fossil fuel-based infrastructure (Seto et al., 2016; Edenhofer et al., 2018).

All available 1.5°C pathways that explore consistent mitigation action from 2020 onwards peak global Kyoto-GHG emissions in the next decade and already decline Kyoto-GHG emissions to below 2010 levels by 2030. The near-term emissions development in these pathways can be compared with estimated emissions in 2030 implied by the Nationally Determined Contributions (NDCs) submitted by Parties to the Paris Agreement (Figure 2.12). Altogether, the unconditional (conditional) NDCs are assessed to result in global Kyoto-GHG emissions on the order of 52–58 (50–54) GtCO2e yr−1 in 2030 (e.g., den Elzen et al., 2016; Fujimori et al., 2016; UNFCCC, 2016; Rogelj et al., 2017; Rose et al., 2017b; Benveniste et al., 2018; Vrontisi et al., 2018; see Cross-Chapter Box 11 in Chapter 4 for detailed assessment). In contrast, 1.5°C pathways with limited overshoot available to this assessment show an interquartile range of about 26–31 (median 28) $GtCO_2e\ yr^{-1}$ in 2030[5] (Table 2.4, Section 2.3.3). Based on these ranges, this report assesses the emissions gap for a two-in-three chance of limiting warming to 1.5°C to be 26 (19–29) and 28 (22–33) $GtCO_2e$ (median and interquartile ranges) for conditional and unconditional NDCs, respectively (Cross-Chapter Box 11, applying GWP-100 values from the IPCC Second Assessment Report).

The later emissions peak and decline, the more CO_2 will have accumulated in the atmosphere. Peak cumulated CO_2 emissions – and consequently peak temperatures – increase with higher 2030 emissions levels (Figure 2.12). Current NDCs (Cross-Chapter Box 11 in Chapter 4) are estimated to lead to CO_2 emissions of about 400–560 $GtCO_2$ from 2018 to 2030 (Rogelj et al., 2016a). Available 1.5°C- and 2°C-consistent pathways with 2030 emissions in the range estimated

[5] Note that aggregated Kyoto-GHG emissions implied by the NDCs from Cross-Chapter Box 11 in Chapter 4 and Kyoto-GHG ranges from the pathway classes in Chapter 2 are only approximately comparable, because this chapter applies GWP-100 values from the IPCC Fourth Assessment Report while the NDC Cross-Chapter Box 11 applies GWP-100 values from the IPCC Second Assessment Report. At a global scale, switching between GWP-100 values of the Second to the Fourth IPCC Assessment Report would result in an increase in estimated aggregated Kyoto-GHG emissions of no more than about 3% in 2030 (UNFCCC, 2016).

for the NDCs rely on an assumed swift and widespread deployment of CDR after 2030, and show peak cumulative CO_2 emissions from 2018 of about 800–1000 $GtCO_2$, above the remaining carbon budget for a one-in-two chance of remaining below 1.5°C. These emissions reflect that no pathway is able to project a phase-out of CO_2 emissions starting from year-2030 NDC levels of about 40 $GtCO_2\ yr^{-1}$ (Fawcett et al., 2015; Rogelj et al., 2016a) to net zero in less than about 15 years. Based on the implied emissions until 2030, the high challenges of the assumed post-2030 transition, and the assessment of carbon budgets in Section 2.2.2, global warming is assessed to exceed 1.5°C if emissions stay at the levels implied by the NDCs until 2030 (Figure 2.12). The chances of remaining below 1.5°C in these circumstances remain conditional upon geophysical properties that are uncertain, but these Earth system response uncertainties would have to serendipitously align beyond current median estimates in order for current NDCs to become consistent with limiting warming to 1.5°C.

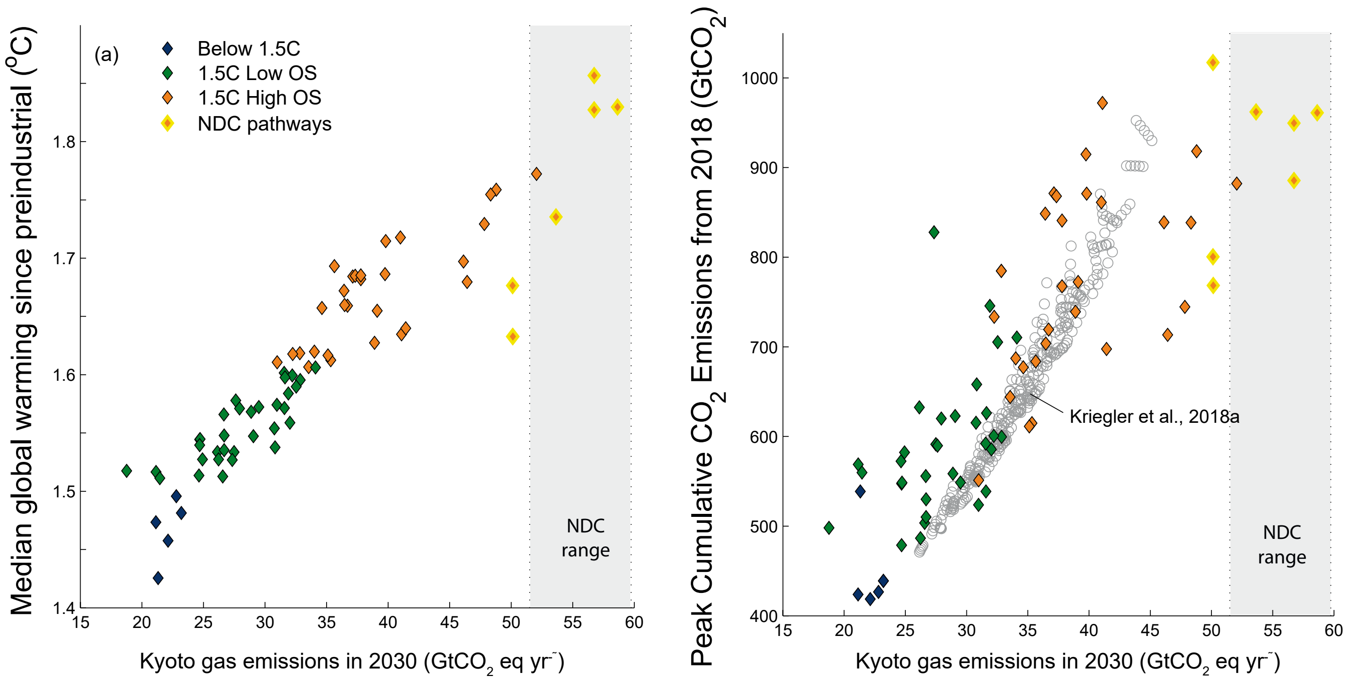


Figure 2.12 | Median global warming estimated by MAGICC (panel a) and peak cumulative CO_2 emissions (panel b) in 1.5°C-consistent pathways in the SR1.5 scenario database, as a function of CO_2-equivalent emissions (based on AR4 GWP-100) of Kyoto-GHGs in 2030. Pathways that were forced to go through the NDCs or a similarly high emissions point in 2030 by design are highlighted by yellow marker edges (see caption of Figure 2.13 and text for further details on the design of these pathways). The combined range of global Kyoto-GHG emissions in 2030 for the conditional and unconditional NDCs assessed in Cross-Chapter Box 11 is shown by the grey shaded area (adjusted to AR4 GWPs for comparison). As a second line of evidence, peak cumulative CO_2 emissions derived from a 1.5°C pathway sensitivity analysis (Kriegler et al., 2018b) are shown by grey circles in the right-hand panel. Circles show gross fossil-fuel and industry emissions of the sensitivity cases, increased by assumptions about the contributions from AFOLU (5 $GtCO_2\ yr^{-1}$ until 2020, followed by a linear phase out until 2040) and non-CO_2 Kyoto-GHGs (median non-CO_2 contribution from 1.5°C-consistent pathways available in the database: 10 $GtCO_2e\ yr^{-1}$ in 2030), and reduced by assumptions about CDR deployment until the time of net zero CO_2 emissions (limiting case for CDR deployment assumed in (Kriegler et al., 2018b) (logistic growth to 1, 4, 10 $GtCO_2\ yr^{-1}$ in 2030, 2040, and 2050, respectively, leading to approximately 100 $GtCO_2$ of CDR by mid-century).

It is unclear whether following NDCs until 2030 would still allow global mean temperature to return to 1.5°C by 2100 after a temporary overshoot, due to the uncertainty associated with the Earth system response to net negative emissions after a peak (Section 2.2). Available IAM studies are working with reduced-form carbon cycle–climate models like MAGICC, which assume a largely symmetric Earth-system response to positive and net negative CO_2 emissions. The IAM findings on returning warming to 1.5°C from NDCs after a temporary temperature overshoot are hence all conditional on this assumption. Two types of pathways with 1.5°C-consistent action starting in 2030 have been considered in the literature (Luderer et al., 2018) (Figure 2.13): pathways aiming to obtain the same end-of-century carbon budget as 1.5°C-consistent pathways starting in 2020 despite higher emissions until 2030, and pathways assuming the same mitigation stringency after 2030 as in 1.5°C-consistent pathways starting in 2020 (approximated by using the same global price of emissions as found in least-cost pathways starting from 2020). An IAM comparison study found increasing challenges to implementing pathways with the same end-of-century carbon budgets after following NDCs until 2030 (Luderer et al., 2018). The majority of model experiments (four out of seven) failed to produce NDC pathways that would return cumulative CO_2 emissions over the 2016–2100 period to 200 $GtCO_2$, indicating limitations to the availability and timing of CDR. The few such pathways that were identified show highly disruptive features in 2030 (including abrupt transitions from moderate to very large emissions reduction and low carbon energy deployment rates) indicating a high risk that the required post-2030 transformations are too steep and abrupt to be achieved by the mitigation measures in the models *(high confidence)*. NDC pathways aiming for a cumulative 2016–2100 CO_2 emissions budget of 800 $GtCO_2$ were more readily obtained (Luderer et al., 2018), and some were classified as 1.5°C-high-OS pathways in this assessment (Section 2.1).

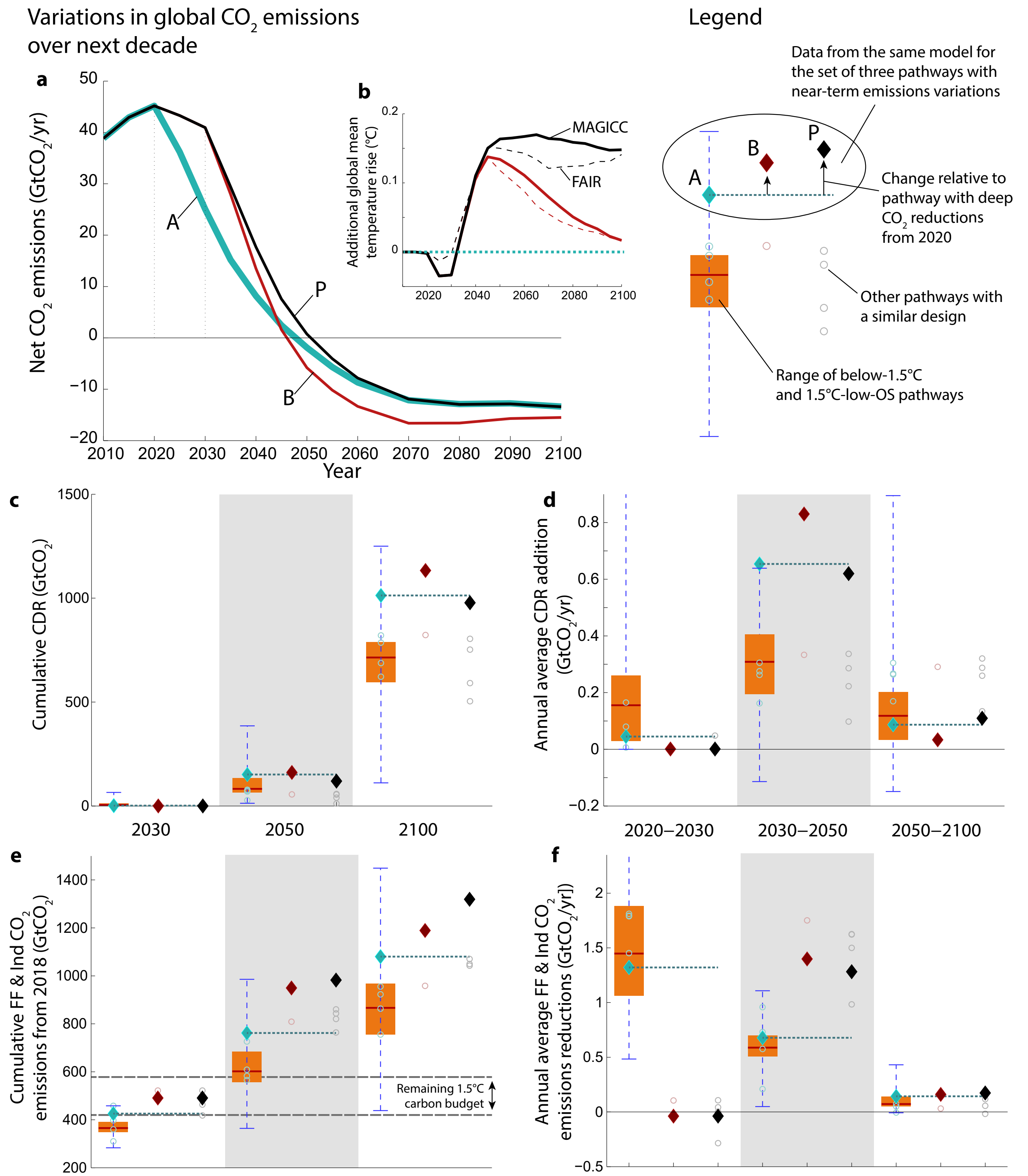


Figure 2.13 | Comparison of 1.5°C-consistent pathways starting action as of 2020 (A; light-blue diamonds) with pathways following the NDCs until 2030 and aiming to limit warming to 1.5°C thereafter. The 1.5°C pathways that follow the NDCs until 2030 either aim for the same cumulative CO_2 emissions by 2100 as the pathways that start action as of 2020 (B; red diamonds) or assume the same mitigation stringency as reflected by the price of emissions in associated least-cost 1.5°C-consistent pathways starting from 2020 (P; black diamonds). Panels show (a) the underlying emissions pathways, (b) additional warming in the delay scenarios compared to 2020 action case, (c) cumulated CDR, (d) CDR ramp-up rates, (e) cumulated gross CO_2 emissions from fossil-fuel combustion and industrial (FFI) processes over the 2018–2100 period, and (f) gross FFI CO_2 emissions reductions rates. Scenario pairs or triplets (circles and diamonds) with 2020 and 2030 action variants were calculated by six (out of seven) models in the ADVANCE study symbols (Luderer et al., 2018) and five of them (passing near-term plausibility checks) are shown by symbols. Only two of five models could identify pathways with post-2030 action leading to a 2016–2100 carbon budget of about 200 $GtCO_2$ (red). The range of all 1.5°C pathways with no and low overshoot is shown by the boxplots.

NDC pathways that apply a post-2030 price of emissions as found in least-cost pathways starting from 2020 show infrastructural carbon lock-in as a result of following NDCs instead of least-cost action until 2030. A key finding is that carbon lock-ins persist long after 2030, with the majority of additional CO_2 emissions occurring during the 2030–2050 period. Luderer et al. (2018) find 90 (80–120) $GtCO_2$ additional emissions until 2030, growing to 240 (190–260) $GtCO_2$ by 2050 and 290 (200–200) $GtCO_2$ by 2100. As a result, peak warming is about 0.2°C higher and not all of the modelled pathways return warming to 1.5°C by the end of the century. There is a four sided trade-off between (i) near-term ambition, (ii) degree of overshoot, (iii) transitional challenges during the 2030–2050 period, and (iv) the amount of CDR deployment required during the century (Figure 2.13) (Holz et al., 2018b; Strefler et al., 2018b). Transition challenges, overshoot, and CDR requirements can be significantly reduced if global emissions peak before 2030 and fall below levels in line with current NDCs by 2030. For example, Strefler et al. (2018b) find that CDR deployment levels in the second half of the century can be halved in 1.5°C-consistent pathways with similar CO_2 emissions reductions rates during the 2030–2050 period if CO_2 emissions by 2030 are reduced by an additional 30% compared to NDC levels. Kriegler et al. (2018a) investigate a global rollout of selected regulatory policies and moderate carbon pricing policies. They show that additional reductions of about 10 $GtCO_2e\ yr^{-1}$ can be achieved in 2030 compared to the current NDCs. Such a 20% reduction of year-2030 emissions compared to current NDCs would effectively lower the disruptiveness of post-2030 action. The strengthening of short-term policies in deep mitigation pathways has hence been identified as a way of bridging options to keep the Paris climate goals within reach (Bertram et al., 2015b; IEA, 2015a; Spencer et al., 2015; Kriegler et al., 2018a).

2.4 Disentangling the Whole-System Transformation

Mitigation pathways map out prospective transformations of the energy, land and economic systems over this century (Clarke et al., 2014). There is a diversity of potential pathways consistent with 1.5°C, yet they share some key characteristics summarized in Table 2.5. To explore characteristics of 1.5°C pathways in greater detail, this section focuses on changes in energy supply and demand, and changes in the AFOLU sector.

2.4.1 Energy System Transformation

The energy system links energy supply (Section 2.4.2) with energy demand (Section 2.4.3) through final energy carriers, including electricity and liquid, solid or gaseous fuels, that are tailored to their end-uses. To chart energy-system transformations in mitigation pathways, four macro-level decarbonization indicators associated with final energy are useful: limits on the increase of final energy demand, reductions in the carbon intensity of electricity, increases in the share of final energy provided by electricity, and reductions in the carbon

Table 2.5 | Overview of Key Characteristics of 1.5°C Pathways.

1.5°C Pathway Characteristic	Supporting Information	Reference
Rapid and profound near-term decarbonisation of energy supply	Strong upscaling of renewables and sustainable biomass and reduction of unabated (no CCS) fossil fuels, along with the rapid deployment of CCS, lead to a zero-emission energy supply system by mid-century.	Section 2.4.1 Section 2.4.2
Greater mitigation efforts on the demand side	All end-use sectors show marked demand reductions beyond the reductions projected for 2°C pathways. Demand reductions from IAMs for 2030 and 2050 lie within the potential assessed by detailed sectoral bottom-up assessments.	Section 2.4.3
Switching from fossil fuels to electricity in end-use sectors	Both in the transport and the residential sector, electricity covers markedly larger shares of total demand by mid-century.	Section 2.4.3.2 Section 2.4.3.3
Comprehensive emission reductions are implemented in the coming decade	Virtually all 1.5°C-consistent pathways decline net annual CO_2 emissions between 2020 and 2030, reaching carbon neutrality around mid-century. In 2030, below-1.5°C and 1.5°C-low-OS pathways show maximum net CO_2 emissions of 18 and 28 $GtCO_2\ yr^{-1}$, respectively. GHG emissions in these scenarios are not higher than 34 $GtCO_2e\ yr^{-1}$ in 2030.	Section 2.3.4
Additional reductions, on top of reductions from both CO_2 and non-CO_2 required for 2°C, are mainly from CO_2	Both CO_2 and the non-CO_2 GHGs and aerosols are strongly reduced by 2030 and until 2050 in 1.5°C pathways. The greatest difference to 2°C pathways, however, lies in additional reductions of CO_2, as the non-CO_2 mitigation potential that is currently included in integrated pathways is mostly already fully deployed for reaching a 2°C pathway.	Section 2.3.1.2
Considerable shifts in investment patterns	Low-carbon investments in the energy supply side (energy production and refineries) are projected to average 1.6–3.8 trillion 2010USD yr^{-1} globally to 2050. Investments in fossil fuels decline, with investments in unabated coal halted by 2030 in most available 1.5°C-consistent projections, while the literature is less conclusive for investments in unabated gas and oil. Energy demand investments are a critical factor for which total estimates are uncertain.	Section 2.5.2
Options are available to align 1.5°C pathways with sustainable development	Synergies can be maximized, and risks of trade-offs limited or avoided through an informed choice of mitigation strategies. Particularly pathways that focus on a lowering of demand show many synergies and few trade-offs.	Section 2.5.3
CDR at scale before mid-century	By 2050, 1.5°C pathways project deployment of BECCS at a scale of 3–7 $GtCO_2yr^{-1}$ (range of medians across 1.5°C pathway classes), depending on the level of energy demand reductions and mitigation in other sectors. Some 1.5°C pathways are available that do not use BECCS, but only focus terrestrial CDR in the AFOLU sector.	Section 2.3.3, 2.3.4.1

intensity of final energy other than electricity (referred to in this section as the carbon intensity of the residual fuel mix). Figure 2.14 shows changes of these four indicators for the pathways in the scenario database (Section 2.1.3 and Supplementary Material 2.SM.1.3) for 1.5°C and 2°C pathways (Table 2.1).

Pathways in both the 1.5°C and 2°C classes (Figure 2.14) generally show rapid transitions until mid-century, with a sustained but slower evolution thereafter. Both show an increasing share of electricity accompanied by a rapid decline in the carbon intensity of electricity. Both also show a generally slower decline in the carbon intensity of the residual fuel mix, which arises from the decarbonization of liquids, gases and solids provided to industry, residential and commercial activities, and the transport sector.

The largest differences between 1.5°C and 2°C pathways are seen in the first half of the century (Figure 2.14), where 1.5°C pathways generally show lower energy demand, a faster electrification of energy end-use, and a faster decarbonization of the carbon intensity of electricity and the residual fuel mix. There are very few pathways in the Below-1.5°C class (Figure 2.14). Those scenarios that are available, however, show a faster decline in the carbon intensity of electricity generation and residual fuel mix by 2030 than most pathways that are projected to temporarily overshoot 1.5°C and return by 2100 (or 2°C pathways). The Below-1.5°C pathways also appear to differentiate themselves from the other pathways as early as 2030 through reductions in final energy demand and increases in electricity share (Figure 2.14).

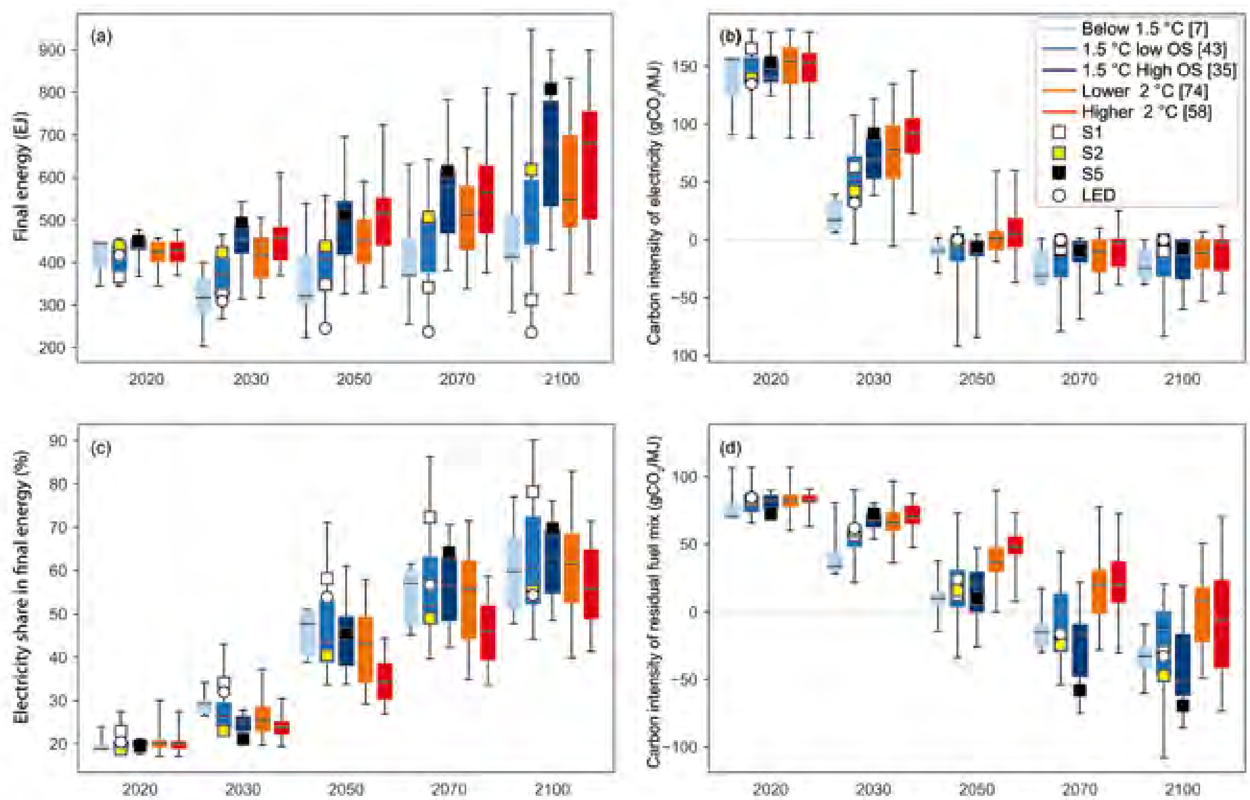


Figure 2.14 | Decomposition of transformation pathways into (a) energy demand, (b) carbon intensity of electricity, (c) the electricity share in final energy, and (d) the carbon intensity of the residual (non-electricity) fuel mix. Box plots show median, interquartile range and full range of pathways. Pathway temperature classes (Table 2.1) and illustrative pathway archetypes are indicated in the legend. Values following the class labels give the number of available pathways in each class.

2.4.2 Energy Supply

Several energy supply characteristics are evident in 1.5°C pathways assessed in this section: (i) growth in the share of energy derived from low-carbon-emitting sources (including renewables, nuclear and fossil fuel with CCS) and a decline in the overall share of fossil fuels without CCS (Section 2.4.2.1), (ii) rapid decline in the carbon intensity of electricity generation simultaneous with further electrification of energy end-use (Section 2.4.2.2), and (iii) the growth in the use of CCS applied to fossil and biomass carbon in most 1.5°C pathways (Section 2.4.2.3).

2.4.2.1 Evolution of primary energy contributions over time

By mid-century, the majority of primary energy comes from non-fossil-fuels (i.e., renewables and nuclear energy) in most 1.5°C pathways (Table 2.6). Figure 2.15 shows the evolution of primary energy supply over this century across 1.5°C pathways, and in detail for the four illustrative pathway archetypes highlighted in this chapter. Note that this section reports primary energy using the direct equivalent method on the basis of lower heating values (Bruckner et al., 2014).

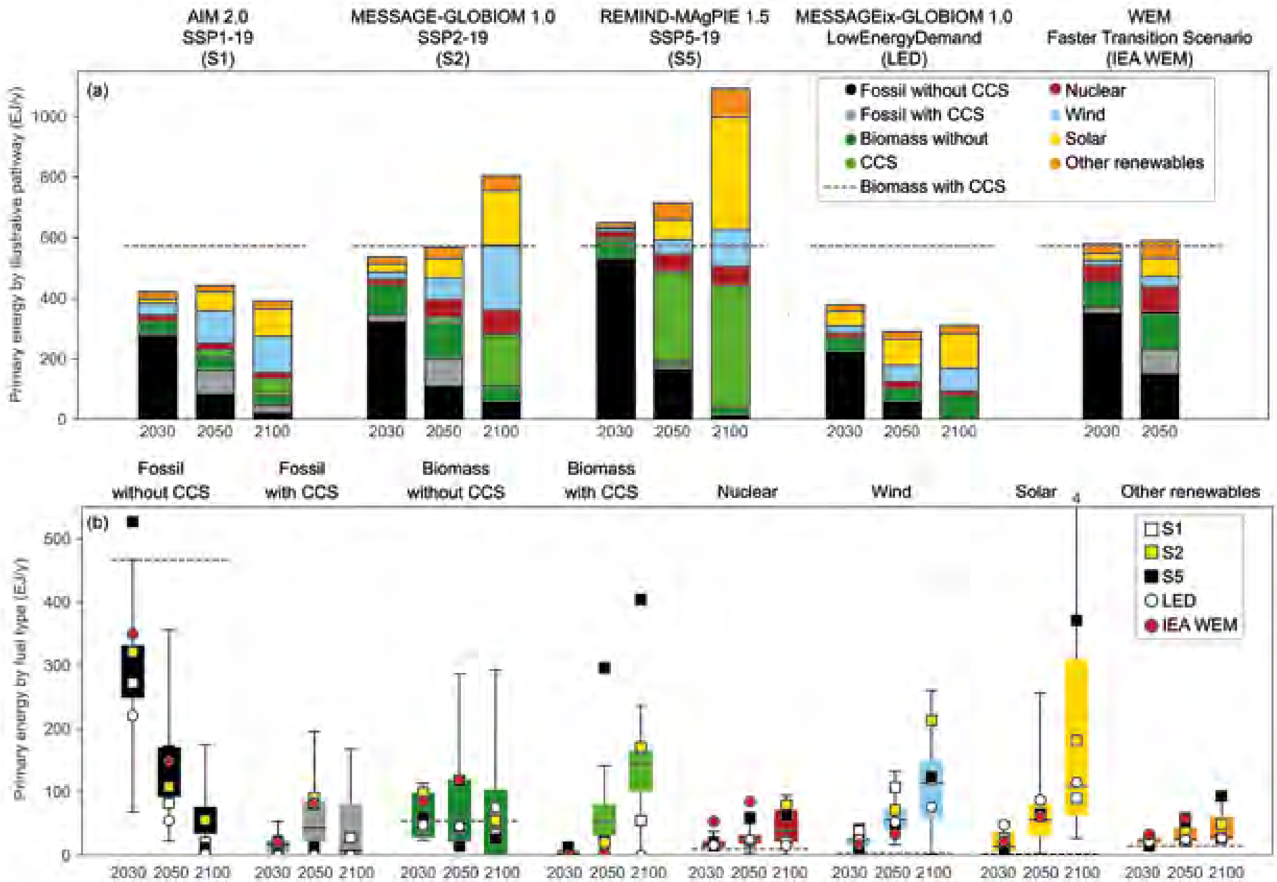


Figure 2.15 | Primary energy supply for the four illustrative pathway archetypes plus the IEA's Faster Transition Scenario (OECD/IEA and IRENA, 2017) (panel a), and their relative location in the ranges for pathways limiting warming to 1.5°C with no or limited overshoot (panel b). The category 'Other renewables' includes primary energy sources not covered by the other categories, for example, hydro and geothermal energy. The number of pathways that have higher primary energy than the scale in the bottom panel are indicated by the numbers above the whiskers. Black horizontal dashed lines indicates the level of primary energy supply in 2015 (IEA, 2017e). Box plots in the lower panel show the minimum–maximum range (whiskers), interquartile range (box), and median (vertical thin black line). Symbols in the lower panel show the four pathway archetypes S1 (white square), S2 (yellow square), S5 (black square), LED (white disc), as well as the IEA–(red disc). Pathways with no or limited overshoot included the Below-1.5°C and 1.5°C-low-OS classes.

The share of energy from renewable sources (including biomass, hydro, solar, wind and geothermal) increases in all 1.5°C pathways with no or limited overshoot, with the renewable energy share of primary energy reaching 38–88% in 2050 (Table 2.6), with an interquartile range of 52–67%. The magnitude and split between bioenergy, wind, solar, and hydro differ between pathways, as can be seen in the illustrative pathway archetypes in Figure 2.15. Bioenergy is a major supplier of primary energy, contributing to both electricity and other forms of final energy such as liquid fuels for transportation (Bauer et al., 2018). In 1.5°C pathways, there is a significant growth in bioenergy used in combination with CCS for pathways where it is included (Figure 2.15).

Nuclear power increases its share in most 1.5°C pathways with no or limited overshoot by 2050, but in some pathways both the absolute capacity and share of power from nuclear generators decrease (Table 2.15). There are large differences in nuclear power between models and across pathways (Kim et al., 2014; Rogelj et al., 2018). One of the reasons for this variation is that the future deployment of nuclear can be constrained by societal preferences assumed in narratives underlying the pathways (O'Neill et al., 2017; van Vuuren et al., 2017b). Some 1.5°C pathways with no or limited overshoot no longer see a role for nuclear fission by the end of the century, while others project about 95 EJ yr^{-1} of nuclear power in 2100 (Figure 2.15).

The share of primary energy provided by total fossil fuels decreases from 2020 to 2050 in all 1.5°C pathways, but trends for oil, gas and coal differ (Table 2.6). By 2050, the share of primary energy from coal decreases to 0–11% across 1.5°C pathways with no or limited overshoot, with an interquartile range of 1–7%. From 2020 to 2050 the primary energy supplied by oil changes by –93 to –9% (interquartile range –77 to –39%); natural gas changes by –88 to +85% (interquartile range –62 to –13%), with varying levels of CCS. Pathways with higher use of coal and gas tend to deploy CCS to control their carbon emissions (see Section 2.4.2.3). As the energy transition is accelerated by several decades in 1.5°C pathways compared to 2°C pathways, residual fossil-fuel use (i.e., fossil fuels not used for electricity generation) without CCS is generally lower in 2050 than in 2°C pathways, while combined hydro, solar, and wind power deployment is generally higher than in 2°C pathways (Figure 2.15).

In addition to the 1.5°C pathways included in the scenario database (Supplementary Material 2.SM.1.3), there are other analyses in the literature including, for example, sector-based analyses of energy demand and supply options. Even though they were not necessarily developed in the context of the 1.5°C target, they explore in greater detail some options for deep reductions in GHG emissions. For example, there are analyses of transitions to up to 100% renewable energy by 2050 (Creutzig et al., 2017; Jacobson et al., 2017), which describe what is entailed for a renewable energy share largely from solar and wind (and electrification) that is above the range of 1.5°C pathways available in the database, although there have been challenges to the assumptions used in high-renewable analyses (e.g., Clack et al., 2017). There are also analyses that result in a large role for nuclear energy in mitigation of GHGs (Hong et al., 2015; Berger et al., 2017a, b; Xiao and Jiang, 2018). BECCS could also contribute a larger share, but faces challenges related to its land use and impact on food supply (Burns and Nicholson, 2017) (assessed in greater detail in Sections 2.3.4.2, 4.3.7 and 5.4). These analyses could, provided their assumptions prove plausible, expand the range of 1.5°C pathways.

In summary, the share of primary energy from renewables increases while that from coal decreases across 1.5°C pathways (*high confidence*). This statement is true for all 1.5°C pathways in the scenario database and associated literature (Supplementary Material 2.SM.1.3), and is consistent with the additional studies mentioned above, an increase in energy supply from lower-carbon-intensity energy supply, and a decrease in energy supply from higher-carbon-intensity energy supply.

Table 2.6 | Global primary energy supply of 1.5°C pathways from the scenario database (Supplementary Material 2.SM.1.3).
Values given for the median (maximum, minimum) across the full range of 85 available 1.5°C pathways. Growth Factor = [(primary energy supply in 2050)/(primary energy supply in 2020) – 1]

	Median (max, min)	Count	Primary Energy Supply (EJ)			Share in Primary Energy (%)			Growth (factor) 2020-2050
			2020	2030	2050	2020	2030	2050	
Below-1.5°C and 1.5°C-low-OS pathways	total primary	50	565.33 (619.70, 483.22)	464.50 (619.87, 237.37)	553.23 (725.40, 289.02)	NA	NA	NA	–0.05 (0.48, –0.51)
	renewables	50	87.14 (101.60, 60.16)	146.96 (203.90, 87.75)	291.33 (584.78, 176.77)	14.90 (20.39, 10.60)	29.08 (62.15, 18.24)	60.24 (87.89, 38.03)	2.37 (6.71, 0.91)
	biomass	50	60.41 (70.03, 40.54)	77.07 (113.02, 44.42)	152.30 (311.72, 40.36)	10.17 (13.66, 7.14)	17.22 (35.61, 9.08)	27.29 (54.10, 10.29)	1.71 (5.56, –0.42)
	non-biomass	50	26.35 (36.57, 17.78)	62.58 (114.41, 25.79)	146.23 (409.94, 53.79)	4.37 (7.19, 3.01)	13.67 (26.54, 5.78)	27.98 (61.61, 12.04)	4.28 (13.46, 1.45)
	wind & solar	44	10.93 (20.16, 2.61)	40.14 (82.66, 7.05)	121.82 (342.77, 27.95)	1.81 (3.66, 0.45)	9.73 (19.56, 1.54)	21.13 (51.52, 4.48)	10.00 (53.70, 3.71)
	nuclear	50	10.91 (18.55, 8.52)	16.26 (36.80, 6.80)	24.51 (66.30, 3.09)	2.10 (3.37, 1.45)	3.52 (9.61, 1.32)	4.49 (12.84, 0.44)	1.24 (5.01, –0.64)
	fossil	50	462.95 (520.41, 376.30)	310.36 (479.13, 70.14)	183.79 (394.71, 54.86)	82.53 (86.65, 77.73)	66.58 (77.30, 29.55)	32.79 60.84, 8.58)	–0.59 (–0.21, –0.89)
	coal	50	136.89 (191.02, 83.23)	44.03 (127.98, 5.97)	24.15 (71.12, 0.92)	25.63 (30.82, 17.19)	9.62 (20.65, 1.31)	5.08 (11.43, 0.15)	–0.83 (–0.57, –0.99)
	gas	50	132.95 (152.80, 105.01)	112.51 (173.56, 17.30)	76.03 (199.18, 14.92)	23.10 (28.39, 18.09)	22.52 (35.05, 7.08)	13.23 (34.83, 3.68)	–0.40 (0.85, –0.88)
	oil	50	197.26 (245.15, 151.02)	156.16 (202.57, 38.94)	69.94 (167.52, 15.07)	34.81 (42.24, 29.00)	31.24 (39.84, 16.41)	12.89 (27.04, 2.89)	–0.66 (–0.09, –0.93)
1.5°C-high-OS	total primary	35	594.96 (636.98, 510.55)	559.04 (749.05, 419.28)	651.46 (1012.50, 415.31)	NA	NA	NA	0.13 (0.59, –0.27)
	renewables	35	89.84 (98.60, 66.57)	135.12 (159.84, 87.93)	323.21 (522.82, 177.66)	15.08 (18.58, 11.04)	23.65 (29.32, 13.78)	62.16 (86.26, 28.47)	2.68 (4.81, 1.17)
	biomass	35	62.59 (73.03, 48.42)	69.05 (98.27, 56.54)	160.16 (310.10, 71.17)	10.30 (14.23, 8.03)	13.64 (16.37, 9.03)	23.79 (45.79, 10.64)	1.71 (3.71, 0.19)
	non-biomass	35	28.46 (36.58, 17.60)	59.81 (92.12, 27.39)	164.91 (329.69, 55.72)	4.78 (6.64, 2.84)	10.23 (16.59, 4.49)	31.17 (45.86, 9.87)	6.10 (10.63, 1.38)
	wind & solar	26	11.32 (20.17, 1.91)	40.31 (65.50, 8.14)	139.20 (275.47, 30.92)	1.95 (3.66, 0.32)	7.31 (11.61, 1.83)	26.01 (38.79, 6.33)	16.06 (63.34, 3.13)
	nuclear	35	10.94 (14.27, 8.52)	16.12 (41.73, 6.80)	22.98 (115.80, 3.09)	1.86 (2.37, 1.45)	2.99 (5.57, 1.20)	4.17 (13.60, 0.43)	1.49 (7.22, –0.64)
	fossil	35	497.30 (543.29, 407.49)	397.76 (568.91, 300.63)	209.80 (608.39, 43.87)	83.17 (86.59, 79.39)	73.87 (82.94, 68.00)	33.58 (60.09, 7.70)	–0.56 (0.12, –0.91)
	coal	35	155.65 (193.55, 118.40)	70.99 (176.99, 19.15)	18.95 (134.69, 0.36)	25.94 (30.82, 19.10)	14.53 (26.35, 3.64)	4.14 (13.30, 0.05)	–0.87 (–0.30, –1.00)
	gas	35	138.01 (169.50, 107.07)	147.43 (208.55, 76.45)	97.71 (265.66, 15.96)	23.61 (27.35, 19.26)	25.79 (32.73, 14.69)	15.67 (33.80, 2.80)	–0.31 (0.99, –0.88)
	oil	35	195.02 (236.40, 154.66)	198.50 (319.80, 102.10)	126.20 (208.04, 24.68)	32.21 (38.87, 28.07)	33.27 (50.12, 24.35)	18.61 (27.30, 4.51)	–0.34 (0.06, –0.87)

Table 2.6 (continued)

	Median (max, min)	Count	Primary Energy Supply (EJ)			Share in Primary Energy (%)			Growth (factor) 2020-2050
			2020	2030	2050	2020	2030	2050	
Two above classes combined	**total primary**	85	582.12 (636.98, 483.22)	502.81 (749.05, 237.37)	580.78 (1012.50, 289.02)	-	-	-	0.03 (0.59, –0.51)
	renewables	85	87.70 (101.60, 60.16)	139.48 (203.90, 87.75)	293.80 (584.78, 176.77)	15.03 (20.39, 10.60)	27.90 (62.15, 13.78)	60.80 (87.89, 28.47)	2.62 (6.71, 0.91)
	biomass	85	61.35 (73.03, 40.54)	75.28 (113.02, 44.42)	154.13 (311.72, 40.36)	10.27 (14.23, 7.14)	14.38 (35.61, 9.03)	26.38 (54.10, 10.29)	1.71 (5.56, –0.42)
	non-biomass	85	26.35 (36.58, 17.60)	61.60 (114.41, 25.79)	157.37 (409.94, 53.79)	4.40 (7.19, 2.84)	11.87 (26.54, 4.49)	28.60 (61.61, 9.87)	4.63 (13.46, 1.38)
	wind & solar	70	10.93 (20.17, 1.91)	40.17 (82.66, 7.05)	125.31 (342.77, 27.95)	1.81 (3.66, 0.32)	8.24 (19.56, 1.54)	22.10 (51.52, 4.48)	11.64 (63.34, 3.13)
	nuclear	85	10.93 (18.55, 8.52)	16.22 (41.73, 6.80)	24.48 (115.80, 3.09)	1.97 (3.37, 1.45)	3.27 (9.61, 1.20)	4.22 (13.60, 0.43)	1.34 (7.22, –0.64)
	fossil	85	489.52 (543.29, 376.30)	343.48 (568.91, 70.14)	198.58 (608.39, 43.87)	83.05 (86.65, 77.73)	69.19 (82.94, 29.55)	33.06 (60.84, 7.70)	–0.58 (0.12, –0.91)
	coal	85	147.09 (193.55, 83.23)	49.46 (176.99, 5.97)	23.84 (134.69, 0.36)	25.72 (30.82, 17.19)	10.76 (26.35, 1.31)	4.99 (13.30, 0.05)	–0.85 (–0.30, –1.00)
	gas	85	135.58 (169.50, 105.01)	127.99 (208.55, 17.30)	88.97 (265.66, 14.92)	23.28 (28.39, 18.09)	24.02 (35.05, 7.08)	13.46 (34.83, 2.80)	–0.37 (0.99, –0.88)
	oil	85	195.02 (245.15, 151.02)	175.69 (319.80, 38.94)	93.48 (208.04, 15.07)	33.79 (42.24, 28.07)	32.01 (50.12, 16.41)	16.22 (27.30, 2.89)	–0.54 (0.06, –0.93)

Table 2.7 | Global electricity generation of 1.5°C pathways from the scenarios database. (Supplementary Material 2.SM.1.3). Values given for the median (maximum, minimum) values across the full range across 89 available 1.5°C pathways. Growth Factor = [(primary energy supply in 2050)/(primary energy supply in 2020) – 1].

	Median (max, min)	Count	Electricity Generation (EJ)			Share in Electricity Generation (%)			Growth (factor) 2020–2050
			2020	2030	2050	2020	2030	2050	
TBelow -1.5°C and 1.5°C-low-OS pathways	**total generation**	50	98.45 (113.98, 83.53)	115.82 (152.40, 81.28)	215.58 (354.48, 126.96)	NA	NA	NA	1.15 (2.55, 0.28)
	renewables	50	26.28 (41.80, 18.50)	63.30 (111.70, 32.41)	145.50 (324.26, 90.66)	26.32 (41.84, 18.99)	53.68 (79.67, 37.30)	77.12 (96.65, 58.89)	4.48 (10.88, 2.65)
	biomass	50	2.02 (7.00, 0.76)	4.29 (11.96, 0.79)	20.35 (39.28, 0.24)	1.97 (6.87, 0.82)	3.69 (13.29, 0.73)	8.77 (30.28, 0.10)	6.42 (38.14, –0.93)
	non-biomass	50	24.21 (35.72, 17.70)	57.12 (101.90, 25.79)	135.04 (323.91, 53.79)	24.38 (40.43, 17.75)	49.88 (78.27, 29.30)	64.68 (96.46, 41.78)	4.64 (10.64, 1.45)
	wind & solar	50	1.66 (6.60, 0.38)	8.91 (48.04, 0.60)	39.04 (208.97, 2.68)	1.62 (7.90, 0.38)	8.36 (41.72, 0.53)	19.10 (60.11, 1.65)	26.31 (169.66, 5.23)
	nuclear	50	10.84 (18.55, 8.52)	15.46 (36.80, 6.80)	21.97 (64.72, 3.09)	12.09 (18.34, 8.62)	14.33 (31.63, 5.24)	8.10 (27.53, 1.02)	0.71 (4.97, –0.64)
	fossil	50	59.43 (68.75, 39.48)	36.51 (66.07, 2.25)	14.81 (57.76, 0.00)	61.32 (67.40, 47.26)	30.04 (52.86, 1.95)	8.61 (25.18, 0.00)	–0.74 (0.01, –1.00)
	coal	50	31.02 (42.00, 14.40)	8.83 (34.11, 0.00)	1.38 (17.39, 0.00)	32.32 40.38, 17.23)	7.28 (27.29, 0.00)	0.82 (7.53, 0.00)	–0.96 (–0.56, –1.00)
	gas	50	24.70 (32.46, 13.44)	22.59 (42.08, 2.01)	12.79 (53.17, 0.00)	24.39 (35.08, 11.80)	20.18 (37.23, 1.75)	6.93 (24.87, 0.00)	–0.47 (1.27, –1.00)
	oil	50	2.48 (13.36, 1.12)	1.89 (7.56, 0.24)	0.10 (8.78, 0.00)	2.82 (11.73, 1.01)	1.95 (5.67, 0.21)	0.05 (3.80, 0.00)	–0.92 (0.36, –1.00)
1.5°C-high-OS	**total generation**	35	101.44 (113.96, 88.55)	125.26 (177.51, 89.60)	251.50 (363.10, 140.65)	NA	NA	NA	1.38 (2.19, 0.39)
	renewables	35	26.38 (31.83, 18.26)	53.32 (86.85, 30.06)	173.29 (273.92, 84.69)	28.37 (32.96, 17.38)	42.73 (65.73, 25.11)	82.39 (94.66, 35.58)	5.97 (8.68, 2.37)
	biomass	35	1.23 (6.47, 0.66)	2.14 (7.23, 0.86)	10.49 (40.32, 0.21)	1.22 (7.30, 0.63)	1.59 (6.73, 0.72)	3.75 (28.09, 0.08)	7.93 (33.32, –0.81)
	non-biomass	35	24.56 (30.70, 17.60)	47.96 (85.83, 27.39)	144.13 (271.17, 55.72)	26.77 (31.79, 16.75)	40.07 (64.96, 23.10)	69.72 (94.58, 27.51)	5.78 (8.70, 1.38)

Table 2.7 (continued next page)

Table 2.7 (continued)

	Median (max, min)	Count	Electricity Generation (EJ)			Share in Electricity Generation (%)			Growth (factor) 2020-2050
			2020	2030	2050	2020	2030	2050	
1.5°C-high-OS	wind & solar	35	2.24 (5.07, 0.42)	8.95 (36.52, 1.18)	65.08 (183.38, 13.79)	2.21 (5.25, 0.41)	7.48 (27.90, 0.99)	25.88 (61.24, 8.71)	30.70 (106.95, 4.87)
	nuclear	35	10.84 (14.08, 8.52)	16.12 (41.73, 6.80)	22.91 (115.80, 3.09)	10.91 (13.67, 8.62)	14.65 (23.51, 5.14)	11.19 (39.61, 1.12)	1.49 (7.22, –0.64)
	fossil	35	62.49 (76.76, 49.09)	48.08 (87.54, 30.99)	11.84 (118.12, 0.78)	61.58 (71.03, 54.01)	42.02 (59.48, 24.27)	6.33 (33.19, 0.27)	–0.80 (0.54, –0.99)
	coal	35	32.37 (46.20, 26.00)	16.22 (43.12, 1.32)	1.18 (46.72, 0.01)	32.39 (40.88, 24.41)	14.23 (29.93, 1.19)	0.55 (12.87, 0.00)	–0.96 (0.01, –1.00)
	gas	35	26.20 (41.20, 20.11)	26.45 (51.99, 16.45)	10.66 (67.94, 0.76)	26.97 (39.20, 19.58)	22.29 (43.43, 14.03)	5.29 (32.59, 0.26)	–0.57 (1.63, –0.97)
	oil	35	1.51 (6.28, 1.12)	0.61 (7.54, 0.36)	0.04 (7.47, 0.00)	1.51 (6.27, 1.01)	0.55 (6.20, 0.26)	0.02 (3.31, 0.00)	–0.99 (0.98, –1.00)
Two above classes combined	total generation	85	100.09 (113.98, 83.53)	120.01 (177.51, 81.28)	224.78 (363.10, 126.96)	NA	NA	NA	1.31 (2.55, 0.28)
	renewables	85	26.38 (41.80, 18.26)	59.50 (111.70, 30.06)	153.72 (324.26, 84.69)	27.95 (41.84, 17.38)	51.51 (79.67, 25.11)	77.52 (96.65, 35.58)	5.08 (10.88, 2.37)
	biomass	85	1.52 (7.00, 0.66)	3.55 (11.96, 0.79)	16.32 (40.32, 0.21)	1.55 (7.30, 0.63)	2.77 (13.29, 0.72)	8.02 (30.28, 0.08)	6.53 (38.14, –0.93)
	non-biomass	85	24.48 (35.72, 17.60)	55.68 (101.90, 25.79)	136.40 (323.91, 53.79)	25.00 (40.43, 16.75)	47.16 (78.27, 23.10)	66.75 (96.46, 27.51)	4.75 (10.64, 1.38)
	wind & solar	85	1.66 (6.60, 0.38)	8.95 (48.04, 0.60)	43.20 (208.97, 2.68)	1.67 (7.90, 0.38)	8.15 (41.72, 0.53)	19.70 (61.24, 1.65)	28.02 (169.66, 4.87)
	nuclear	85	10.84 (18.55, 8.52)	15.49 (41.73, 6.80)	22.64 (115.80, 3.09)	10.91 (18.34, 8.62)	14.34 (31.63, 5.14)	8.87 (39.61, 1.02)	1.21 (7.22, –0.64)
	fossil	85	61.35 (76.76, 39.48)	38.41 (87.54, 2.25)	14.10 (118.12, 0.00)	61.55 (71.03, 47.26)	33.96 (59.48, 1.95)	8.05 (33.19, 0.00)	–0.76 (0.54, –1.00)
	coal	85	32.37 (46.20, 14.40)	10.41 (43.12, 0.00)	1.29 (46.72, 0.00)	32.39 (40.88, 17.23)	8.95 (29.93, 0.00)	0.59 (12.87, 0.00)	–0.96 (0.01, –1.00)
	gas	85	24.70 (41.20, 13.44)	25.00 (51.99, 2.01)	11.92 (67.94, 0.00)	24.71 (39.20, 11.80)	21.03 (43.43, 1.75)	6.78 (32.59, 0.00)	–0.52 (1.63, –1.00)
	oil	85	1.82 (13.36, 1.12)	0.92 (7.56, 0.24)	0.08 (8.78, 0.00)	2.04 (11.73, 1.01)	0.71 (6.20, 0.21)	0.04 (3.80, 0.00)	–0.97 (0.98, –1.00)

2.4.2.2 Evolution of electricity supply over time

Electricity supplies an increasing share of final energy, reaching 34–71% in 2050, across 1.5°C pathways with no or limited overshoot (Figure 2.14), extending the historical increases in electricity share seen over the past decades (Bruckner et al., 2014). From 2020 to 2050, the quantity of electricity supplied in most 1.5°C pathways with no or limited overshoot more than doubles (Table 2.7). By 2050, the carbon intensity of electricity has fallen rapidly to –92 to +11 gCO_2 MJ^{-1} electricity across 1.5°C pathways with no or limited overshoot from a value of around 140 gCO_2 MJ^{-1} (range: 88–181 gCO_2 MJ^{-1}) in 2020 (Figure 2.14). A negative contribution to carbon intensity is provided by BECCS in most pathways (Figure 2.16).

By 2050, the share of electricity supplied by renewables increases from 23% in 2015 (IEA, 2017b) to 59–97% across 1.5°C pathways with no or limited overshoot. Wind, solar, and biomass together make a major contribution in 2050, although the share for each spans a wide range across 1.5°C pathways (Figure 2.16). Fossil fuels on the other hand have a decreasing role in electricity supply, with their share falling to 0–25% by 2050 (Table 2.7).

In summary, 1.5°C pathways include a rapid decline in the carbon intensity of electricity and an increase in electrification of energy end-use (*high confidence*). This is the case across all 1.5°C pathways and their associated literature (Supplementary Material 2.SM.1.3), with pathway trends that extend those seen in past decades, and results that are consistent with additional analyses (see Section 2.4.2.2).

2.4.2.3 Deployment of carbon capture and storage

Studies have shown the importance of CCS for deep mitigation pathways (Krey et al., 2014a; Kriegler et al., 2014b), based on its multiple roles to limit fossil-fuel emissions in electricity generation, liquids production, and industry applications along with the projected ability to remove CO_2 from the atmosphere when combined with bioenergy. This remains a valid finding for those 1.5°C and 2°C pathways that do not radically reduce energy demand or do not offer carbon-neutral alternatives to liquids and gases that do not rely on bioenergy.

There is a wide range of CCS that is deployed across 1.5°C pathways (Figure 2.17). A few 1.5°C pathways with very low energy demand do not include CCS at all (Grubler et al., 2018). For example, the LED pathway has no CCS, whereas other pathways, such as the S5 pathway,

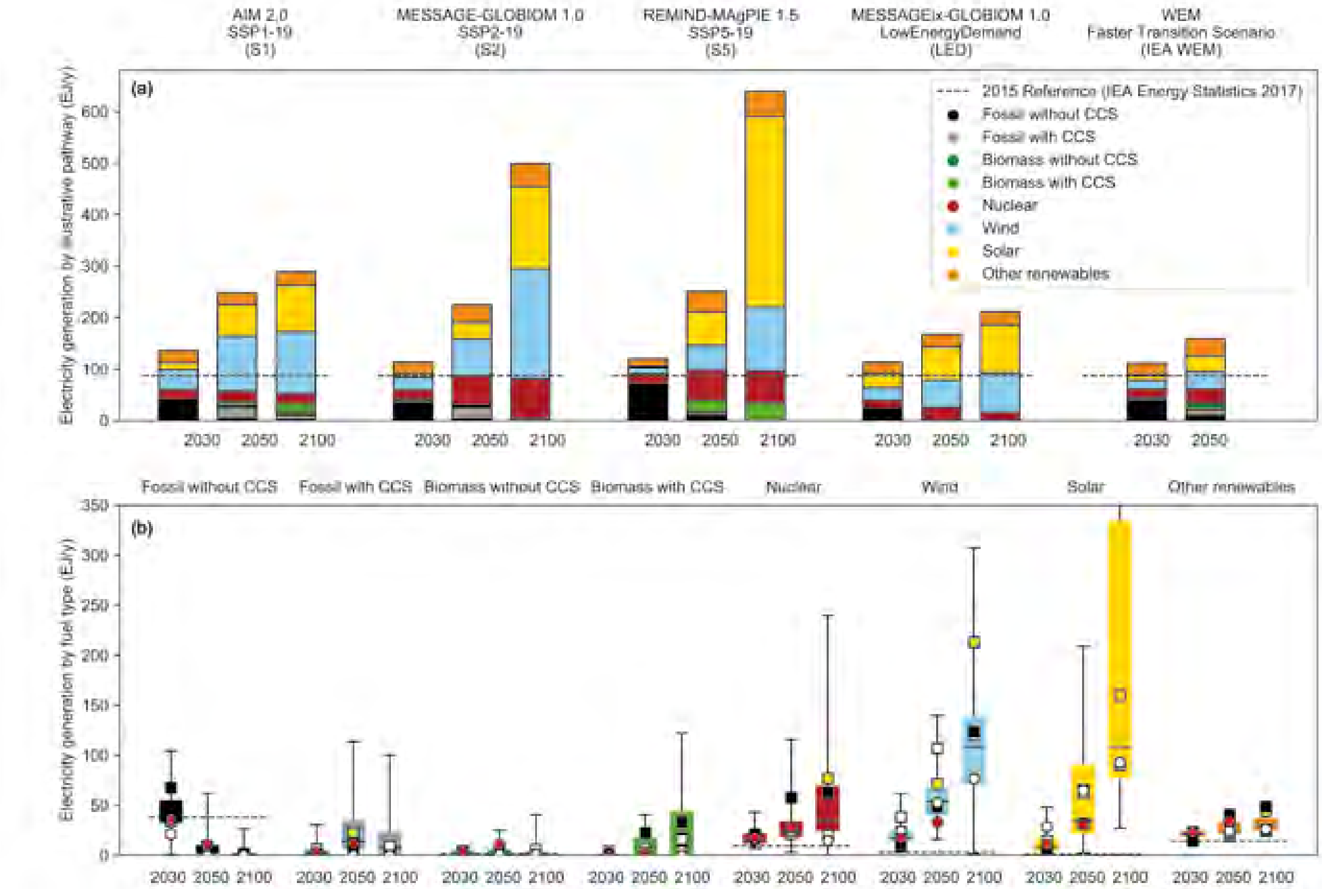


Figure 2.16 | Electricity generation for the four illustrative pathway archetypes plus the IEA's Faster Transition Scenario (IEA, 2017d) (panel a), and their relative location in the ranges for pathways limiting warming to 1.5°C with no or limited overshoot (panel b). The category 'Other renewables' includes electricity generation not covered by the other categories, for example, hydro and geothermal. The number of pathways that have higher primary energy than the scale in the bottom panel are indicated by the numbers above the whiskers. Black horizontal dashed lines indicate the level of primary energy supply in 2015 (IEA, 2017e). Box plots in the lower panel show the minimum–maximum range (whiskers), interquartile range (box), and median (vertical thin black line). Symbols in the lower panel show the four pathway archetypes – S1 (white square), S2 (yellow square), S5 (black square), LED (white disc) – as well as the IEA's Faster Transition Scenario (red disc). Pathways with no or limited overshoot included the Below-1.5°C and 1.5°C-low-OS classes.

rely on a large amount of BECCS to get to net-zero carbon emissions. The cumulative fossil and biomass CO_2 stored through 2050 ranges from zero to 300 $GtCO_2$ across 1.5°C pathways with no or limited overshoot, with zero up to 140 $GtCO_2$ from biomass captured and stored. Some pathways have very low fossil-fuel use overall, and consequently little CCS applied to fossil fuels. In 1.5°C pathways where the 2050 coal use remains above 20 EJ yr^{-1} in 2050, 33–100% is combined with CCS. While deployment of CCS for natural gas and coal vary widely across pathways, there is greater natural gas primary energy connected to CCS than coal primary energy connected to CCS in many pathways (Figure 2.17).

CCS combined with fossil-fuel use remains limited in some 1.5°C pathways (Rogelj et al., 2018), as the limited 1.5°C carbon budget penalizes CCS if it is assumed to have incomplete capture rates or if fossil fuels are assumed to continue to have significant lifecycle GHG emissions (Pehl et al., 2017). However, high capture rates are technically achievable now at higher cost, although efforts to date have focussed on reducing the costs of capture (IEAGHG, 2006; NETL, 2013).

The quantity of CO_2 stored via CCS over this century in 1.5°C pathways with no or limited overshoot ranges from zero to more than 1,200 $GtCO_2$, (Figure 2.17). The IPCC Special Report on Carbon Dioxide Capture and Storage (IPCC, 2005) found that that, worldwide, it is *likely* that there is a technical potential of at least about 2,000 $GtCO_2$ of storage capacity in geological formations. Furthermore, the IPCC (2005) recognized that there could be a much larger potential for geological storage in saline formations, but the upper limit estimates are uncertain due to lack of information and an agreed methodology. Since IPCC (2005), understanding has improved and there have been detailed regional surveys of storage capacity (Vangkilde-Pedersen et al., 2009; Ogawa et al., 2011; Wei et al., 2013; Bentham et al., 2014; Riis and Halland, 2014; Warwick et al., 2014; NETL, 2015) and improvement and standardization of methodologies (e.g., Bachu et al. 2007a, b). Dooley (2013) synthesized published literature on both the global geological storage resource as well as the potential demand for geologic storage in mitigation pathways, and found that the cumulative demand for CO_2 storage was small compared to a practical storage capacity estimate (as defined by Bachu et al., 2007a) of 3,900 $GtCO_2$ worldwide. Differences remain, however, in estimates of storage capacity due to, for example, the potential storage limitations of

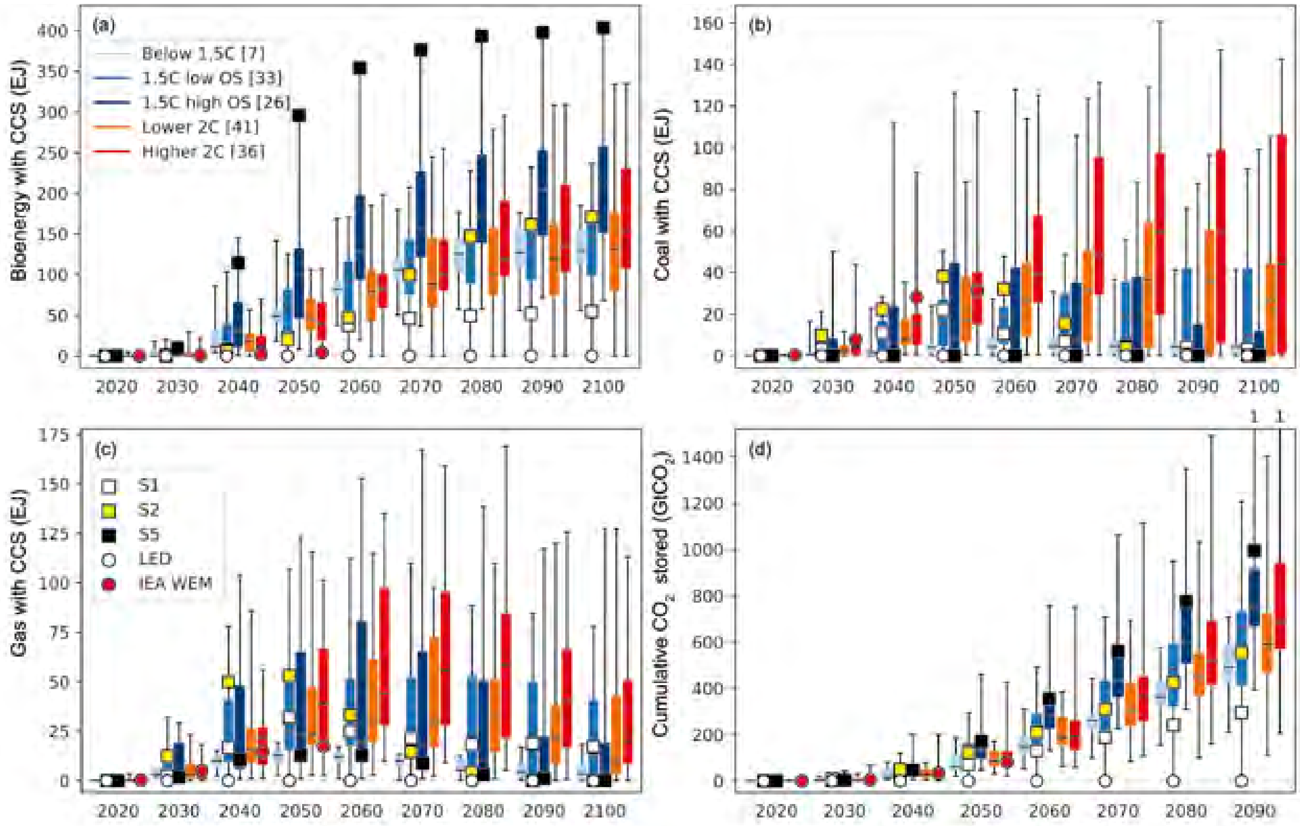


Figure 2.17 | CCS deployment in 1.5°C and 2°C pathways for (a) biomass, (b) coal and (c) natural gas (EJ of primary energy) and (d) the cumulative quantity of fossil (including from, e.g., cement production) and biomass CO_2 stored via CCS (in $GtCO_2$ stored). TBox plots show median, interquartile range and full range of pathways in each temperature class. Pathway temperature classes (Table 2.1), illustrative pathway archetypes, and the IEA's Faster Transition Scenario (IEA WEM) (OECD/IEA and IRENA, 2017) are indicated in the legend.

subsurface pressure build-up (Szulczewski et al., 2014) and assumptions on practices that could manage such issues (Bachu, 2015). Kearns et al. (2017) constructed estimates of global storage capacity of 8,000 to 55,000 $GtCO_2$ (accounting for differences in detailed regional and local estimates), which is sufficient at a global level for this century, but found that at a regional level, robust demand for CO_2 storage exceeds their lower estimate of regional storage available for some regions. However, storage capacity is not solely determined by the geological setting, and Bachu (2015) describes storage engineering practices that could further extend storage capacity estimates. In summary, the storage capacity of all of these global estimates is larger than the cumulative CO_2 stored via CCS in 1.5°C pathways over this century.

There is uncertainty in the future deployment of CCS given the limited pace of current deployment, the evolution of CCS technology that would be associated with deployment, and the current lack of incentives for large-scale implementation of CCS (Bruckner et al., 2014; Clarke et al., 2014; Riahi et al., 2017). Given the importance of CCS in most mitigation pathways and its current slow pace of improvement, the large-scale deployment of CCS as an option depends on the further development of the technology in the near term. Chapter 4 discusses how progress on CCS might be accelerated.

2.4.3 Energy End-Use Sectors

Since the power sector is almost decarbonized by mid-century in both 1.5°C and 2°C pathways, major differences come from CO_2 emission reductions in end-use sectors. Energy-demand reductions are key and common features in 1.5°C pathways, and they can be achieved by efficiency improvements and various specific demand-reduction measures. Another important feature is end-use decarbonization including by electrification, although the potential and challenges in each end-use sector vary significantly.

In the following sections, the potential and challenges of CO_2 emission reductions towards 1.5°C and 2°C- consistent pathways are discussed for each end-use energy sector (industry, buildings, and transport). For this purpose, two types of pathways are analysed and compared: IAM (integrated assessment modelling) studies and sectoral (detailed) studies. IAM data are extracted from the database that was compiled for this assessment (see Supplementary Material 2.SM.1.3), and the sectoral data are taken from a recent series of publications; 'Energy Technology Perspectives' (ETP) (IEA, 2014, 2015b, 2016a, 2017a), the IEA/IRENA report (OECD/IEA and IRENA, 2017), and the Shell Sky report (Shell International B.V., 2018). The IAM pathways are categorized according to their temperature rise in 2100 and the overshoot of temperature during the century (see Table 2.1 in Section 2.1). Since the number of Below-1.5°C pathways is small, the following analyses focus only on the features of the 1.5°C-low-OS and 1.5°C-high-OS pathways (hereafter denoted together as 1.5°C overshoot pathways or IAM-1.5DS-OS) and 2°C-consistent pathways (IAM-2DS). In order to show the diversity of IAM pathways, we again show specific data from the four illustrative pathways archetypes used throughout this chapter (see Sections 2.1 and 2.3).

IEA ETP-B2DS ('Beyond 2 Degrees') and ETP-2DS are pathways with a 50% chance of limiting temperature rise below 1.75°C and 2°C by 2100, respectively (IEA, 2017a). The IEA-66%2DS pathway keeps global mean temperature rise below 2°C, not just in 2100 but also over the course of the 21st century, with a 66% chance of being below 2°C by 2100 (OECD/IEA and IRENA, 2017). The comparison of CO_2 emission trajectories between ETP-B2DS and IAM-1.5DS-OS show that these are consistent up to 2060 (Figure 2.18). IEA scenarios assume that only a very low level of BECCS is deployed to help offset emissions in difficult-to-decarbonize sectors, and that global energy-related CO_2 emissions do not turn net negative at any time but stay at zero from 2060 to 2100 (IEA, 2017a). Therefore, although its temperature rise in 2100 is below 1.75°C rather than below 1.5°C, this scenario can give information related to a 1.5°C overshoot pathway up to 2050. The trajectory of IEA-66%2DS (also referred to in other publications as IEA's 'Faster Transition Scenario') lies between IAM-1.5DS-OS and IAM-2DS pathway ranges, and IEA-2DS stays in the range of 2°C-consistent IAM pathways. The Shell-Sky scenario aims to hold the temperature rise to well below 2°C, but it is a delayed action pathway relative to others, as can be seen in Figure 2.18.

Energy-demand reduction measures are key to reducing CO_2 emissions from end-use sectors for low-carbon pathways. The upstream energy reductions can be from several times to an order of magnitude larger than the initial end-use demand reduction. There are interdependencies among the end-use sectors and between energy-supply and end-use sectors, which elevate the importance of a wide, systematic approach. As shown in Figure 2.19, global final energy consumption grows by 30% and 10% from 2010 to 2050 for 2°C-consistent and 1.5°C overshoot pathways from IAMs, respectively, while much higher growth of 75% is projected for reference scenarios. The ranges within a specific pathway class are due to a variety of factors as introduced in Section 2.3.1, as well as differences between modelling frameworks. The important energy efficiency and conservation improvements that facilitate many of the 1.5°C pathways raise the issue of potential rebound effects (Saunders, 2015), which, while promoting development, can make the achievement of low-energy demand futures more difficult than modelling studies anticipate (see Sections 2.5 and 2.6).

Final energy demand is driven by demand in energy services for mobility, residential and commercial activities (buildings), and manufacturing. Projections of final energy demand depend heavily on assumptions about socio-economic futures as represented by the SSPs (Bauer et al., 2017) (see Sections 2.1, 2.3 and 2.5). The structure of this demand drives the composition of final energy use in terms of energy carriers (electricity, liquids, gases, solids, hydrogen etc.).

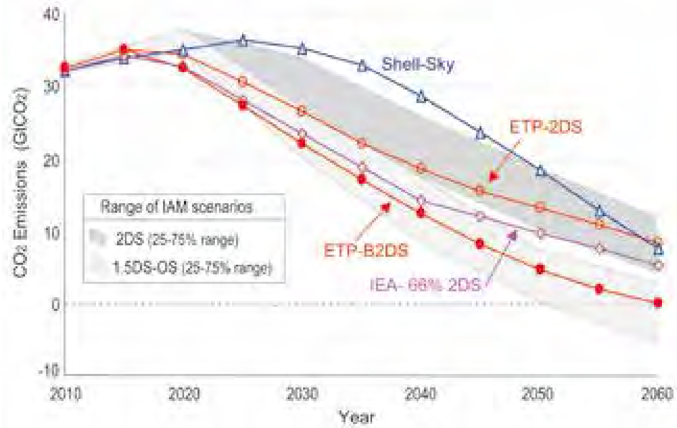


Figure 2.18 | Comparison of CO_2 emission trajectories of sectoral pathways (IEA ETP-B2DS, ETP-2DS, IEA-66%2DS, Shell-Sky) with the ranges of IAM pathway (2DS are 2°C-consistent pathways and 1.5DS-OS are1.5°C overshoot pathways). The CO_2 emissions shown here are the energy-related emissions, including industrial process emissions.

Figure 2.19 shows the structure of global final energy demand in 2030 and 2050, indicating the trend toward electrification and fossil fuel usage reduction. This trend is more significant in 1.5°C pathways than 2°C pathways. Electrification continues throughout the second half of the century, leading to a 3.5- to 6-fold increase in electricity demand (interquartile range; median 4.5) by the end of the century relative to today (Grubler et al., 2018; Luderer et al., 2018). Since the electricity sector is completely decarbonized by mid-century in 1.5°C pathways (see Figure 2.20), electrification is the primary means to decarbonize energy end-use sectors.

The CO_2 emissions[6] of end-use sectors and carbon intensity are shown in Figure 2.20. The projections of IAMs and IEA studies show rather different trends, especially in the carbon intensity. These differences come from various factors, including the deployment of CCS, the level of fuel switching and efficiency improvements, and the effect of structural and behavioural changes. IAM projections are generally optimistic for the industry sectors, but not for buildings and transport sectors. Although GDP increases by a factor of 3.4 from 2010 to 2050, the total energy consumption of end-use sectors grows by only about 30% and 20% in 1.5°C overshoot and 2°C-consistent pathways, respectively. However, CO_2 emissions would need to be reduced further to achieve the stringent temperature limits. Figure 2.20 shows that the reduction in CO_2 emissions of end-use sectors is larger and more rapid in 1.5°C overshoot than 2°C-consistent pathways, while emissions from the power sector are already almost zero in 2050 in both sets of pathways, indicating that supply-side emissions reductions are almost fully exploited already in 2°C-consistent pathways (see Figure 2.20) (Rogelj et al., 2015b, 2018; Luderer et al., 2016b). The emission reductions in end-use sectors are largely made possible by efficiency improvements, demand reduction measures and electrification, but the level of emissions reductions varies across end-use sectors. While the carbon intensity of the industry and buildings sectors decreases

6 This section reports 'direct' CO_2 emissions as reported for pathways in the database for the report. As shown below, the emissions from electricity are nearly zero around 2050, so the impact of indirect emissions on the whole emission contributions of each sector is very small in 2050.

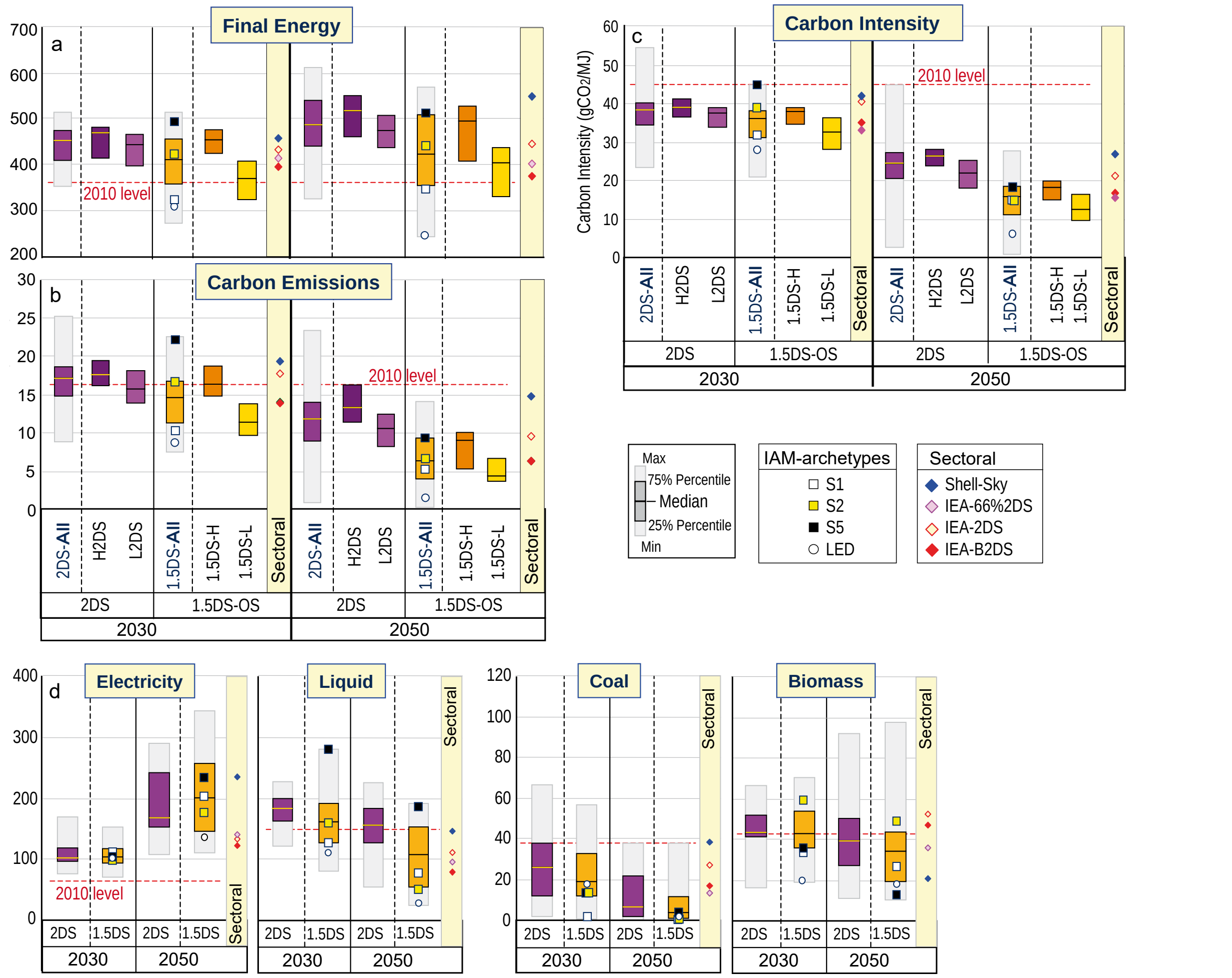


Figure 2.19 | (a) Global final energy, (b) direct CO_2 emissions from the all energy demand sectors, (c) carbon intensity, and (d) structure of final energy (electricity, liquid fuel, coal, and biomass). The squares and circles indicate the IAM archetype pathways and diamonds indicate the data of sectoral scenarios. The red dotted line indicates the 2010 level. H2DS = Higher-2°C, L2DS = Lower-2°C, 1.5DS-H = 1.5°C-high-OS, 1.5DS-L = 1.5°C-low-OS. The label 1.5DS combines both high and low overshoot 1.5°C-consistent pathway. See Section 2.1 for descriptions.

to a very low level of around 10 gCO_2 MJ^{-1}, the carbon intensity of transport becomes the highest of any sector by 2040 due to its higher reliance on oil-based fuels. In the following subsections, the potential and challenges of CO_2 emission reduction in each end-use sector are discussed in detail.

2.4.3.1 Industry

The industry sector is the largest end-use sector, both in terms of final energy demand and GHG emissions. Its direct CO_2 emissions currently account for about 25% of total energy-related and process CO_2 emissions, and emissions have increased at an average annual rate of 3.4% between 2000 and 2014, significantly faster than total CO_2 emissions (Hoesly et al., 2018). In addition to emissions from the combustion of fossil fuels, non-energy uses of fossil fuels in the petrochemical industry and metal smelting, as well as non-fossil fuel process emissions (e.g., from cement production) contribute a small amount (~5%) to the sector's CO_2 emissions inventory. Material industries are particularly energy and emissions intensive: together, the steel, non-ferrous metals, chemicals, non-metallic minerals, and pulp and paper industries accounted for close to 66% of final energy demand and 72% of direct industry-sector emissions in 2014 (IEA, 2017a). In terms of end-uses, the bulk of energy in manufacturing industries is required for process heating and steam generation, while most electricity (but smaller shares of total final energy) is used for mechanical work (Banerjee et al., 2012; IEA, 2017a).

As shown in Figure 2.21, a major share of the additional emission reductions required for 1.5°C-overshoot pathways compared to those in 2°C-consistent pathways comes from industry. Final energy, CO_2 emissions, and carbon intensity are consistent in IAM and sectoral studies, but in IAM-1.5°C-overshoot pathways the share of electricity is higher than IEA-B2DS (40% vs. 25%) and hydrogen is also considered to have a share of about 5% versus 0%. In 2050, final energy is increased by 30% and 5% compared with the 2010 level (red dotted line) for 1.5°C-overshoot and 2°C-consistent pathways, respectively, but CO_2 emissions are decreased by 80% and 50% and carbon intensity by 80% and 60%, respectively. This additional decarbonization is brought by switching to low-carbon fuels and CCS deployment.

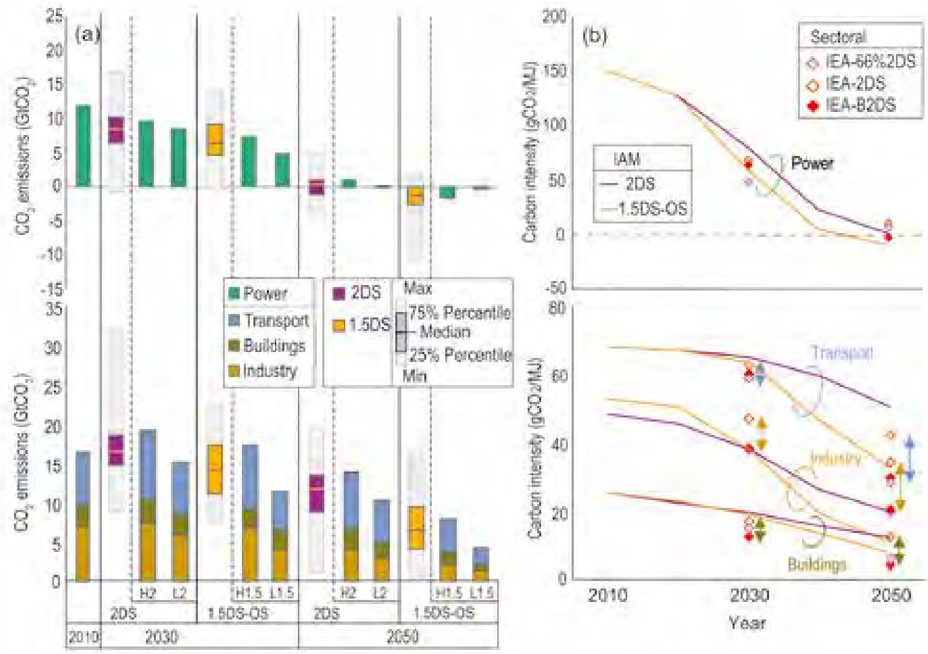


Figure 2.20 | Comparison of (a) direct CO_2 emissions and (b) carbon intensity of the power and energy end-use sectors (industry, buildings, and transport sectors) between IAMs and sectoral studies (IEA-ETP and IEA/IRENA). Diamond markers in panel (b) show data for IEA-ETP scenarios (2DS and B2DS), and IEA/IRENA scenario (66%2DS). Note: for the data from IAM studies, there is rather large variation of projections for each indicator. Please see the details in the following figures in each end-use sector section.

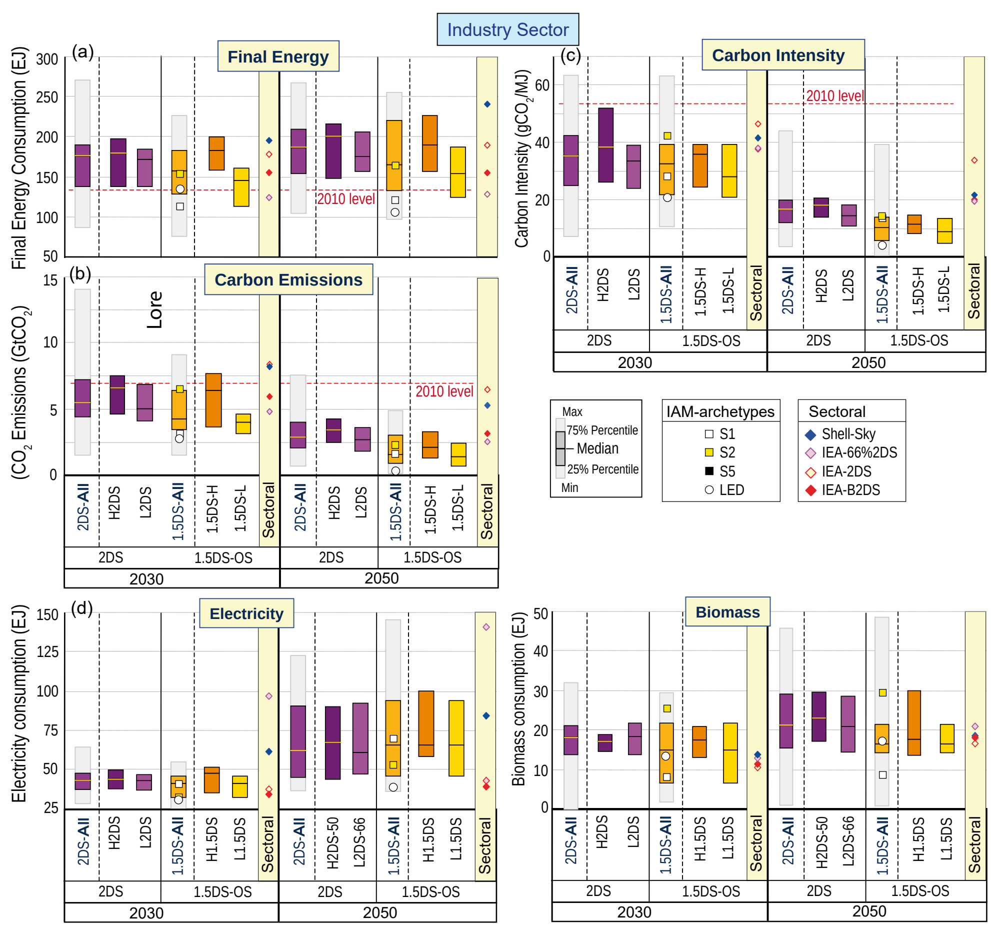


Figure 2.21 | Comparison of (a) final energy, (b) direct CO_2 emissions, (c) carbon intensity, (d) electricity and biomass consumption in the industry sector between IAM and sectoral studies. The squares and circles indicate the IAM archetype pathways and diamonds the data of sectoral scenarios. The red dotted line indicates the 2010 level. H2DS = Higher-2°C, L2DS = Lower-2°C, 1.5DS-H = 1.5°C-high-OS, 1.5DS-L = 1.5°C-low-OS. The label 1.5DS combines both high and low overshoot 1.5°C-consistent pathways. Section 2.1 for descriptions.

Broadly speaking, the industry sector's mitigation measures can be categorized in terms of the following five strategies: (i) reducing demand, (ii) energy efficiency, (iii) increasing electrification of energy demand, (iv) reducing the carbon content of non-electric fuels, and (v) deploying innovative processes and application of CCS. IEA ETP estimates the relative contribution of different measures for CO_2 emission reduction in their B2DS scenario compared with their reference scenario in 2050 as follows: energy efficiency 42%, innovative process and CCS 37%, switching to low-carbon fuels and feedstocks 13% and material efficiency (include efficient production and use to contribute to demand reduction) 8%. The remainder of this section delves more deeply into the potential mitigation contributions of these strategies as well as their limitations.

2

Reduction in the use of industrial materials, while delivering similar services, or improving the quality of products could help to reduce energy demand and overall system-level CO_2 emissions. Strategies include using materials more intensively, extending product lifetimes, increasing recycling, and increasing inter-industry material synergies, such as clinker substitution in cement production (Allwood et al., 2013; IEA, 2017a). Related to material efficiency, use of fossil-fuel feedstocks could shift to lower-carbon feedstocks, such as from oil to natural gas and biomass, and end-uses could shift to more sustainable materials, such as biomass-based materials, reducing the demand for energy-intensive materials (IEA, 2017a).

Reaping energy efficiency potentials hinges critically on advanced management practices, such as energy management systems, in industrial facilities as well as targeted policies to accelerate adoption of the best available technology (see Section 2.5). Although excess energy, usually as waste heat, is inevitable, recovering and reusing this waste heat under economically and technically viable conditions benefits the overall energy system. Furthermore, demand-side management strategies could modulate the level of industrial activity in line with the availability of resources in the power system. This could imply a shift away from peak demand and as power supply decarbonizes, this demand-shaping potential could shift some load to times with high portions of low-carbon electricity generation (IEA, 2017a).

In the industry sector, energy demand increases more than 40% between 2010 and 2050 in baseline scenarios. However, in the 1.5°C-overshoot and 2°C-consistent pathways from IAMs, the increase is only 30% and 5%, respectively (Figure 2.21). These energy-demand reductions encompass both efficiency improvements in production and reductions in material demand, as most IAMs do not discern these two factors.

CO_2 emissions from industry increase by 30% in 2050 compared to 2010 in baseline scenarios. By contrast, these emissions are reduced by 80% and 50% relative to 2010 levels in 1.5°C-overshoot and 2°C-consistent pathways from IAMs, respectively (Figure 2.21). By mid-century, CO_2 emissions per unit of electricity are projected to decrease to near zero in both sets of pathways (see Figure 2.20). An accelerated electrification of the industry sector thus becomes an increasingly powerful mitigation option. In the IAM pathways, the share of electricity increases up to 30% by 2050 in 1.5°C-overshoot pathways (Figure 2.21) from 20% in 2010. Some industrial fuel uses are substantially more difficult to electrify than others, and electrification would have other effects on the process, including impacts on plant design, cost and available process integration options (IEA, 2017a).[7]

In 1.5°C-overshoot pathways, the carbon intensity of non-electric fuels consumed by industry decreases to 16 $gCO_2\ MJ^{-1}$ by 2050, compared to 25 $gCO_2\ MJ^{-1}$ in 2°C-consistent pathways. Considerable carbon intensity reductions are already achieved by 2030, largely via a rapid phase-out of coal. Biomass becomes an increasingly important energy carrier in the industry sector in deep-decarbonization pathways, but primarily in the longer term (in 2050, biomass accounts for only 10% of final energy consumption even in 1.5°C-overshoot pathways). In addition, hydrogen plays a considerable role as a substitute for fossil-based non-electric energy demands in some pathways.

Without major deployment of new sustainability-oriented low-carbon industrial processes, the 1.5°C-overshoot target is difficult to achieve. Bringing such technologies and processes to commercial deployment requires significant investment in research and development. Some examples of innovative low-carbon process routes include: new steelmaking processes such as upgraded smelt reduction and upgraded direct reduced iron, inert anodes for aluminium smelting, and full oxy-fuelling kilns for clinker production in cement manufacturing (IEA, 2017a).

CCS plays a major role in decarbonizing the industry sector in the context of 1.5°C and 2°C pathways, especially in industries with higher process emissions, such as cement, iron and steel industries. In 1.5°C-overshoot pathways, CCS in industry reaches 3 $GtCO_2\ yr^{-1}$ by 2050, albeit with strong variations across pathways. Given the projected long-lead times and need for technological innovation, early scale-up of industry-sector CCS is essential to achieving the stringent temperature target. Development and demonstration of such projects has been slow, however. Currently, only two large-scale industrial CCS projects outside of oil and gas processing are in operation (Global CCS Institute, 2016). The estimated current cost[8] of CO_2 avoided (in USD2015) ranges from \$20–27 tCO_2^{-1} for gas processing and bio-ethanol production, and \$60–138 tCO_2^{-1} for fossil fuel-fired power generation up to \$104–188 tCO_2^{-1} for cement production (Irlam, 2017).

2.4.3.2 Buildings

In 2014, the buildings sector accounted for 31% of total global final energy use, 54% of final electricity demand, and 8% of energy-related CO_2 emissions (excluding indirect emissions due to electricity). When

7 Electrification can be linked with the heating and drying process by electric boilers and electro-thermal processes, and also with low-temperature heat demand by heat pumps. In the iron and steel industry, hydrogen produced by electrolysis can be used as a reduction agent of iron instead of coke. Excess resources, such as black liquor, will provide the opportunity to increase the systematic efficiency to use for electricity generation.

8 These are first-of-a-kind (FOAK) cost data.

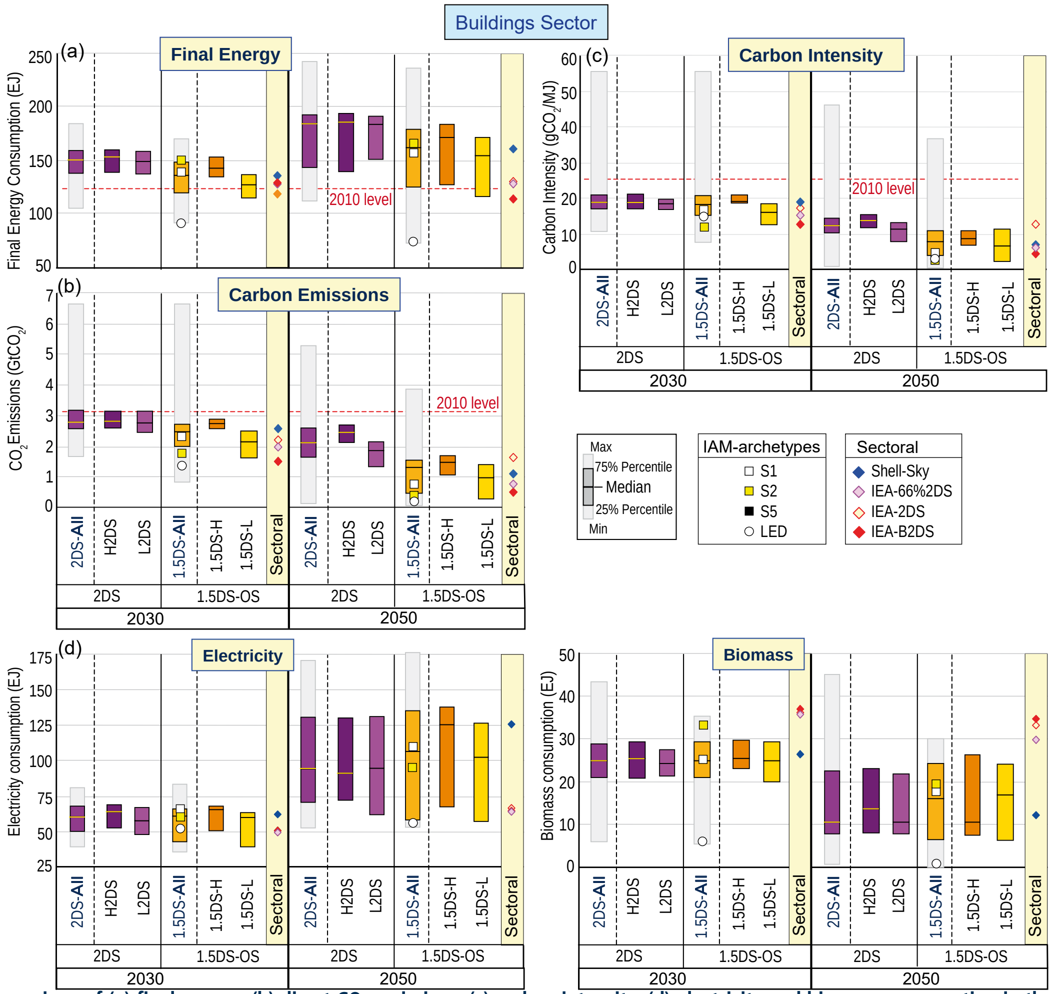


Figure 2.22 | Comparison of (a) final energy, (b) direct CO_2 emissions, (c) carbon intensity, (d) electricity and biomass consumption in the buildings sector between IAM and sectoral studies. The squares and circles indicate the IAM archetype pathways and diamonds the data of sectoral scenarios. The red dotted line indicates the 2010 level. H2DS = Higher-2°C, L2DS = Lower-2°C, 1.5DS-H = 1.5°C-high-OS, 1.5DS-L = 1.5°C-low-OS. The label 1.5DS combines both high and low overshoot 1.5°C-consistent pathways. Section 2.1 for descriptions.

upstream electricity generation is taken into account, buildings were responsible for 23% of global energy-related CO_2 emissions, with one-third of those from direct fossil fuel consumption (IEA, 2017a).

Past growth of energy consumption has been mainly driven by population and economic growth, with improved access to electricity, and higher use of electrical appliances and space cooling resulting from increasing living standards, especially in developing countries (Lucon et al., 2014). These trends will continue in the future and in 2050, energy consumption is projected to increase by 20% and 50% compared to 2010 in the IAM-1.5°C-overshoot and 2°C-consistent pathways, respectively (Figure 2.22). However, sectoral studies (IEA-ETP scenarios) show different trends. Energy consumption in 2050 decreases compared to 2010 in ETP-B2DS, and the reduction rate of CO_2 emissions is higher than in IAM pathways (Figure 2.22). Mitigation options are often more widely covered in sectoral studies (Lucon et al., 2014), leading to greater reductions in energy consumption and CO_2 emissions.

Emissions reductions are driven by a clear tempering of energy demand and a strong electrification of the buildings sector. The share of electricity in 2050 is 60% in 1.5°C-overshoot pathways, compared with 50% in 2°C-consistent pathways (Figure 2.22). Electrification contributes to the reduction of direct CO_2 emissions by replacing carbon-intensive fuels, like oil and coal. Furthermore, when combined with a rapid decarbonization of the power system (see Section 2.4.1) it also enables further reduction of indirect CO_2 emissions from electricity. Sectoral bottom-up models generally estimate lower electrification potentials for the buildings sector in comparison to global IAMs (see Figure 2.22). Besides CO_2 emissions, increasing global demand for air conditioning in buildings may also lead to increased emissions of HFCs in this sector over the next few decades. Although these gases are currently a relatively small proportion of annual GHG emissions, their use in the air conditioning sector is expected to grow rapidly over the next few decades if alternatives are not adopted. However, their projected future impact can be significantly mitigated through better servicing and maintenance of equipment and switching of cooling gases (Shah et al., 2015; Purohit and Höglund-Isaksson, 2017).

IEA-ETP (IEA, 2017a) analysed the relative importance of various technology measures toward the reduction of energy and CO_2 emissions in the buildings sector. The largest energy savings potential is in heating and cooling demand, largely due to building envelope improvements and high efficiency and renewable equipment. In the

ETP-B2DS, energy demand for space heating and cooling is 33% lower in 2050 than in the reference scenario, and these reductions account for 54% of total reductions from the reference scenario. Energy savings from shifts to high-performance lighting, appliances, and water heating equipment account for a further 24% of the total reduction. The long-term, strategic shift away from fossil-fuel use in buildings, alongside the rapid uptake of energy efficient, integrated and renewable energy technologies (with clean power generation), leads to a drastic reduction of CO_2 emissions. In ETP-B2DS, the direct CO_2 emissions are 79% lower than the reference scenario in 2050, and the remaining emissions come mainly from the continued use of natural gas.

The buildings sector is characterized by very long-living infrastructure, and immediate steps are hence important to avoid lock-in of inefficient carbon and energy-intensive buildings. This applies both to new buildings in developing countries where substantial new construction is expected in the near future and to retrofits of existing building stock in developed regions. This represents both a significant risk and opportunity for mitigation.[9] A recent study highlights the benefits of deploying the most advanced renovation technologies, which would avoid lock-in into less efficient measures (Güneralp et al., 2017). Aside from the effect of building envelope measures, adoption of energy-efficient technologies such as heat pumps and, more recently, light-emitting diodes is also important for the reduction of energy and CO_2 emissions (IEA, 2017a). Consumer choices, behaviour and building operation can also significantly affect energy consumption (see Chapter 4, Section 4.3).

2.4.3.3 Transport

Transport accounted for 28% of global final energy demand and 23% of global energy-related CO_2 emissions in 2014. Emissions increased by 2.5% annually between 2010 and 2015, and over the past half century the sector has witnessed faster emissions growth than any other. The transport sector is the least diversified energy end-use sector; the sector consumed 65% of global oil final energy demand, with 92% of transport final energy demand consisting of oil products (IEA, 2017a), suggesting major challenges for deep decarbonization.

Final energy, CO_2 emissions, and carbon intensity for the transport sector are shown in Figure 2.23. The projections of IAMs are more pessimistic than IEA-ETP scenarios, though both clearly project deep cuts in energy consumption and CO_2 emissions by 2050. For example, 1.5°C-overshoot pathways from IAMs project a reduction of 15% in energy consumption between 2015 and 2050, while ETP-B2DS projects a reduction of 30% (Figure 2.23). Furthermore, IAM pathways are generally more pessimistic in the projections of CO_2 emissions and carbon intensity reductions. In AR5 (Clarke et al., 2014; Sims et al., 2014), similar comparisons between IAMs and sectoral studies were performed and these were in good agreement with each other. Since the AR5, two important changes can be identified: rapid growth of electric vehicle sales in passenger cars, and more attention towards structural changes in this sector. The former contributes to reduction of CO_2 emissions and the latter to reduction of energy consumption.

Deep emissions reductions in the transport sector would be achieved by several means. Technology-focused measures such as energy efficiency and fuel-switching are two of these. Structural changes that avoid or shift transport activity are also important. While the former solutions (technologies) always tend to figure into deep decarbonization pathways in a major way, this is not always the case with the latter, especially in IAM pathways. Comparing different types of global transport models, Yeh et al. (2016) find that sectoral (intensive) studies generally envision greater mitigation potential from structural changes in transport activity and modal choice. Though, even there, it is primarily the switching of passengers and freight from less- to more-efficient travel modes (e.g., cars, trucks and airplanes to buses and trains) that is the main strategy; other actions, such as increasing vehicle load factors (occupancy rates) and outright reductions in travel demand (e.g., as a result of integrated transport, land-use and urban planning), figure much less prominently. Whether these dynamics accurately reflect the actual mitigation potential of structural changes in transport activity and modal choice is a point of investigation. According to the recent IEA-ETP scenarios, the share of avoid (reduction of mobility demand) and shift (shifting to more efficient modes) measures in the reduction of CO_2 emissions from the reference to B2DS scenarios in 2050 amounts to 20% (IEA, 2017a).

The potential and strategies to reduce energy consumption and CO_2 emissions differ significantly among transport modes. In ETP-B2DS, the shares of energy consumption and CO_2 emissions in 2050 for each mode are rather different (see Table 2.8), indicating the challenge of decarbonizing heavy-duty vehicles (HDV, trucks), aviation, and shipping. The reduction of CO_2 emissions in the whole sector from the reference scenario to ETP-B2DS is 60% in 2050, with varying contributions per mode (Table 2.8). Since there is no silver bullet for this deep decarbonization, every possible measure would be required to achieve this stringent emissions outcome. The contribution of various measures for the CO_2 emission reduction from the reference scenario to the IEA-B2DS in 2050 can be decomposed to efficiency improvement (29%), biofuels (36%), electrification (15%), and avoid/shift (20%) (IEA, 2017a). It is noted that the share of electrification becomes larger compared with older studies, reflected by the recent growth of electric vehicle sales worldwide. Another new trend is the allocation of biofuels to each mode of transport. In IEA-B2DS, the total amount of biofuels consumed in the transport sector is 24EJ[10] in 2060, and allocated to LDV (light-duty vehicles, 17%), HDV (35%), aviation (28%), and shipping (21%), that is, more biofuels is allocated to the difficult-to-decarbonize modes (see Table 2.8).

In road transport, incremental vehicle improvements (including engines) are relevant, especially in the short to medium term. Hybrid electric vehicles are also instrumental to enabling the transition from

[9] In this section, we only discuss the direct emissions from the sector, but the selection of building materials has a significant impact on the reduction of energy and emissions during production, such as shift from the steel and concrete to wood-based materials.

[10] This is estimated for the biofuels produced in a "sustainable manner" from non-food crop feedstocks, which are capable of delivering significant lifecycle GHG emissions savings compared with fossil fuel alternatives, and which do not directly compete with food and feed crops for agricultural land or cause adverse sustainability impacts.

Table 2.8 | Transport sector indicators by mode in 2050 (IEA, 2017a).
Share of energy consumption, biofuel consumption, CO_2 emissions, and reduction of energy consumption and CO_2 emissions from 2014. (CO_2 emissions are well-to-wheel emissions, including the emission during the fuel production.), LDV: light duty vehicle, HDV: heavy duty vehicle.

	Share of Each Mode (%)			Reduction from 2014 (%)	
	Energy	Biofuel	CO_2	Energy	CO_2
LDV	36	17	30	51	81
HDV	33	35	36	8	56
Rail	6	-	–1	–136	107
Aviation	12	28	14	14	56
Shipping	17	21	21	26	29

internal combustion engine vehicles to electric vehicles, especially plug-in hybrid electric vehicles. Electrification is a powerful measure to decarbonize short-distance vehicles (passenger cars and two and three wheelers) and the rail sector. In road freight transport (trucks), systemic improvements (e.g., in supply chains, logistics, and routing) would be effective measures in conjunction with efficiency improvement of vehicles. Shipping and aviation are more challenging to decarbonize, while their demand growth is projected to be higher than other transport modes. Both modes would need to pursue highly ambitious efficiency improvements and use of low-carbon fuels. In the near and medium term, this would be advanced biofuels while in the long term it could be hydrogen as direct use for shipping or an intermediate product for synthetic fuels for both modes (IEA, 2017a).

The share of low-carbon fuels in the total transport fuel mix increases to 10% and 16% by 2030 and to 40% and 58% by 2050

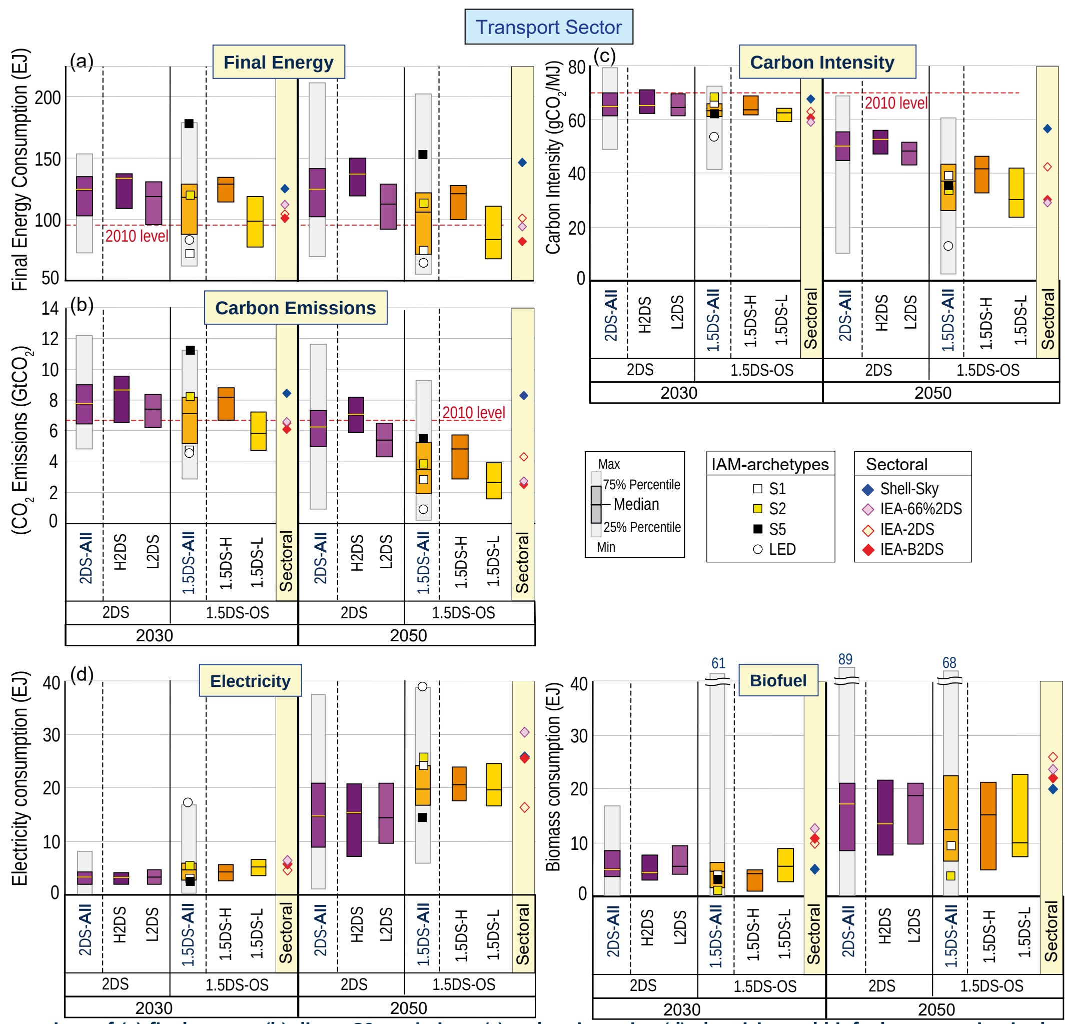


Figure 2.23 | Comparison of (a) final energy, (b) direct CO_2 emissions, (c) carbon intensity, (d) electricity and biofuel consumption in the transport sector between IAM and sectoral studies. The squares and circles indicate the IAM archetype pathways and diamonds the data of sectoral scenarios. The red dotted line indicates the 2010 level. H2DS = Higher-2°C, L2DS = Lower-2°C, 1.5DS-H = 1.5°C-high-OS, 1.5DS-L = 1.5°C-low-OS. The label 1.5DS combines both high and low overshoot 1.5°C-consistent pathways. Section 2.1 for descriptions.

in 1.5°C-overshoot pathways from IAMs and the IEA-B2DS pathway, respectively. The IEA-B2DS scenario is on the more ambitious side, especially in the share of electricity. Hence, there is wide variation among scenarios, including the IAM pathways, regarding changes in the transport fuel mix over the first half of the century. As seen in Figure 2.23, the projections of energy consumption, CO_2 emissions and carbon intensity are quite different between IAM and ETP scenarios. These differences can be explained by more weight on efficiency improvements and avoid/shift decreasing energy consumption, and the higher share of biofuels and electricity accelerating the speed of decarbonization in ETP scenarios. Although biofuel consumption and electric vehicle sales have increased significantly in recent years, the growth rates projected in these pathways would be unprecedented and far higher than has been experienced to date.

The 1.5°C pathways require an acceleration of the mitigation solutions already featured in 2°C-consistent pathways (e.g., more efficient vehicle technologies operating on lower-carbon fuels), as well as those having received lesser attention in most global transport decarbonization pathways up to now (e.g., mode-shifting and travel demand management). Current-generation, global pathways generally do not include these newer transport sector developments, whereby technological solutions are related to shifts in traveller's behaviour.

2.4.4 Land-Use Transitions and Changes in the Agricultural Sector

The agricultural and land system described together under the umbrella of the AFOLU (agriculture, forestry, and other land use) sector plays an important role in 1.5°C pathways (Clarke et al., 2014; Smith and Bustamante, 2014; Popp et al., 2017). On the one hand, its emissions need to be limited over the course of this century to be in line with pathways limiting warming to 1.5°C (see Sections 2.2-3). On the other hand, the AFOLU system is responsible for food and feed production; for wood production for pulp and construction; for the production of biomass that is used for energy, CDR or other uses; and for the supply of non-provisioning (ecosystem) services (Smith and Bustamante, 2014). Meeting all demands together requires changes in land use, as well as in agricultural and forestry practices, for which a multitude of potential options have been identified (Smith and Bustamante, 2014; Popp et al., 2017) (see also Supplementary Material 2.SM.1.2 and Chapter 4, Section 4.3.1, 4.3.2 and 4.3.7).

This section assesses the transformation of the AFOLU system, mainly making use of pathways from IAMs (see Section 2.1) that are based on quantifications of the SSPs and that report distinct land-use evolutions in line with limiting warming to 1.5°C (Calvin et al., 2017; Fricko et al., 2017; Fujimori, 2017; Kriegler et al., 2017; Popp et al., 2017; Riahi et al., 2017; van Vuuren et al., 2017b; Doelman et al., 2018; Rogelj et al., 2018). The SSPs were designed to vary mitigation challenges (O'Neill et al., 2014) (Cross-Chapter Box 1 in Chapter 1), including for the AFOLU sector (Popp et al., 2017; Riahi et al., 2017). The SSP pathway ensemble hence allows for a structured exploration of AFOLU transitions in the context of climate change mitigation in line with 1.5°C, taking into account technological and socio-economic aspects. Other considerations, like food security, livelihoods and biodiversity, are also of importance when identifying AFOLU strategies. These are at present only tangentially explored by the SSPs. Further assessments of AFOLU mitigation options are provided in other parts of this report and in the IPCC Special Report on Climate Change and Land (SRCCL). Chapter 4 provides an assessment of bioenergy (including feedstocks, see Section 4.3.1), livestock management (Section 4.3.1), reducing rates of deforestation and other land-based mitigation options (as mitigation and adaptation option, see Section 4.3.2), and BECCS, afforestation and reforestation options (including the bottom-up literature of their sustainable potential, mitigation cost and side effects, Section 4.3.7). Chapter 3 discusses impacts land-based CDR (Cross-Chapter Box 7 in Chapter 3). Chapter 5 assesses the sustainable development implications of AFOLU mitigation, including impacts on biodiversity (Section 5.4). Finally, the SRCCL will undertake a more comprehensive assessment of land and climate change aspects. For the sake of complementarity, this section focusses on the magnitude and pace of land transitions in 1.5°C pathways, as well as on the implications of different AFOLU mitigation strategies for different land types. The interactions with other societal objectives and potential limitations of identified AFOLU measures link to these large-scale evolutions, but these are assessed elsewhere (see above).

Land-use changes until mid-century occur in the large majority of SSP pathways, both under stringent mitigation and in absence of mitigation (Figure 2.24). In the latter case, changes are mainly due to socio-economic drivers like growing demands for food, feed and wood products. General transition trends can be identified for many land types in 1.5°C pathways, which differ from those in baseline scenarios and depend on the interplay with mitigation in other sectors (Figure 2.24) (Popp et al., 2017; Riahi et al., 2017; Rogelj et al., 2018). Mitigation that demands land mainly occurs at the expense of agricultural land for food and feed production. Additionally, some biomass is projected to be grown on marginal land or supplied from residues and waste, but at lower shares. Land for second-generation energy crops (such as *Miscanthus* or poplar) expands by 2030 and 2050 in all available pathways that assume a cost-effective achievement of a 1.5°C temperature goal in 2100 (Figure 2.24), but the scale depends strongly on underlying socio-economic assumptions (see later discussion of land pathway archetypes). Reducing rates of deforestation restricts agricultural expansion, and forest cover can expand strongly in 1.5°C and 2°C pathways alike compared to its extent in no-climate-policy baselines due to reduced deforestation and afforestation and reforestation measures. However, the extent to which forest cover expands varies highly across models in the literature, with some models projecting forest cover to stay virtually constant or decline slightly. This is due to whether afforestation and reforestation is included as a mitigation technology in these pathways and interactions with other sectors.

As a consequence of other land-use changes, pasture land is generally projected to be reduced compared to both baselines in which no climate change mitigation action is undertaken and 2°C-consistent pathways. Furthermore, cropland for food and feed production decreases in most 1.5°C pathways, both compared to a no-climate baseline and relative to 2010. These reductions in agricultural land for food and feed production are facilitated by intensification on agricultural land and in livestock production systems (Popp et al., 2017), as well as changes in consumption patterns (Frank et al., 2017; Fujimori, 2017) (see

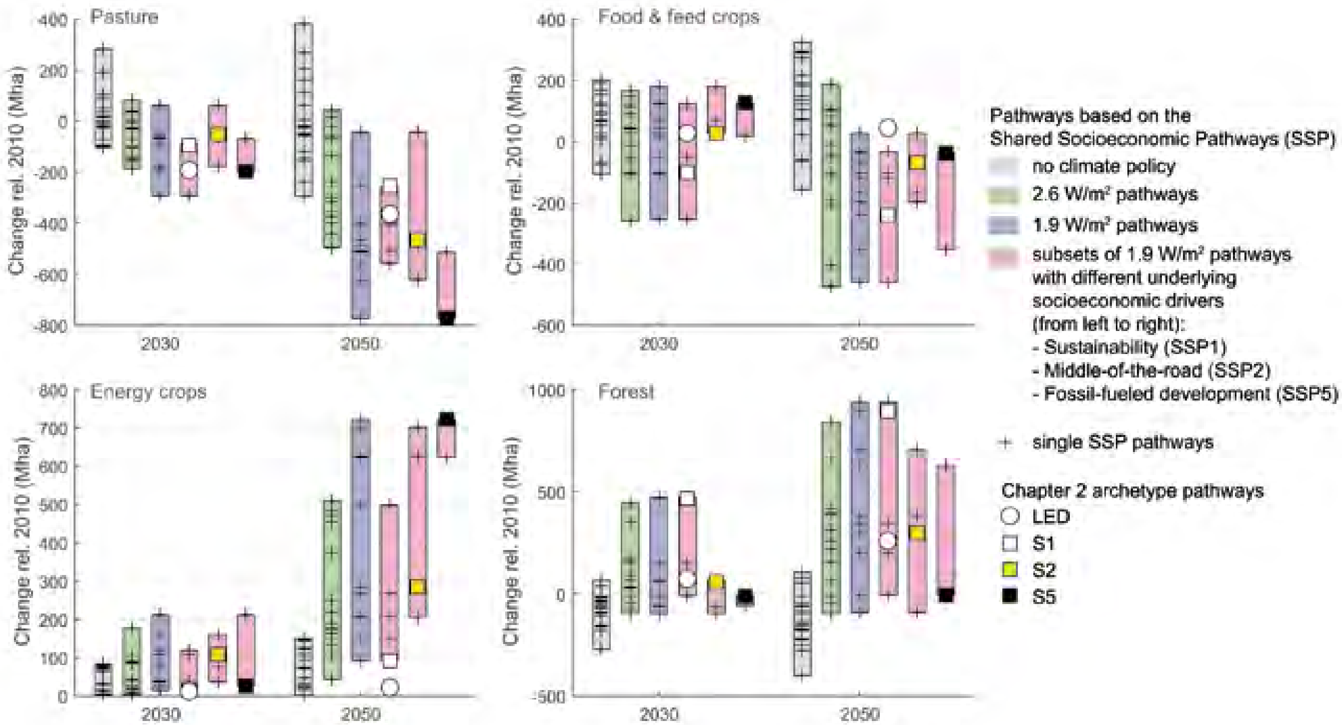


Figure 2.24 | Overview of land-use change transitions in 2030 and 2050, relative to 2010 based on pathways based on the Shared Socio-Economic Pathways (SSPs) (Popp et al., 2017; Riahi et al., 2017; Rogelj et al., 2018). Grey: no-climate-policy baseline; green: 2.6 W m^{-2} pathways; blue: 1.9 W m^{-2} pathways. Pink: 1.9 W m^{-2} pathways grouped per underlying socio-economic assumption (from left to right: SSP1 sustainability, SSP2 middle-of-the-road, SSP5 fossil-fuelled development). Ranges show the minimum–maximum range across the SSPs. Single pathways are shown with plus signs. Illustrative archetype pathways are highlighted with distinct icons. Each panel shows the changes for a different land type. The 1.9 and 2.6 W m^{-2} pathways are taken as proxies for 1.5°C and 2°C pathways, respectively. The 2.6 W m^{-2} pathways are mostly consistent with the Lower-2°C and Higher-2°C pathway classes. The 1.9 W m^{-2} pathways are consistent with the 1.5°C-low-OS (mostly SSP1 and SSP2) and 1.5°C-high-OS (SSP5) pathway classes. In 2010, pasture was estimated to cover about 3–3.5 103 Mha, food and feed crops about 1.5–1.6 103 Mha, energy crops about 0–14 Mha and forest about 3.7–4.2 103 Mha, across the models that reported SSP pathways (Popp et al., 2017). When considering pathways limiting warming to 1.5°C with no or limited overshoot, the full set of scenarios shows a conversion of 50–1100 Mha of pasture into 0–600 Mha for energy crops, a 200 Mha reduction to 950 Mha increase forest, and a 400 Mha decrease to a 250 Mha increase in non-pasture agricultural land for food and feed crops by 2050 relative to 2010. The large range across the literature and the understanding of the variations across models and assumptions leads to *medium confidence* in the size of these ranges.

also Chapter 4, Section 4.3.2 for an assessment of these mitigation options). For example, in a scenario based on rapid technological progress (Kriegler et al., 2017), global average cereal crop yields in 2100 are assumed to be above 5 tDM ha^{-1} yr^{-1} in mitigation scenarios aiming at limiting end-of-century radiative forcing to 4.5 or 2.6 W m^{-2}, compared to 4 tDM ha^{-1} yr^{-1} in the SSP5 baseline to ensure the same food production. Similar improvements are present in 1.5°C variants of such scenarios. Historically, cereal crop yields are estimated at 1 tDM ha^{-1} yr^{-1} and about 3 tDM ha^{-1} yr^{-1} in 1965 and 2010, respectively (calculations based on FAOSTAT, 2018). For aggregate energy crops, models assume 4.2–8.9 tDM ha^{-1} yr^{-1} in 2010, increasing to about 6.9–17.4 tDM ha^{-1} yr^{-1} in 2050, which fall within the range found in the bottom-up literature yet depend on crop, climatic zone, land quality and plot size (Searle and Malins, 2014).

The pace of projected land transitions over the coming decades can differ strongly between 1.5°C and baseline scenarios without climate change mitigation and from historical trends (Table 2.9). However, there is uncertainty in the sign and magnitude of these future land-use changes (Prestele et al., 2016; Popp et al., 2017; Doelman et al., 2018). The pace of projected cropland changes overlaps with historical trends over the past four decades, but in several cases also goes well beyond this range. By the 2030–2050 period, the projected reductions in pasture and potentially strong increases in forest cover imply a reversed dynamic compared to historical and baseline trends. This suggests that distinct policy and government measures would be needed to achieve forest increases, particularly in a context of projected increased bioenergy use.

Changes in the AFOLU sector are driven by three main factors: demand changes, efficiency of production, and policy assumptions (Smith et al., 2013; Popp et al., 2017). Demand for agricultural products and other land-based commodities is influenced by consumption patterns (including dietary preferences and food waste affecting demand for food and feed) (Smith et al., 2013; van Vuuren et al., 2018), demand for forest products for pulp and construction (including less wood waste), and demand for biomass for energy production (Lambin and Meyfroidt, 2011; Smith and Bustamante, 2014). Efficiency of agricultural and forestry production relates to improvements in agricultural and forestry practices (including product cascades, by-products and more waste- and residue-based biomass for energy production), agricultural and forestry yield increases, and intensification of livestock production systems leading to higher feed efficiency and changes in feed composition (Havlík et al., 2014; Weindl et al., 2015). Policy assumptions relate to the level of land protection, the treatment of food waste, policy choices about the timing of mitigation action (early vs late), the choice and

Table 2.9 | Annual pace of land-use change in baseline, 2°C and 1.5°C pathways.

All values in Mha yr^{-1}. The 2.6 W m^{-2} pathways are mostly consistent with the Lower-2°C and Higher-2°C pathway classes. The 1.9 W m^{-2} pathways are broadly consistent with the 1.5°C-low-OS (mostly SSP1 and SSP2) and 1.5°C-high-OS (SSP5) pathway classes. Baseline projections reflect land-use developments projected by integrated assessment models under the assumptions of the Shared Socio-Economic Pathways (SSPs) in absence of climate policies (Popp et al., 2017; Riahi et al., 2017; Rogelj et al., 2018). Values give the full range across SSP scenarios. According to the Food and Agriculture Organization of the United Nations (FAOSTAT, 2018), 4.9 billion hectares (approximately 40% of the land surface) was under agricultural use in 2005, either as cropland (1.5 billion hectares) or pasture (3.4 billion hectares). FAO data in the table are equally from FAOSTAT (2018).

Annual Pace of Land-Use Change [Mha yr^{-1}]					
Land Type	**Pathway**	**Time Window**		**Historical**	
		2010–2030	**2030–2050**	**1970–1990**	**1990–2010**
Pasture	1.9 W m^{-2}	[–14.6/3.0]	[–28.7/–5.2]	8.7 Permanent meadows and pastures (FAO)	0.9 Permanent meadows and pastures (FAO)
	2.6 W m^{-2}	[–9.3/4.1]	[–21.6/0.4]		
	Baseline	[–5.1/14.1]	[–9.6/9.0]		
Cropland for food, feed and material	1.9 W m^{-2}	[–12.7/9.0]	[–18.5/0.1]		
	2.6 W m^{-2}	[–12.9/8.3]	[–16.8/2.3]		
	Baseline	[–5.3/9.9]	[–2.7/6.7]		
Cropland for energy	1.9 W m^{-2}	[0.7/10.5]	[3.9/34.8]		
	2.6 W m^{-2}	[0.2/8.8]	[2.0/22.9]		
	Baseline	[0.2/4.2]	[–0.2/6.1]		
Total cropland (Sum of cropland for food and feed & energy)	1.9 W m^{-2}	[–6.8/12.8]	[–5.8/26.7]	4.6 Arable land and Permanent crops	0.9 Arable land and Permanent crops
	2.6 W m^{-2}	[–8.4/9.3]	[–7.1/17.8]		
	Baseline	[–3.0/11.3]	[0.6/11.0]		
Forest	1.9 W m^{-2}	[–4.8/23.7]	[0.0/34.3]	N.A. Forest (FAO)	–5.6 Forest (FAO)
	2.6 W m^{-2}	[–4.7/22.2]	[–2.4/31.7]		
	Baseline	[–13.6/3.3]	[–6.5/4.3]		

preference of land-based mitigation options (for example, the inclusion of afforestation and reforestation as mitigation options), interactions with other sectors (Popp et al., 2017), and trade (Schmitz et al., 2012; Wiebe et al., 2015).

A global study (Stevanović et al., 2017) reported similar GHG reduction potentials for both production-side (agricultural production measures in combination with reduced deforestation) and consumption-side (diet change in combination with lower shares of food waste) measures on the order of 40% in 2100[11] (compared to a baseline scenario without land-based mitigation). Lower consumption of livestock products by 2050 could also substantially reduce deforestation and cumulative carbon losses (Weindl et al., 2017). On the supply side, minor productivity growth in extensive livestock production systems is projected to lead to substantial CO_2 emission abatement, but the emission-saving potential of productivity gains in intensive systems is limited, mainly due to trade-offs with soil carbon stocks (Weindl et al., 2017). In addition, even within existing livestock production systems, a transition from extensive to more productive systems bears substantial GHG abatement potential, while improving food availability (Gerber et al., 2013; Havlík et al., 2014). Many studies highlight the capability of agricultural intensification for reducing GHG emissions in the AFOLU sector or even enhancing terrestrial carbon stocks (Valin et al., 2013; Popp et al., 2014a; Wise et al., 2014). Also the importance of immediate and global land-use regulations for a comprehensive reduction of land-related GHG emissions (especially related to deforestation) has been shown by several studies (Calvin et al., 2017; Fricko et al., 2017; Fujimori, 2017). Ultimately, there are also interactions between these three factors and the wider society and economy, for example, if CDR technologies that are not land-based are deployed (like direct air capture – DACCS, see Chapter 4, Section 4.3.7) or if other sectors over- or underachieve their projected mitigation contributions (Clarke et al., 2014). Variations in these drivers can lead to drastically different land-use implications (Popp et al., 2014b) (Figure 2.24).

Stringent mitigation pathways inform general GHG dynamics in the AFOLU sector. First, CO_2 emissions from deforestation can be abated at relatively low carbon prices if displacement effects in other regions (Calvin et al., 2017) or other land-use types with high carbon density (Calvin et al., 2014; Popp et al., 2014a; Kriegler et al., 2017) can be avoided. However, efficiency and costs of reducing rates of deforestation strongly depend on governance performance, institutions and macroeconomic factors (Wang et al., 2016). Secondly, besides CO_2 reductions, the land system can play an important role for overall CDR efforts (Rogelj et al., 2018) via BECCS, afforestation and reforestation, or a combination of options. The AFOLU sector also provides further potential for active terrestrial carbon sequestration, for example, via land restoration, improved management of forest and agricultural land (Griscom et al., 2017), or biochar applications (Smith, 2016) (see also Chapter 4, Section 4.3.7). These options have so far

11 Land-based mitigation options on the supply and the demand side are assessed in 4.3.2, and CDR options with a land component in 4.3.7. Chapter 5 (Section 5.4) assesses the implications of land-based mitigation for related SDGs, e.g., food security.

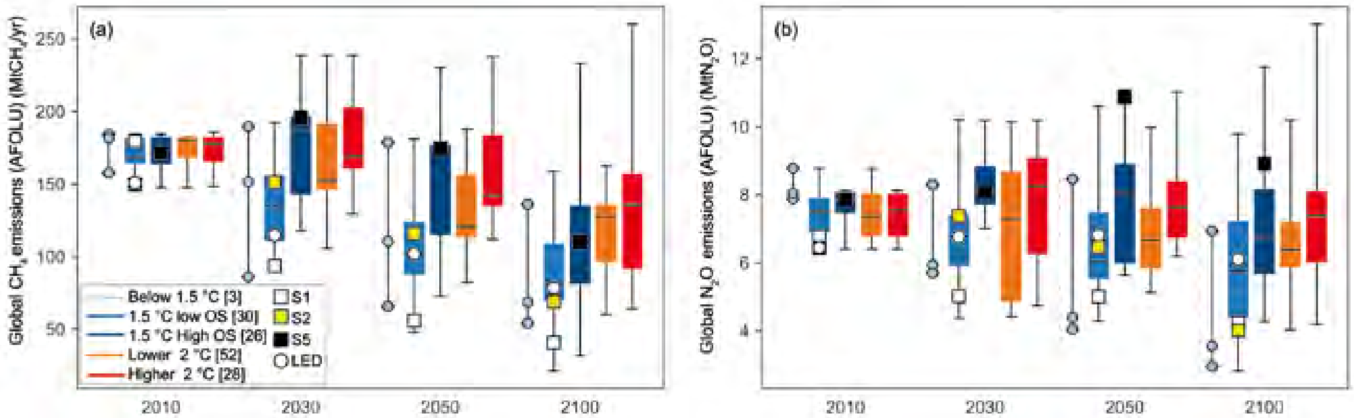


Figure 2.25 | Agricultural emissions in transformation pathways. Global agricultural (a) CH_4 and (b) N_2O emissions. Box plots show median, interquartile range and full range. Classes are defined in Section 2.1.

not been extensively integrated in the mitigation pathway literature (see Supplementary Material 2.SM.1.2), but in theory their availability would impact the deployment of other CDR technologies, like BECCS (Section 2.3.4) (Strefler et al., 2018a). These interactions will be discussed further in the SRCCL.

Residual agricultural non-CO_2 emissions of CH_4 and N_2O play an important role for temperature stabilization pathways, and their relative importance increases in stringent mitigation pathways in which CO_2 is reduced to net zero emissions globally (Gernaat et al., 2015; Popp et al., 2017; Stevanović et al., 2017; Rogelj et al., 2018), for example, through their impact on the remaining carbon budget (Section 2.2). Although agricultural non-CO_2 emissions show marked reduction potentials in 2°C-consistent pathways, complete elimination of these emission sources does not occur in IAMs based on the evolution of agricultural practice assumed in integrated models (Figure 2.25) (Gernaat et al., 2015). Methane emissions in 1.5°C pathways are reduced through improved agricultural management (e.g., improved management of water in rice production, manure and herds, and better livestock quality through breeding and improved feeding practices) as well as dietary shifts away from emissions-intensive livestock products. Similarly, N_2O emissions decrease due to improved N-efficiency and manure management (Frank et al., 2018). However, high levels of bioenergy production can also result in increased N_2O emissions (Kriegler et al., 2017), highlighting the importance of appropriate management approaches (Davis et al., 2013). Residual agricultural emissions can be further reduced by limiting demand for GHG-intensive foods through shifts to healthier and more sustainable diets (Tilman and Clark, 2014; Erb et al., 2016b; Springmann et al., 2016) and reductions in food waste (Bajželj et al., 2014; Muller et al., 2017; Popp et al., 2017) (see also Chapter 4 and SRCCL). Finally, several mitigation measures that could affect these agricultural non-CO_2 emissions are not, or only to a limited degree, considered in the current integrated pathway literature (see Supplementary Material 2.SM.1.2). Such measures (like plant-based and synthetic proteins, methane inhibitors and vaccines in livestock, alternate wetting and drying in paddy rice, or nitrification inhibitors) are very diverse and differ in their development or deployment stages. Their potentials have not been explicitly assessed here.

Pathways consistent with 1.5°C rely on one or more of the three strategies highlighted above (demand changes, efficiency gains, and policy assumptions), and can apply these in different configurations. For example, among the four illustrative archetypes used in this chapter (Section 2.1), the LED and S1 pathways focus on generally low resource and energy consumption (including healthy diets with low animal-calorie shares and low food waste) as well as significant agricultural intensification in combination with high levels of nature protection. Under such assumptions, comparably small amounts of land are needed for land-demanding mitigation activities such as BECCS and afforestation and reforestation, leaving the land footprint for energy crops in 2050 virtually the same compared to 2010 levels for the LED pathway. In contrast, future land-use developments can look very different under the resource- and energy-intensive S5 pathway that includes less healthy diets with high animal shares and high shares of food waste (Tilman and Clark, 2014; Springmann et al., 2016) combined with a strong orientation towards technology solutions to compensate for high reliance on fossil-fuel resources and associated high levels of GHG emissions in the baseline. In such pathways, climate change mitigation strategies strongly depend on the availability of CDR through BECCS (Humpenöder et al., 2014). As a consequence, the S5 pathway sources significant amounts of biomass through bioenergy crop expansion in combination with agricultural intensification. Also, further policy assumptions can strongly affect land-use developments, highlighting the importance for land use of making appropriate policy choices. For example, within the SSP set, some pathways rely strongly on a policy to incentivize afforestation and reforestation for CDR together with BECCS, which results in an expansion of forest area and a corresponding increase in terrestrial carbon stock. Finally, the variety of pathways illustrates how policy choices in the AFOLU and other sectors strongly affect land-use developments and associated sustainable development interactions (Chapter 5, Section 5.4) in 1.5°C pathways.

The choice of strategy or mitigation portfolio impacts the GHG dynamics of the land system and other sectors (see Section 2.3), as well as the synergies and trade-offs with other environmental and societal objectives (see Section 2.5.3 and Chapter 5, Section 5.4). For example, AFOLU developments in 1.5°C pathways range from strategies that differ by almost an order of magnitude in their projected land requirements for bioenergy (Figure 2.24), and some strategies would allow an increase in forest cover over the 21st century compared to strategies under which forest cover remains approximately constant.

High agricultural yields and application of intensified animal husbandry, implementation of best-available technologies for reducing non-CO_2 emissions, or lifestyle changes including a less-meat-intensive diet and less CO_2-intensive transport modes, have been identified as allowing for such a forest expansion and reduced footprints from bioenergy without compromising food security (Frank et al., 2017; Doelman et al., 2018; van Vuuren et al., 2018).

The IAMs used in the pathways underlying this assessment (Popp et al., 2017; Riahi et al., 2017; Rogelj et al., 2018) do not include all potential land-based mitigation options and side-effects, and their results are hence subject to uncertainty. For example, recent research has highlighted the potential impact of forest management practices on land carbon content (Erb et al., 2016a; Naudts et al., 2016) and the uncertainty surrounding future crop yields (Haberl et al., 2013; Searle and Malins, 2014) and water availability (Liu et al., 2014). These aspects are included in IAMs in varying degrees but were not assessed in this report. Furthermore, land-use modules of some IAMs can depict spatially resolved climate damages to agriculture (Nelson et al., 2014), but this option was not used in the SSP quantifications (Riahi et al., 2017). Damages (e.g., due to ozone exposure or varying indirect fertilization due to atmospheric N and Fe deposition (e.g., Shindell et al., 2012; Mahowald et al., 2017) are also not included. Finally, this assessment did not look into the literature of agricultural sector models which could provide important additional detail and granularity to the discussion presented here.[12] This limits their ability to capture the full mitigation potentials and benefits between scenarios. An in-depth assessment of these aspects lies outside the scope of this Special Report. However, their existence affects the confidence assessment of the AFOLU transition in 1.5°C pathways.

Despite the limitations of current modelling approaches, there is *high agreement* and *robust evidence* across models and studies that the AFOLU sector plays an important role in stringent mitigation pathways. The findings from these multiple lines of evidence also result in *high confidence* that AFOLU mitigation strategies can vary significantly based on preferences and policy choices, facilitating the exploration of strategies that can achieve multiple societal objectives simultaneously (see also Section 2.5.3). At the same time, given the many uncertainties and limitations, only *low to medium confidence* can be attributed by this assessment to the more extreme AFOLU developments found in the pathway literature, and *low to medium confidence* to the level of residual non-CO_2 emissions.

2.5 Challenges, Opportunities and Co-Impacts of Transformative Mitigation Pathways

This section examines aspects other than climate outcomes of 1.5°C mitigation pathways. Focus is given to challenges and opportunities related to policy regimes, price of carbon and co-impacts, including sustainable development issues, which can be derived from the existing integrated pathway literature. Attention is also given to uncertainties and critical assumptions underpinning mitigation pathways. The challenges and opportunities identified in this section are further elaborated Chapter 4 (e.g., policy choice and implementation) and Chapter 5 (e.g., sustainable development). The assessment indicates unprecedented policy and geopolitical challenges.

2.5.1 Policy Frameworks and Enabling Conditions

Moving from a 2°C to a 1.5°C pathway implies bold integrated policies that enable higher socio-technical transition speeds, larger deployment scales, and the phase-out of existing systems that may lock in emissions for decades *(high confidence)* (Geels et al., 2017; Kuramochi et al., 2017; Rockström et al., 2017; Vogt-Schilb and Hallegatte, 2017; Kriegler et al., 2018a; Michaelowa et al., 2018). This requires higher levels of transformative policy regimes in the near term, which allow deep decarbonization pathways to emerge and a net zero carbon energy–economy system to emerge in the 2040–2060 period (Rogelj et al., 2015b; Bataille et al., 2016b). This enables accelerated levels of technological deployment and innovation (Geels et al., 2017; IEA, 2017a; Grubler et al., 2018) and assumes more profound behavioural, economic and political transformation (Sections 2.3, 2.4 and 4.4). Despite inherent levels of uncertainty attached to modelling studies (e.g., related to climate and carbon cycle response), studies stress the urgency for transformative policy efforts to reduce emissions in the short term (Riahi et al., 2015; Kuramochi et al., 2017; Rogelj et al., 2018).

The available literature indicates that mitigation pathways in line with 1.5°C pathways would require stringent and integrated policy interventions (*very high confidence*). Higher policy ambition often takes the form of stringent economy-wide emission targets (and resulting peak-and-decline of emissions), larger coverage of NDCs to more gases and sectors (e.g., land-use, international aviation), much lower energy and carbon intensity rates than historically seen, carbon prices much higher than the ones observed in real markets, increased climate finance, global coordinated policy action, and implementation of additional initiatives (e.g., by non-state actors) (Sections 2.3, 2.4 and 2.5.2). The diversity (beyond explicit carbon pricing) and effectiveness of policy portfolios are of prime importance, particularly in the short-term (Mundaca and Markandya, 2016; Kuramochi et al., 2017; OECD, 2017; Kriegler et al., 2018a; Michaelowa et al., 2018). For instance, deep decarbonization pathways in line with a 2°C target (covering 74% of global energy-system emissions) include a mix of stringent regulation (e.g., building codes, minimum performance standards), carbon pricing mechanisms and R&D (research and development) innovation policies (Bataille et al., 2016a). Explicit carbon pricing, direct regulation and public investment to enable innovation are critical for deep decarbonization pathways (Grubb et al., 2014). Effective planning (including compact city measures) and integrated regulatory frameworks are also key drivers in the IEA-ETP B2DS study for the transport sector (IEA, 2017a). Effective urban planning can reduce GHG emissions from urban transport between 20% and 50% (Creutzig, 2016). Comprehensive policy frameworks would be needed if the decarbonization of the power system is pursued while increasing end-use electrification (including transport) (IEA, 2017a). Technology policies (e.g., feed-in-tariffs), financing instruments, carbon pricing

[12] For example, the GLEAM (http://www.fao.org/gleam/en/) model from the UN Food and Agricultural Organisation (FAO).

and system integration management driving the rapid adoption of renewable energy technologies are critical for the decarbonization of electricity generation (Bruckner et al., 2014; Luderer et al., 2014; Creutzig et al., 2017; Pietzcker et al., 2017). Likewise, low-carbon and resilient investments are facilitated by a mix of coherent policies, including fiscal and structural reforms (e.g., labour markets), public procurement, carbon pricing, stringent standards, information schemes, technology policies, fossil-fuel subsidy removal, climate risk disclosure, and land-use and transport planning (OECD, 2017). Pathways in which CDR options are restricted emphasize the strengthening of near-term policy mixes (Luderer et al., 2013; Kriegler et al., 2018a). Together with the decarbonization of the supply side, ambitious policies targeting fuel switching and energy efficiency improvements on the demand side play a major role across mitigation pathways (Clarke et al., 2014; Kriegler et al., 2014b; Riahi et al., 2015; Kuramochi et al., 2017; Brown and Li, 2018; Rogelj et al., 2018; Wachsmuth and Duscha, 2018).

The combined evidence suggests that aggressive policies addressing energy efficiency are central in keeping 1.5°C within reach and lowering energy system and mitigation costs (*high confidence*) (Luderer et al., 2013; Rogelj et al., 2013b, 2015b; Grubler et al., 2018). Demand-side policies that increase energy efficiency or limit energy demand at a higher rate than historically observed are critical enabling factors for reducing mitigation costs in stringent mitigation pathways across the board (Luderer et al., 2013; Rogelj et al., 2013b, 2015b; Clarke et al., 2014; Bertram et al., 2015a; Bataille et al., 2016b). Ambitious sector-specific mitigation policies in industry, transportation and residential sectors are needed in the short run for emissions to peak in 2030 (Méjean et al., 2018). Stringent demand-side policies (e.g., tightened efficiency standards for buildings and appliances) driving the expansion, efficiency and provision of high-quality energy services are essential to meet a 1.5˚C mitigation target while reducing the reliance on CDR (Grubler et al., 2018). A 1.5˚C pathway for the transport sector is possible using a mix of additional and stringent policy actions preventing (or reducing) the need for transport, encouraging shifts towards efficient modes of transport, and improving vehicle-fuel efficiency (Gota et al., 2018). Stringent demand-side policies also reduce the need for CCS (Wachsmuth and Duscha, 2018). Even in the presence of weak near term policy frameworks, increased energy efficiency lowers mitigation costs noticeably compared to pathways with reference energy intensity (Bertram et al., 2015a). Common issues in the literature relate to the rebound effect, the potential overestimation of the effectiveness of energy efficiency policy, and policies to counteract the rebound (Saunders, 2015; van den Bergh, 2017; Grubler et al., 2018) (Sections 2.4 and 4.4).

SSP-based modelling studies underline that socio-economic and climate policy assumptions strongly influence mitigation pathway characteristics and the economics of achieving a specific climate target (*very high confidence*) (Bauer et al., 2017; Guivarch and Rogelj, 2017; Riahi et al., 2017; Rogelj et al., 2018). SSP assumptions related to economic growth and energy intensity are critical determinants of projected CO2 emissions (Marangoni et al., 2017). A multimodel inter-comparison study found that mitigation challenges in line with a 1.5˚C target vary substantially across SSPs and policy assumptions (Rogelj et al., 2018). Under SSP1-SPA1 (sustainability) and SSP2-SPA2 (middle-of-the-road), the majority of IAMs were capable of producing 1.5˚C pathways. On the contrary, none of the IAMs contained in the SR1.5 database could produce a 1.5°C pathway under SSP3-SPA3 assumptions. Preventing elements include, for instance, climate policy fragmentation, limited control of land-use emissions, heavy reliance on fossil fuels, unsustainable consumption and marked inequalities (Rogelj et al., 2018). Dietary aspects of the SSPs are also critical: climate-friendly diets were contained in 'sustainability' (SSP1) and meat-intensive diets in SSP3 and SSP5 (Popp et al., 2017). CDR requirements are reduced under 'sustainability' related assumptions (Strefler et al., 2018b). These are major policy-related reasons for why SSP1-SPA1 translates into relatively low mitigation challenges whereas SSP3-SPA3 and SSP5-SPA5 entail futures that pose the highest socio-technical and economic challenges. SSPs/SPAs assumptions indicate that policy-driven pathways that encompass accelerated change away from fossil fuels, large-scale deployment of low-carbon energy supplies, improved energy efficiency and sustainable consumption lifestyles reduce the risks of climate targets becoming unreachable (Clarke et al., 2014; Riahi et al., 2015, 2017; Marangoni et al., 2017; Rogelj et al., 2017, 2018; Strefler et al., 2018b).

Policy assumptions that lead to weak or delayed mitigation action from what would be possible in a fully cooperative world strongly influence the achievability of mitigation targets (*high confidence*) (Luderer et al., 2013; Rogelj et al., 2013b; OECD, 2017; Holz et al., 2018a; Strefler et al., 2018b). Such regimes also include current NDCs (Fawcett et al., 2015; Aldy et al., 2016; Rogelj et al., 2016a, 2017; Hof et al., 2017; van Soest et al., 2017), which have been reported to make achieving a 2°C pathway unattainable without CDR (Strefler et al., 2018b). Not strengthening NDCs would make it very challenging to keep 1.5°C within reach (see Section 2.3 and Cross-Chapter Box 11 in Chapter 4). One multimodel inter-comparison study (Luderer et al., 2016b, 2018) explored the effects on 1.5°C pathways assuming the implementation of current NDCs until 2030 and stringent reductions thereafter. It finds that delays in globally coordinated actions lead to various models reaching no 1.5°C pathways during the 21st century. Transnational emission reduction initiatives (TERIs) outside the UNFCCC have also been assessed and found to overlap (70–80%) with NDCs and be inadequate to bridge the gap between NDCs and a 2°C pathway (Roelfsema et al., 2018). Weak and fragmented short-term policy efforts use up a large share of the long-term carbon budget before 2030–2050 (Bertram et al., 2015a; van Vuuren et al., 2016) and increase the need for the full portfolio of mitigation measures, including CDR (Clarke et al., 2014; Riahi et al., 2015; Xu and Ramanathan, 2017). Furthermore, fragmented policy scenarios also exhibit 'carbon leakage' via energy and capital markets (Arroyo-Currás et al., 2015; Kriegler et al., 2015b). A lack of integrated policy portfolios can increase the risks of trade-offs between mitigation approaches and sustainable development objectives (see Sections 2.5.3 and 5.4). However, more detailed analysis is needed about realistic (less disruptive) policy trajectories until 2030 that can strengthen near-term mitigation action and meaningfully decrease post-2030 challenges (see Chapter 4, Section 4.4).

Whereas the policy frameworks and enabling conditions identified above pertain to the 'idealized' dimension of mitigation pathways, aspects related to 1.5°C mitigation pathways in practice are of prime importance. For example, issues related to second-best stringency levels, international cooperation, public acceptance, distributional consequences, multilevel governance, non-state actions, compliance levels, capacity building, rebound effects, linkages across highly heterogeneous policies, sustained behavioural change, finance and intra- and inter-generational issues need to be considered (see Chapter 4, Section 4.4) (Bataille et al., 2016a; Mundaca and Markandya, 2016; Baranzini et al., 2017; MacDougall et al., 2017; van den Bergh, 2017; Vogt-Schilb and Hallegatte, 2017; Chan et al., 2018; Holz et al., 2018a; Klinsky and Winkler, 2018; Michaelowa et al., 2018; Patterson et al., 2018). Furthermore, policies interact with a wide portfolio of pre-existing policy instruments that address multiple areas (e.g., technology markets, economic growth, poverty alleviation, climate adaptation) and deal with various market failures (e.g., information asymmetries) and behavioural aspects (e.g., heuristics) that prevent or hinder mitigation actions (Kolstad et al., 2014; Mehling and Tvinnereim, 2018). The socio-technical transition literature points to multiple complexities in real-world settings that prevent reaching 'idealized' policy conditions but at the same time can still accelerate transformative change through other co-evolutionary processes of technology and society (Geels et al., 2017; Rockström et al., 2017). Such co-processes are complex and go beyond the role of policy (including carbon pricing) and comprise the role of citizens, businesses, stakeholder groups or governments, as well as the interplay of institutional and socio-political dimensions (Michaelowa et al., 2018; Veland et al., 2018). It is argued that large system transformations, similar to those in 1.5°C pathways, require prioritizing an evolutionary and behavioural framework in economic theory rather than an optimization or equilibrium framework as is common in current IAMs (Grubb et al., 2014; Patt, 2017). Accumulated know-how, accelerated innovation and public investment play a key role in (rapid) transitions (see Sections 4.2 and 4.4) (Geels et al., 2017; Michaelowa et al., 2018).

In summary, the emerging literature supports the AR5 on the need for integrated, robust and stringent policy frameworks targeting both the supply and demand-side of energy-economy systems (*high confidence*). Continuous ex-ante policy assessments provide learning opportunities for both policy makers and stakeholders.

Cross-Chapter Box 5 | Economics of 1.5°C Pathways and the Social Cost of Carbon

Contributing Authors:
Luis Mundaca (Sweden/Chile), Mustafa Babiker (Sudan), Johannes Emmerling (Italy/Germany), Sabine Fuss (Germany), Jean-Charles Hourcade (France), Elmar Kriegler (Germany), Anil Markandya (Spain/UK), Joyashree Roy (India), Drew Shindell (USA)

Two approaches have been commonly used to assess alternative emissions pathways: **cost-effectiveness analysis (CEA)** and **cost–benefit analysis (CBA). CEA** aims at identifying emissions pathways minimising the total mitigation costs of achieving a given warming or GHG limit (Clarke et al., 2014). **CBA** has the goal to identify the optimal emissions trajectory minimising the discounted flows of abatement expenditures and monetized climate change damages (Boardman et al., 2006; Stern, 2007). A third concept, the **Social Cost of Carbon (SCC)** measures the total net damages of an extra metric ton of CO_2 emissions due to the associated climate change (Nordhaus, 2014; Pizer et al., 2014; Rose et al., 2017a). Negative and positive impacts are monetized, discounted and the net value is expressed as an equivalent loss of consumption today. The SCC can be evaluated for any emissions pathway under policy consideration (Rose, 2012; NASEM, 2016, 2017).

Along the optimal trajectory determined by CBA, the SCC equals the discounted value of the marginal abatement cost of a metric ton of CO_2 emissions. Equating the present value of future damages and marginal abatement costs includes a number of critical value judgements in the formulation of the social welfare function (SWF), particularly in how non-market damages and the distribution of damages across countries and individuals and between current and future generations are valued (Kolstad et al., 2014). For example, since climate damages accrue to a larger extent farther in the future and can persist for many years, assumptions and approaches to determine the social discount rate (normative 'prescriptive' vs. positive 'descriptive') and social welfare function (e.g., discounted utilitarian SWF vs. undiscounted prioritarian SWF) can heavily influence CBA outcomes and associated estimates of SCC (Kolstad et al., 2014; Pizer et al., 2014; Adler and Treich, 2015; Adler et al., 2017; NASEM, 2017; Nordhaus, 2017; Rose et al., 2017a).

In CEA, the marginal abatement cost of carbon is determined by the climate goal under consideration. It equals the shadow price of carbon associated with the goal which in turn can be interpreted as the willingness to pay for imposing the goal as a political constraint. Emissions prices are usually expressed in carbon (equivalent) prices using the GWP-100 metric as the exchange rate for pricing emissions of non-CO_2 GHGs controlled under internationally climate agreements (like CH_4, N_2O and fluorinated gases, see Cross-Chapter Box 2 in Chapter 1).[13] Since policy goals like the goals of limiting warming to 1.5°C or well below 2°C do not directly result from a money metric trade-off between mitigation and damages, associated shadow prices can differ from the SCC in a CBA. In CEA, value judgments are to a large extent concentrated in the choice of climate goal and related implications, while more explicit assumptions about social values are required to perform CBA. For example, in CEA assumptions about the social discount rate no longer affect the overall abatement levels now set by the climate goal, but the choice and timing of investments in individual measures to reach these levels.

[13] Also other metrics to compare emissions have been suggested and adopted by governments nationally (Kandlikar, 1995; Marten et al., 2015; Shindell, 2015; IWG, 2016).

Cross Chapter Box 5 (continued)

Although CBA-based and CEA-based assessment are both subject to large uncertainty about socio-techno-economic trends, policy developments and climate response, the range of estimates for the SCC along an optimal trajectory determined by CBA is far wider than for estimates of the shadow price of carbon in CEA-based approaches. In CBA, the value judgments about inter- and intra-generational equity combined with uncertainties in the climate damage functions assumed, including their empirical basis, are important (Pindyck, 2013; Stern, 2013; Revesz et al., 2014). In a CEA-based approach, the value judgments about the aggregate welfare function matter less, and uncertainty about climate response and impacts can be tied into various climate targets and related emissions budgets (Clarke et al., 2014).

The CEA- and CBA-based carbon cost estimates are derived with a different set of tools. They are all summarised as integrated assessment models (IAMs) but in fact are of very different nature (Weyant, 2017). Detailed process IAMs such as AIM (Fujimori, 2017), GCAM (Thomson et al., 2011; Calvin et al., 2017), IMAGE (van Vuuren et al., 2011b, 2017b), MESSAGE-GLOBIOM (Riahi et al., 2011; Havlík et al., 2014; Fricko et al., 2017), REMIND-MAgPIE (Popp et al., 2010; Luderer et al., 2013; Kriegler et al., 2017) and WITCH (Bosetti et al., 2006, 2008, 2009) include a process-based representation of energy and land systems, but in most cases lack a comprehensive representation of climate damages, and are typically used for CEA. Diagnostic analyses across CBA-IAMs indicate important dissimilarities in modelling assembly, implementation issues and behaviour (e.g., parametric uncertainty, damage responses, income sensitivity) that need to be recognized to better understand SCC estimates (Rose et al., 2017a).

CBA-IAMs such as DICE (Nordhaus and Boyer, 2000; Nordhaus, 2013, 2017), PAGE (Hope, 2006) and FUND (Tol, 1999; Anthoff and Tol, 2009) attempt to capture the full feedback from climate response to socio-economic damages in an aggregated manner, but are usually much more stylised than detailed process IAMs. In a nutshell, the methodological framework for estimating SCC involves projections of population growth, economic activity and resulting emissions; computations of atmospheric composition and global mean temperatures as a result of emissions; estimations of physical impacts of climate changes; monetization of impacts (positive and negative) on human welfare; and the discounting of the future monetary value of impacts to year of emission (Kolstad et al., 2014; Revesz et al., 2014; NASEM, 2017; Rose et al., 2017a). There has been a discussion in the literature to what extent CBA-IAMs underestimate the SCC due to, for example, a limited treatment or difficulties in addressing damages to human well-being, labour productivity, value of capital stock, ecosystem services and the risks of catastrophic climate change for future generations (Ackerman and Stanton, 2012; Revesz et al., 2014; Moore and Diaz, 2015; Stern, 2016). However, there has been progress in 'bottom-up' empirical analyses of climate damages (Hsiang et al., 2017), the insights of which could be integrated into these models (Dell et al., 2014). Most of the models used in Chapter 2 on 1.5°C mitigation pathways are detailed process IAMs and thus deal with CEA.

An important question is how results from CEA- and CBA-type approaches can be compared and synthesized. Such synthesis needs to be done with care, since estimates of the shadow price of carbon under the climate goal and SCC estimates from CBA might not be directly comparable due to different tools, approaches and assumptions used to derive them. Acknowledging this caveat, the SCC literature has identified a range of factors, assumptions and value judgements that support SCC values above \$100 tCO_2^{-1} that are also found as net present values of the shadow price of carbon in 1.5°C pathways. These factors include accounting for tipping points in the climate system (Lemoine and Traeger, 2014; Cai et al., 2015; Lontzek et al., 2015), a low social discount rate (Nordhaus, 2007a; Stern, 2007) and inequality aversion (Schmidt et al., 2013; Dennig et al., 2015; Adler et al., 2017).

The SCC and the shadow price of carbon are not merely theoretical concepts but used in regulation (Pizer et al., 2014; Revesz et al., 2014; Stiglitz et al., 2017). As stated by the report of the High-Level Commission on Carbon Pricing (Stiglitz et al., 2017), in the real world there is a distinction to be made between the implementable and efficient explicit carbon prices and the implicit (notional) carbon prices to be retained for policy appraisal and the evaluation of public investments, as is already done in some jurisdictions such as the USA, UK and France. Since 2008, the U.S. government has used SCC estimates to assess the benefits and costs related to CO_2 emissions resulting from federal policymaking (NASEM, 2017; Rose et al., 2017a).

The use of the SCC for policy appraisals is, however, not straightforward in an SDG context. There are suggestions that a broader range of polluting activities than only CO_2 emissions, for example emissions of air pollutants, and a broader range of impacts than only climate change, such as impacts on air quality, health and sustainable development in general (see Chapter 5 for a detailed discussion), would need to be included in social costs (Sarofim et al., 2017; Shindell et al., 2017a). Most importantly, a consistent valuation of the SCC in a sustainable development framework would require accounting for the SDGs in the social welfare formulation (see Chapter 5).

2.5.2 Economic and Investment Implications of 1.5°C Pathways

2.5.2.1 Price of carbon emissions

The price of carbon assessed here is fundamentally different from the concepts of optimal carbon price in a cost–benefit analysis, or the social cost of carbon (see Cross-Chapter Box 5 in this chapter and Chapter 3, Section 3.5.2). Under a cost-effectiveness analysis (CEA) modelling framework, prices for carbon (mitigation costs) reflect the stringency of mitigation requirements at the margin (i.e., cost of mitigating one extra unit of emission). Explicit carbon pricing is briefly addressed here to the extent it pertains to the scope of Chapter 2. For detailed policy issues about carbon pricing see Section 4.4.5.

Based on data available for this special report, the price of carbon varies substantially across models and scenarios, and their values increase with mitigation efforts (see Figure 2.26) *(high confidence)*. For instance, undiscounted values under a Higher-2°C pathway range from 15–220 USD2010 tCO_{2-eq}^{-1} in 2030, 45–1050 USD2010 tCO_{2-eq}^{-1} in 2050, 120–1100 USD2010 tCO_{2-eq}^{-1} in 2070 and 175–2340 USD2010 tCO_{2-eq}^{-1} in 2100. On the contrary, estimates for a Below-1.5°C pathway range from 135–6050 USD2010 tCO_{2-eq}^{-1} in 2030, 245–14300 USD2010 tCO_{2-eq}^{-1} in 2050, 420–19300 USD2010 tCO_{2-eq}^{-1} in 2070 and 690–30100 USD2010 tCO_{2-eq}^{-1} in 2100. Values for 1.5°C-low-OS pathway are relatively higher than 1.5°C-high-OS pathway in 2030, but the difference decreases over time, particularly between 2050 and 2070. This is because in 1.5°C-high-OS pathways there is relatively less mitigation activity in the first half of the century, but more in the second half. The low energy demand (LED, P1 in the Summary for Policymakers) scenario exhibits the lowest values across the illustrative pathway archetypes. As a whole, the global average discounted price of emissions across 1.5°C- and 2°C pathways differs by a factor of four across models (assuming a 5% annual discount rate, comparing to Below-1.5°C and 1.5°C-low-OS pathways). If 1.5°C-high-OS pathways (with peak warming 0.1–0.4°C higher than 1.5°C) or pathways with very large land-use sinks are also considered, the differential value is reduced to a limited degree, from a factor 4 to a factor 3. The increase in mitigation costs between 1.5°C and 2°C pathways is based on a direct comparison of pathway pairs from the same model and the same study in which the 1.5°C pathway assumes a significantly smaller carbon budget compared to the 2°C pathway (e.g., 600 $GtCO_2$ smaller in the CD-LINKS and ADVANCE studies). This assumption is the main driver behind the increase in the price of carbon (Luderer et al., 2018; McCollum et al., 2018).[14]

The wide range of values depends on numerous aspects, including methodologies, projected energy service demands, mitigation targets, fuel prices and technology availability (*high confidence*) (Clarke et al., 2014; Kriegler et al., 2015b; Rogelj et al., 2015c; Riahi et al., 2017; Stiglitz et al., 2017). The characteristics of the technology portfolio, particularly in terms of investment costs and deployment rates, play a key role (Luderer et al., 2013, 2016a; Clarke et al., 2014; Bertram et al., 2015a; Riahi et al., 2015; Rogelj et al., 2015c). Models that encompass a higher degree of technology granularity and that entail more flexibility regarding mitigation response often produce relatively lower mitigation costs than those that show less flexibility from a technology perspective (Bertram et al., 2015a; Kriegler et al., 2015a). Pathways providing high estimates often have limited flexibility of substituting fossil fuels with low-carbon technologies and the associated need to compensate fossil-fuel emissions with CDR. The price of carbon is also sensitive to the non-availability of BECCS (Bauer et al., 2018). Furthermore, and due to the treatment of future price anticipation, recursive-dynamic modelling approaches (with 'myopic anticipation') exhibit higher prices in the short term but modest increases in the long term compared to optimization modelling frameworks with 'perfect foresight' that show exponential pricing trajectories (Guivarch and Rogelj, 2017). The chosen social discount rate in CEA studies (range of 2–8% per year in the reported data, varying over time and sectors) can also affect the choice and timing of investments in mitigation measures (Clarke et al., 2014; Kriegler et al., 2015b; Weyant, 2017). However, the impacts of varying discount rates on 1.5°C (and 2°C) mitigation strategies can only be assessed to a limited degree. The above highlights the importance of sampling bias in pathway analysis ensembles towards outcomes derived from models which are more flexible, have more mitigation options and cheaper cost assumptions and thus can provide feasible pathways in contrast to other who are unable to do so (Tavoni and Tol, 2010; Clarke et al., 2014; Bertram et al., 2015a; Kriegler et al., 2015a; Guivarch and Rogelj, 2017). All CEA-based IAM studies reveal no unique path for the price of emissions (Bertram et al., 2015a; Kriegler et al., 2015b; Akimoto et al., 2017; Riahi et al., 2017).

Socio-economic conditions and policy assumptions also influence the price of carbon (*very high confidence*) (Bauer et al., 2017; Guivarch and Rogelj, 2017; Hof et al., 2017; Riahi et al., 2017; Rogelj et al., 2018). A multimodel study (Riahi et al., 2017) estimated the average discounted price of carbon (2010–2100, 5% discount rate) for a 2°C target to be nearly three times higher in the SSP5 marker than in the SSP1 marker. Another multimodel study (Rogelj et al., 2018) estimated the average discounted price of carbon (2020–2100, 5%) to be 35–65% lower in SSP1 compared to SSP2 in 1.5°C pathways. Delayed near-term mitigation policies and measures, including the limited extent of international global cooperation, result in increases in total economic mitigation costs and corresponding prices of carbon (Luderer et al., 2013; Clarke et al., 2014). This is because stronger efforts are required in the period after the delay to counterbalance the higher emissions in the near term. Staged accession scenarios also produce higher mitigation costs than immediate action mitigation scenarios under the same stringency level of emissions (Kriegler et al., 2015b).

It has been long argued that an explicit carbon pricing mechanism (whether via a tax or cap-and-trade scheme) can theoretically achieve cost-effective emission reductions (Nordhaus, 2007b; Stern, 2007; Aldy and Stavins, 2012; Goulder and Schein, 2013; Somanthan et al., 2014; Weitzman, 2014; Tol, 2017). Whereas the integrated assessment literature is mostly focused on the role of carbon pricing to reduce emissions (Clarke et al., 2014; Riahi et al., 2017; Weyant, 2017), there

[14] Unlike AR5, which only included cost-effective scenarios for estimating discounted average carbon prices for 2015–2100 (also using a 5% discount rate) (see Clarke et al., 2014, p.450), please note that values shown in Figure 2.26b include delays or technology constraint cases (see Sections 2.1 and 2.3).

is an emerging body of studies (including bottom-up approaches) that focuses on the interaction and performance of various policy mixes (e.g., regulation, subsidies, standards). Assuming global implementation of a mix of regionally existing best-practice policies (mostly regulatory policies in the electricity, industry, buildings, transport and agricultural sectors) and moderate carbon pricing (between 5–20 USD2010 tCO_2^{-1} in 2025 in most world regions and average prices around 25 USD2010 tCO_2^{-1} in 2030), early action mitigation pathways are generated that reduce global CO2 emissions by an additional 10 $GtCO_2e$ in 2030 compared to the NDCs (Kriegler et al., 2018a) (see Section 2.3.5). Furthermore, a mix of stringent energy efficiency policies (e.g., minimum performance standards, building codes) combined with a carbon tax (rising from 10 USD2010 tCO_2^{-1} in 2020 to 27 USD2010 tCO_2^{-1} in 2040) is more cost-effective than a carbon tax alone (from 20 to 53 USD2010 tCO_2^{-1}) to generate a 1.5°C pathway for the U.S. electric sector (Brown and Li, 2018). Likewise, a policy mix encompassing a moderate carbon price (7 USD2010 tCO_2^{-1} in 2015) combined with a ban on new coal-based power plants and dedicated policies addressing renewable electricity generation capacity and electric vehicles reduces efficiency losses compared with an optimal carbon pricing in 2030 (Bertram et al., 2015b). One study estimates the carbon prices in high energy-intensive pathways to be 25–50% higher than in low energy-intensive pathways that assume ambitious regulatory instruments, economic incentives (in addition to a carbon price) and voluntary initiatives (Méjean et al., 2018). A bottom-up approach shows that stringent minimum performance standards (MEPS) for appliances (e.g., refrigerators) can effectively complement explicit carbon pricing, as tightened MEPS can achieve ambitious efficiency improvements that cannot be assured by carbon prices of 100 USD2010 tCO_2^{-1} or higher (Sonnenschein et al., 2018). In addition, the revenue recycling effect of carbon pricing can reduce mitigation costs by displacing distortionary taxes (Baranzini et al., 2017; OECD, 2017; McFarland et al., 2018; Sands, 2018; Siegmeier et al., 2018), and the reduction of capital tax (compared to a labour tax) can yield greater savings in welfare costs (Sands, 2018). The effect on public budgets is particularly important in the near term; however, it can decline in the long term as carbon neutrality is achieved (Sands, 2018). The literature indicates that explicit carbon pricing is relevant but needs to be complemented with other policies to drive the required changes in line with 1.5°C cost-effective pathways (*low to medium evidence, high agreement*) (see Chapter 4, Section 4.4.5) (Stiglitz et al., 2017; Mehling and Tvinnereim, 2018; Méjean et al., 2018; Michaelowa et al., 2018).

In summary, new analyses are consistent with AR5 and show that the price of carbon increases significantly if a higher level of stringency is pursued (*high confidence*). Values vary substantially across models, scenarios and socio-economic, technology and policy assumptions. While an explicit carbon pricing mechanism is central to prompt mitigation scenarios compatible with 1.5°C pathways, a complementary mix of stringent policies is required.

2.5.2.2 Investments

Realizing the transformations towards a 1.5°C world would require a major shift in investment patterns (McCollum et al., 2018). Literature on global climate change mitigation investments is relatively sparse, with most detailed literature having focused on 2°C pathways (McCollum

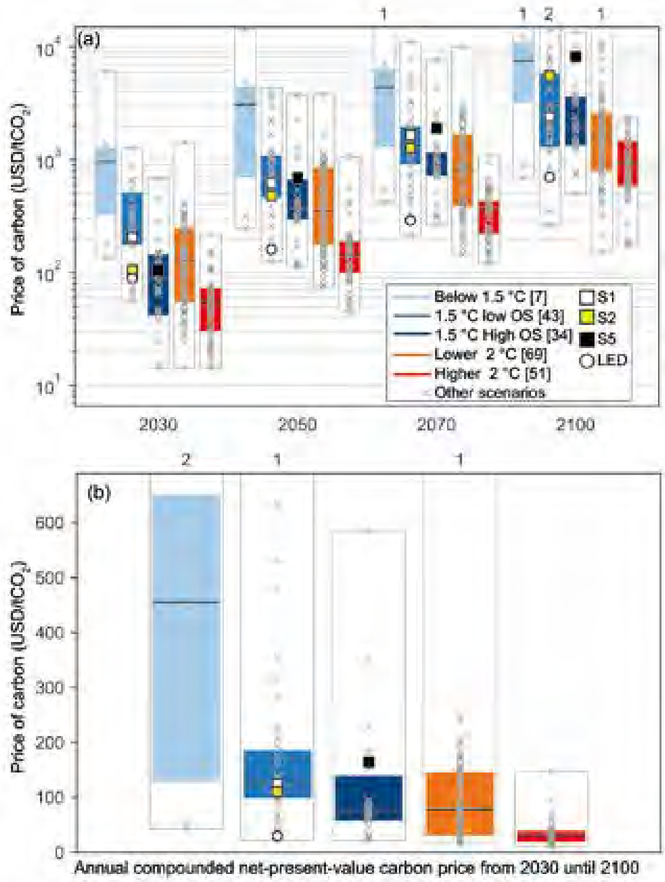


Figure 2.26 | Global price of carbon emissions consistent with mitigation pathways. Panels show (a) undiscounted price of carbon (2030–2100) and (b) average price of carbon (2030–2100) discounted at a 5% discount rate to 2020 in USD2010. AC: Annually compounded. NPV: Net present value. Median values in floating black line. The number of pathways included in box plots is indicated in the legend. Number of pathways outside the figure range is noted at the top.

et al., 2013; Bowen et al., 2014; Gupta and Harnisch, 2014; Marangoni and Tavoni, 2014; OECD/IEA and IRENA, 2017).

Global energy-system investments in the year 2016 are estimated at approximately 1.7 trillion USD2010 (approximately 2.2% of global GDP and 10% of gross capital formation), of which 0.23 trillion USD2010 was for incremental end-use energy efficiency and the remainder for supply-side capacity installations (IEA, 2017c). There is some uncertainty surrounding this number because not all entities making investments report them publicly, and model-based estimates show an uncertainty range of about ±15% (McCollum et al., 2018). Notwithstanding, the trend for global energy investments has been generally upward over the last two decades: increasing about threefold between 2000 and 2012, then levelling off for three years before declining in both 2015 and 2016 as a result of the oil price collapse and simultaneous capital cost reductions for renewables (IEA, 2017c).

Estimates of demand-side investments, either in total or for incremental efficiency efforts, are more uncertain, mainly due to a lack of reliable statistics and definitional issues about what exactly is counted towards a demand-side investment and what the reference should be for estimating incremental efficiency (McCollum et al., 2013). Grubler and

Wilson (2014) use two working definitions (a broader and a narrower one) to provide a first-order estimate of historical end-use technology investments in total. The broad definition defines end-use technologies as the technological systems purchasable by final consumers in order to provide a useful service, for example, heating and air conditioning systems, cars, freezers, or aircraft. The narrow definition sets the boundary at the specific energy-using components or subsystems of the larger end-use technologies (e.g., compressor, car engine, heating element). Based on these two definitions, demand-side energy investments for the year 2005 were estimated about 1–3.5 trillion USD2010 (central estimate 1.7 trillion USD2010) using the broad definition and 0.1–0.6 trillion USD2010 (central estimate 0.3 trillion USD2010) using the narrower definition. Due to these definitional issues, demand-side investment projections are uncertain, often underreported, and difficult to compare. Global IAMs often do not fully and explicitly represent all the various measures that could improve end-use efficiency.

Research carried out by six global IAM teams found that 1.5°C-consistent climate policies would require a marked upscaling of energy system supply-side investments (resource extraction, power generation, fuel conversion, pipelines/transmission, and energy storage) between now and mid-century, reaching levels of between 1.6–3.8 trillion USD2010 yr^{-1} globally on average over the 2016–2050 timeframe (McCollum et al., 2018) (Figure 2.27). How these investment needs compare to those in a policy baseline scenario is uncertain: they could be higher, much higher, or lower. Investments in the policy baselines from these same models are 1.6–2.7 trillion USD2010 yr^{-1}. Much hinges on the reductions in energy demand growth embodied in the 1.5°C pathways, which require investing in energy efficiency. Studies suggest that annual supply-side investments by mid-century could be lowered by around 10% (McCollum et al., 2018) and in some cases up to 50% (Grubler et al., 2018) if strong policies to limit energy demand growth are successfully implemented. However, the degree to which these supply-side reductions would be partially offset by an increase in demand-side investments is unclear.

Some trends are robust across scenarios (Figure 2.27). First, pursuing 1.5°C mitigation efforts requires a major reallocation of the investment portfolio, implying a financial system aligned to mitigation challenges. The path laid out by countries' current NDCs until 2030 will not drive these structural changes; and despite increasing low-carbon investments in recent years (IEA, 2016b; Frankfurt School-UNEP Centre/BNEF, 2017), these are not yet aligned with 1.5°C. Second, additional annual average energy-related investments for the period 2016 to 2050 in pathways limiting warming to 1.5°C compared to the baseline (i.e., pathways without new climate policies beyond those in place today) are estimated by the models employed in McCollum et al. (2018) to be around 830 billion USD2010 (range of 150 billion to 1700 billion USD2010 across six models). This compares to total annual average energy *supply* investments in 1.5°C pathways of 1460 to 3510 billion USD2010 and total annual average energy *demand* investments of 640 to 910 billion USD2010 for the period 2016 to 2050. Total energy-related investments increase by about 12% (range of 3% to 24%) in 1.5°C pathways relative to 2°C pathways. Average annual investment in low-carbon energy technologies and energy efficiency are upscaled by roughly a factor of six (range of factor of 4 to 10) by 2050 compared to 2015. Specifically, annual investments in low-carbon energy are projected to average 0.8–2.9 trillion USD2010 yr^{-1} globally to 2050 in 1.5°C pathways, overtaking fossil investments globally already by around 2025 (McCollum et al., 2018). The bulk of these investments are projected to be for clean electricity generation, particularly solar and wind power (0.09–1.0 trillion USD2010 yr^{-1} and 0.1–0.35 trillion USD2010 yr^{-1}, respectively) as well as nuclear power (0.1–0.25 trillion USD2010 yr^{-1}). Third, the precise apportioning of these investments depends on model assumptions and societal preferences related to mitigation strategies and policy choices (see Sections 2.1 and 2.3). Investments for electricity transmission and distribution and storage are also scaled up in 1.5°C pathways (0.3–1.3 trillion USD2010 yr^{-1}), given their widespread electrification of the end-use sectors (see Section 2.4). Meanwhile, 1.5°C pathways see a reduction in annual investments for fossil-fuel extraction and unabated fossil electricity generation (to 0.3–0.85 trillion USD2010 yr^{-1} on average over the 2016–2050 period). Investments in unabated coal are halted by 2030 in most 1.5°C projections, while the literature is less conclusive for investments in unabated gas (McCollum et al., 2018). This illustrates how mitigation strategies vary between models, but in the real world should be considered in terms of their societal desirability (see Section 2.5.3). Furthermore, some fossil investments made over the next few years – or those made in the last few – will *likely* need to be retired prior to fully recovering their capital investment or before the end of their operational lifetime (Bertram et al., 2015a; Johnson et al., 2015; OECD/IEA and IRENA, 2017). How the pace of the energy transition will be affected by such dynamics, namely with respect to politics and society, is not well captured by global IAMs at present. Modelling studies have, however, shown how the reliability of institutions influences investment risks and hence climate mitigation investment decisions (Iyer et al., 2015), finding that a lack of regulatory credibility or policy commitment fails to stimulate low-carbon investments (Bosetti and Victor, 2011; Faehn and Isaksen, 2016).

Low-carbon supply-side investment needs are projected to be largest in OECD countries and those of developing Asia. The regional distribution of investments in 1.5°C pathways estimated by the multiple models in (McCollum et al., 2018) are the following (average over 2016–2050 timeframe): 0.30–1.3 trillion USD2010 yr^{-1}(ASIA), 0.35–0.85 trillion USD2010 yr^{-1} (OECD), 0.08–0.55 trillion USD2010 yr^{-1} (MAF), 0.07–0.25 trillion USD2010 yr^{-1} (LAM), and 0.05–0.15 trillion USD2010 yr^{-1} (REF) (regions are defined consistent with their use in AR5 WGIII, see Table A.II.8 in Krey et al., 2014b).

Until now, IAM investment analyses of 1.5°C pathways have focused on middle-of-the-road socio-economic and technological development futures (SSP2) (Fricko et al., 2017). Consideration of a broader range of development futures would yield different outcomes in terms of the magnitudes of the projected investment levels. Sensitivity analyses indicate that the magnitude of supply-side investments as well as the investment portfolio do not change strongly across the SSPs for a given level of climate policy stringency (McCollum et al., 2018). With only one dedicated multimodel comparison study published, there is *limited to medium evidence* available. For some features, there is *high agreement* across modelling frameworks leading, for example, to *medium to high confidence* that limiting global temperature increase to 1.5°C would require a major reallocation of the investment portfolio. Given the limited amount of sensitivity cases available compared to the default SSP2 assumptions, *medium confidence* can be assigned to the specific energy and climate mitigation investment estimates reported here.

Assumptions in modelling studies indicate a number of challenges. For instance, access to finance and mobilization of funds are critical (Fankhauser et al., 2016; OECD, 2017). In turn, policy efforts need to be effective in redirecting financial resources (UNEP, 2015; OECD, 2017) and reducing transaction costs for bankable mitigation projects (i.e. projects that have adequate future cash flow, collateral, etc. so lenders are willing to finance it), particularly on the demand side (Mundaca et al., 2013; Brunner and Enting, 2014; Grubler et al., 2018). Assumptions also imply that policy certainty, regulatory oversight mechanisms and fiduciary duty need to be robust and effective to safeguard credible and stable financial markets and de-risk mitigation investments in the long term (Clarke et al., 2014; Mundaca et al., 2016; EC, 2017; OECD, 2017). Importantly, the different time horizons that actors have in the competitive finance industry are typically not explicitly captured by modelling assumptions (Harmes, 2011). See Chapter 4, Section 4.4.5 for details of climate finance in practice.

In summary and despite inherent uncertainties, the emerging literature indicates a gap between current investment patterns and those compatible with 1.5°C (or 2°C) pathways (*limited to medium evidence, high agreement*). Estimates and assumptions from modelling frameworks suggest a major shift in investment patterns and entail a financial system effectively aligned with mitigation challenges (*high confidence*).

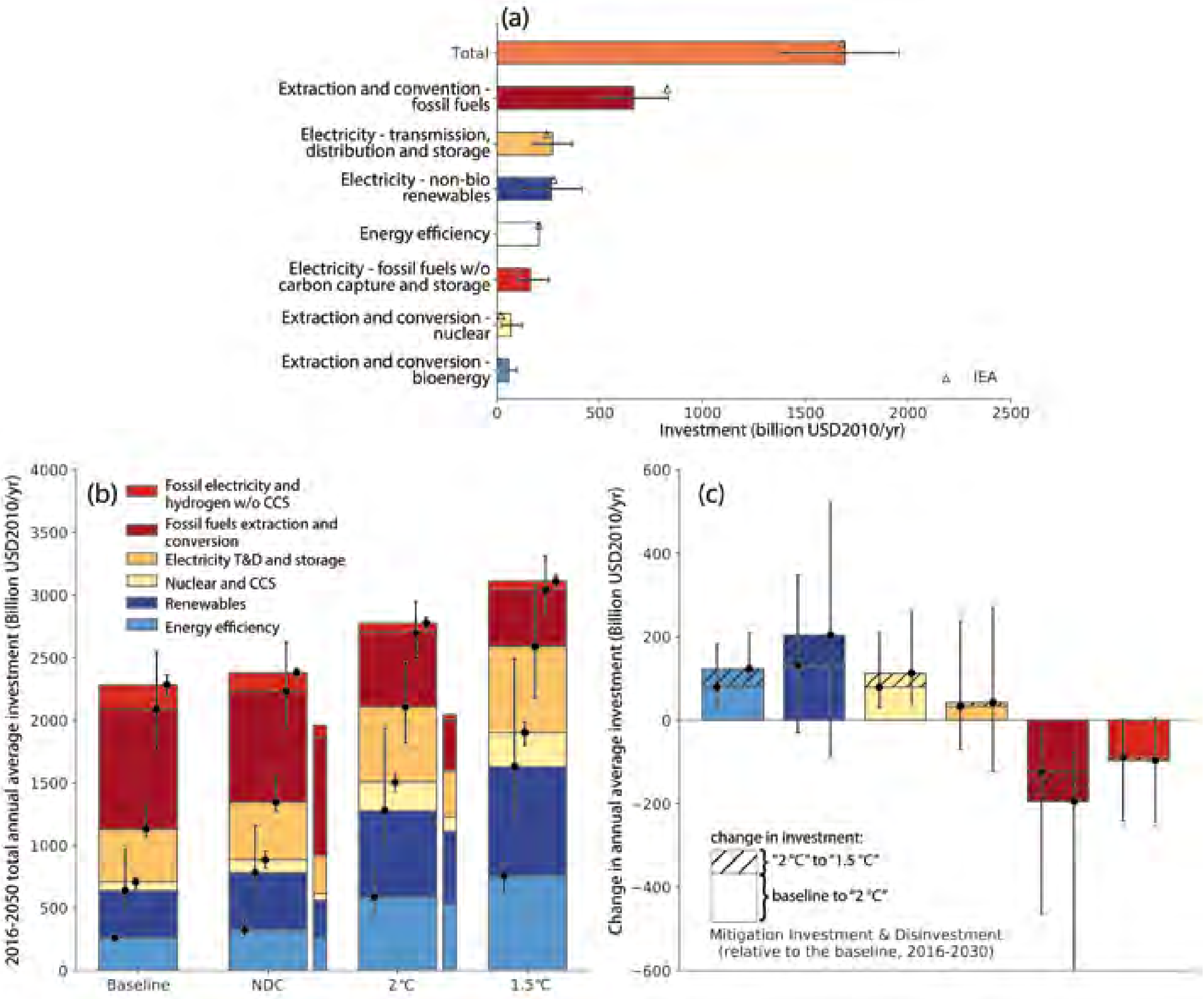


Figure 2.27 | Historical and projected global energy investments. (a) Historical investment estimates across six global models from (McCollum et al., 2018) (bars = model means, whiskers full model range) compared to historical estimates from IEA (International Energy Agency (IEA) 2016) (triangles). (b) Average annual investments over the 2016–2050 period in the "baselines" (i.e., pathways without new climate policies beyond those in place today), scenarios which implement the NDCs ('NDC', including conditional NDCs), scenarios consistent with the Lower-2°C pathway class ('2°C'), and scenarios in line with the 1.5°C-low-OS pathway class ('1.5°C'). Whiskers show the range of models; wide bars show the multimodel means; narrow bars represent analogous values from individual IEA scenarios (OECD/IEA and IRENA, 2017). (c) Average annual mitigation investments and disinvestments for the 2016–2030 periods relative to the baseline. The solid bars show the values for '2°C' pathways, while the hatched areas show the additional investments for the pathways labelled with '1.5°C'. Whiskers show the full range around the multimodel means. T&D stands for transmission and distribution, and CCS stands for carbon capture and storage. Global cumulative carbon dioxide emissions, from fossil fuels and industrial processes (FF&I) but excluding land use, over the 2016-2100 timeframe range from 880 to 1074 $GtCO_2$ (multimodel mean: 952 $GtCO_2$) in the '2°C' pathway and from 206 to 525 $GtCO_2$ (mean: 390 $GtCO_2$) in the '1.5°C' pathway.

2.5.3 Sustainable Development Features of 1.5°C Pathways

Potential synergies and trade-offs between 1.5°C mitigation pathways and different sustainable development (SD) dimensions (see Cross-Chapter Box 4 in Chapter 1) are an emerging field of research. Chapter 5, Section 5.4 assesses interactions between individual mitigation measures with other societal objectives, as well as the Sustainable Development Goals (SDGs) (Table 5.1). This section synthesized the Chapter 5 insights to assess how these interactions play out in integrated 1.5°C pathways, and the four illustrative pathway archetypes of this chapter in particular (see Section 2.1). Information from integrated pathways is combined with the interactions assessed in Chapter 5 and aggregated for each SDG, with a level of confidence attributed to each interaction based on the amount and agreement of the scientific evidence (see Chapter 5).

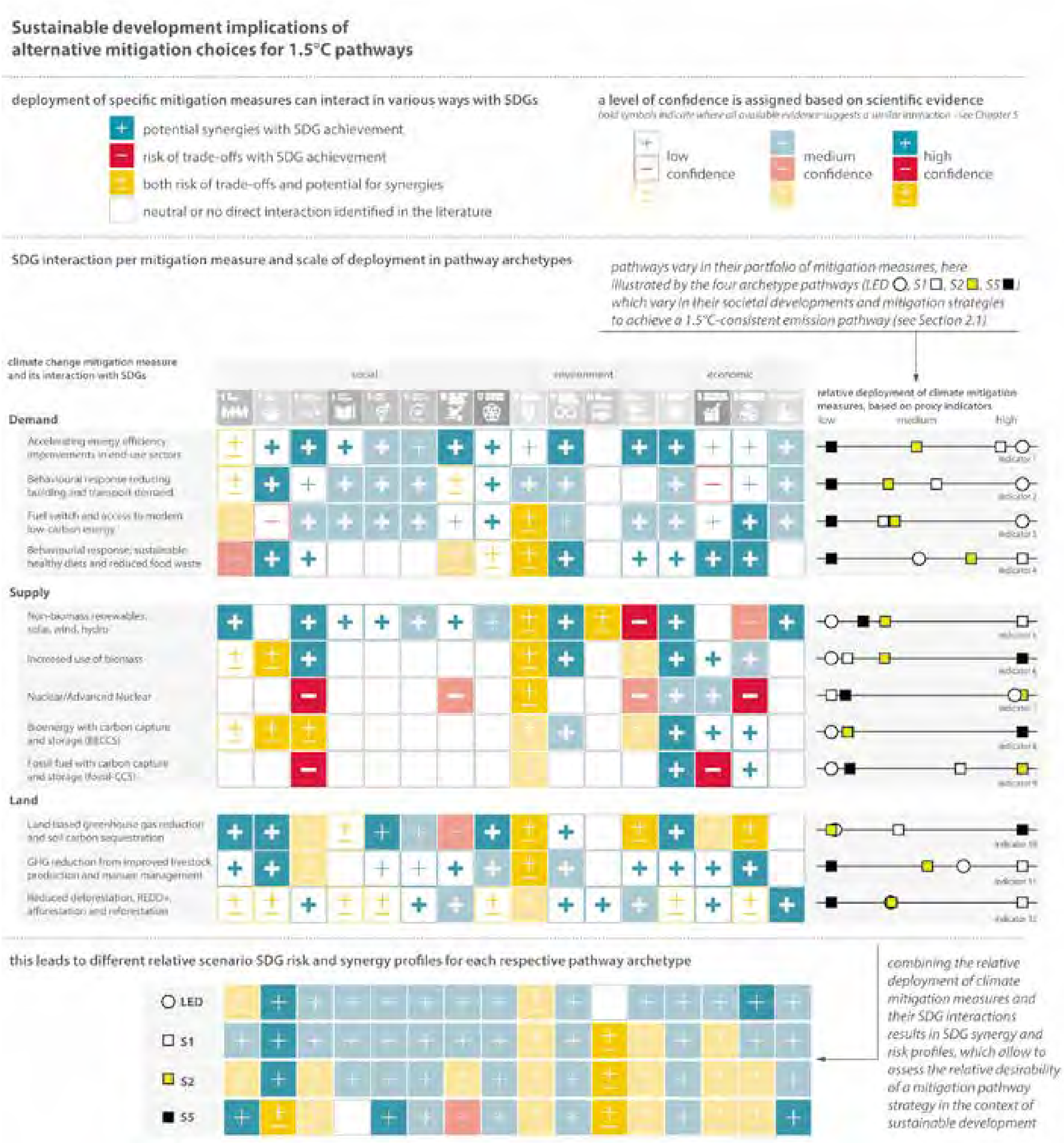


Figure 2.28 | Interactions of individual mitigation measures and alternative mitigations portfolios for 1.5°C with Sustainable Development Goals (SDGs). The assessment of interactions between mitigation measures and individual SDGs is based on the assessment of Chapter 5, Section 5.4. Proxy indicators and synthesis method are described in Supplementary Material 2.SM.1.5.

Figure 2.28 shows how the scale and combination of individual mitigation measures (i.e., their mitigation portfolios) influence the extent of synergies and trade-offs with other societal objectives. All pathways generate multiple synergies with sustainable development dimensions and can advance several other SDGs simultaneously. Some, however, show higher risks for trade-offs. An example is increased biomass production and its potential to increase pressure on land and water resources, food production, and biodiversity and to reduce air quality when combusted inefficiently. At the same time, mitigation actions in energy-demand sectors and behavioural response options with appropriate management of rebound effects can advance multiple SDGs simultaneously, more so than energy supply-side mitigation actions (see Chapter 5, Section 5.4, Table 5.1 and Figure 5.3 for more examples). Of the four pathway archetypes used in this chapter (LED, S1, S2, and S5, referred to as P1, P2, P3, and P4 in the Summary for Policymakers), the S1 and LED pathways show the largest number of synergies and least number of potential trade-offs, while for the S5 pathway more potential trade-offs are identified. In general, pathways with emphasis on demand reductions and policies that incentivize behavioural change, sustainable consumption patterns, healthy diets and relatively low use of CDR (or only afforestation) show relatively more synergies with individual SDGs than other pathways.

There is *robust evidence* and *high agreement* in the pathway literature that multiple strategies can be considered to limit warming to 1.5°C (see Sections 2.1.3, 2.3 and 2.4). Together with the extensive evidence on the existence of interactions of mitigation measures with other societal objectives (Chapter 5, Section 5.4), this results in *high confidence* that the choice of mitigation portfolio or strategy can markedly affect the achievement of other societal objectives. For instance, action on SLCFs has been suggested to facilitate the achievement of SDGs (Shindell et al., 2017b) and to reduce regional impacts, for example, from black carbon sources on snow and ice loss in the Arctic and alpine regions (Painter et al., 2013), with particular focus on the warming sub-set of SLCFs. Reductions in both surface aerosols and ozone through methane reductions provide health and ecosystem co-benefits (Jacobson, 2002, 2010; Anenberg et al., 2012; Shindell et al., 2012; Stohl et al., 2015; Collins et al., 2018). Public health benefits of stringent mitigation pathways in line with 1.5°C pathways can be sizeable. For instance, a study examining a more rapid reduction of fossil-fuel usage to achieve 1.5°C relative to 2°C, similar to that of other recent studies (Grubler et al., 2018; van Vuuren et al., 2018), found that improved air quality would lead to more than 100 million avoided premature deaths over the 21st century (Shindell et al., 2018). These benefits are assumed to be in addition to those occurring under 2°C pathways (e.g., Silva et al., 2016), and could in monetary terms offset either a large portion or all of the initial mitigation costs (West et al., 2013; Shindell et al., 2018). However, some sources of SLCFs with important impacts for public health (e.g., traditional biomass burning) are only mildly affected by climate policy in the available integrated pathways and are more strongly impacted by baseline assumptions about future societal development and preferences, and technologies instead (Rao et al., 2016, 2017).

At the same time, the literature on climate–SDG interactions is still an emergent field of research and hence there is *low to medium confidence* in the precise magnitude of the majority of these interactions. Very limited literature suggests that achieving co-benefits is not automatically assured but results from conscious and carefully coordinated policies and implementation strategies (Shukla and Chaturvedi, 2012; Clarke et al., 2014; McCollum et al., 2018). Understanding these mitigation–SDG interactions is key for selecting mitigation options that maximize synergies and minimize trade-offs towards the 1.5°C and sustainable development objectives (van Vuuren et al., 2015; Hildingsson and Johansson, 2016; Jakob and Steckel, 2016; von Stechow et al., 2016; Delponte et al., 2017).

In summary, the combined evidence indicates that the chosen mitigation portfolio can have a distinct impact on the achievement of other societal policy objectives (*high confidence*); however, there is uncertainty regarding the specific extent of climate–SDG interactions.

2.6 Knowledge Gaps

This section summarizes the knowledge gaps articulated in earlier sections of the chapter.

2.6.1 Geophysical Understanding

Knowledge gaps are associated with the carbon cycle response, the role of non-CO_2 emissions and the evaluation of an appropriate historic baseline.

Quantifying how the carbon cycle responds to negative emissions is an important knowledge gap for strong mitigation pathways (Section 2.2). Earth system feedback uncertainties are important to consider for the longer-term response, particularly in how permafrost melting might affect the carbon budget (Section 2.2). Future research and ongoing observations over the next years will provide a better indication as to how the 2006-2015 base period compares with the long-term trends and might at present bias the carbon budget estimates.

The future emissions of short-lived climate forcers and their temperature response are a large source of uncertainty in 1.5°C pathways, having a greater relative uncertainty than in higher CO_2 emission pathways. Their global emissions, their sectoral and regional disaggregation, and their climate response are generally less well quantified than for CO_2 (Sections 2.2 and 2.3). Emissions from the agricultural sector, including land-use based mitigation options, in 1.5°C pathways constitute the main source of uncertainty here and are an important gap in understanding the potential achievement of stringent mitigation scenarios (Sections 2.3 and 2.4). This also includes uncertainties surrounding the mitigation potential of the long-lived GHG nitrous oxide (Sections 2.3 and 2.4).

There is considerable uncertainty in how future emissions of aerosol precursors will affect the effective radiative forcing from aerosol–cloud interaction. The potential future warming from mitigation of these emissions reduces remaining carbon budgets and increases peak temperatures (Section 2.2). The potential co-benefits of mitigating air pollutants and how the reduction in air pollution may affect the carbon sink are also important sources of uncertainty (Sections 2.2 and 2.5).

The pathway classification employed in this chapter employs results from the MAGICC model with its AR5 parameter sets. The alternative representation of the relationship between emissions and effective radiative forcing and response in the FAIR model would lead to a different classification that would make 1.5°C targets more achievable (Section 2.2 and Supplementary Material 2.SM.1.1). Such a revision would significantly alter the temperature outcomes for the pathways and, if the result is found to be robust, future research and assessments would need to adjust their classifications accordingly. Any possible high bias in the MAGICC response may be partly or entirely offset by missing Earth system feedbacks that are not represented in either climate emulator and that would act to increase the temperature response (Section 2.2). For this assessment report, any possible bias in the MAGICC setup applied in this and earlier reports is not established enough in the literature to change the classification approach. However, we only place *medium confidence* in the classification adopted by the chapter.

2.6.2 Integrated Assessment Approaches

IAMs attempt to be as broad as possible in order to explore interactions between various societal subsystems, like the economy, land, and energy system. They hence include stylized and simplified representations of these subsystems. Climate damages, avoided impacts and societal co-benefits of the modelled transformations remain largely unaccounted for and are important knowledge gaps. Furthermore, rapid technological changes and uncertainties about input data present continuous challenges.

The IAMs used in this report do not account for climate impacts (Section 2.1), and similarly, none of the Gross Domestic Product (GDP) projections in the mitigation pathway literature assessed in this chapter included the feedback of climate damages on economic growth (Section 2.3). Although some IAMs do allow for climate impact feedbacks in their modelling frameworks, particularly in their land components, such feedbacks were by design excluded in pathways developed in the context of the SSP framework. The SSP framework aims at providing an integrative framework for the assessment of climate change adaptation and mitigation. IAMs are typically developed to inform the mitigation component of this question, while the assessment of impacts is carried out by specialized impact models. However, the use of a consistent set of socio-economic drivers embodied by the SSPs allows for an integrated assessment of climate change impacts and mitigation challenges at a later stage. Further integration of these two strands of research will allow a better understanding of climate impacts on mitigation studies.

Many of the IAMs that contributed mitigation pathways to this assessment include a process-based description of the land system in addition to the energy system, and several have been extended to cover air pollutants and water use. These features make them increasingly fit to explore questions beyond those that touch upon climate mitigation only. The models do not, however, fully account for all constraints that could affect realization of pathways (Section 2.1).

While the representation of renewable energy resource potentials, technology costs and system integration in IAMs has been updated since AR5, bottom-up studies find higher mitigation potentials in the industry, buildings, and transport sector in that realized by selected pathways from IAMs, indicating the possibility to strengthen sectoral decarbonization strategies compared to the IAM 1.5°C pathways assessed in this chapter (Section 2.1).

Studies indicate that a major shift in investment patterns is required to limit global warming to 1.5°C. This assessment would benefit from a more explicit representation and understanding of the financial sector within the modelling approaches. Assumptions in modelling studies imply low-to-zero transaction costs for market agents and that regulatory oversight mechanisms and fiduciary duty need to be highly robust to guarantee stable and credible financial markets in the long term. This area can be subject to high uncertainty, however. The heterogeneity of actors (e.g., banks, insurance companies, asset managers, or credit rating agencies) and financial products also needs to be taken into account, as does the mobilization of capital and financial flows between countries and regions (Section 2.5).

The literature on interactions between 1.5˚C mitigation pathways and SDGs is an emergent field of research (Section 2.3.5, 2.5 and Chapter 5). Whereas the choice of mitigation strategies can noticeably affect the attainment of various societal objectives, there is uncertainty regarding the extent of the majority of identified interactions. Understanding climate–SDG interactions helps inform the choice of mitigation options that minimize trade-offs and risks and maximize synergies towards sustainable development objectives and the 1.5°C goal (Section 2.5).

2.6.3 Carbon Dioxide Removal (CDR)

Most 1.5°C and 2°C pathways are heavily reliant on CDR at a speculatively large scale before mid-century. There are a number of knowledge gaps associated which such technologies. Chapter 4 performs a detailed assessment of CDR technologies.

There is uncertainty in the future deployment of CCS given the limited pace of current deployment, the evolution of CCS technology that would be associated with deployment, and the current lack of incentives for large-scale implementation of CCS (Chapter 4, Section 4.2.7). Technologies other than BECCS and afforestation have yet to be comprehensively assessed in integrated assessment approaches. No proposed technology is close to deployment at scale, and regulatory frameworks are not established. This limits how they can be realistically implemented within IAMs. (Section 2.3)

Evaluating the potential from BECCS is problematic due to large uncertainties in future land projections due to differences in modelling approaches in current land-use models, and these differences are at least as great as the differences attributed to climate scenario variations. (Section 2.3)

There is substantial uncertainty about the adverse effects of large-scale CDR deployment on the environment and societal sustainable development goals. It is not fully understood how land-use and land-management choices for large-scale BECCS will affect various ecosystem services and sustainable development, and how they further translate into indirect impacts on climate, including GHG emissions other than CO_2. (Section 2.3, Section 2.5.3)

Frequently Asked Questions

FAQ 2.1 | What Kind of Pathways Limit Warming to 1.5°C and are we on Track?

Summary: *There is no definitive way to limit global temperature rise to 1.5°C above pre-industrial levels. This Special Report identifies two main conceptual pathways to illustrate different interpretations. One stabilizes global temperature at, or just below, 1.5°C. Another sees global temperature temporarily exceed 1.5°C before coming back down. Countries' pledges to reduce their emissions are currently not in line with limiting global warming to 1.5°C.*

Scientists use computer models to simulate the emissions of greenhouse gases that would be consistent with different levels of warming. The different possibilities are often referred to as 'greenhouse gas emission pathways'. There is no single, definitive pathway to limiting warming to 1.5°C.

This IPCC special report identifies two main pathways that explore global warming of 1.5°C. The first involves global temperature stabilizing at or below before 1.5°C above pre-industrial levels. The second pathway sees warming exceed 1.5°C around mid-century, remain above 1.5°C for a maximum duration of a few decades, and return to below 1.5°C before 2100. The latter is often referred to as an 'overshoot' pathway. Any alternative situation in which global temperature continues to rise, exceeding 1.5°C permanently until the end of the 21st century, is not considered to be a 1.5°C pathway.

The two types of pathway have different implications for greenhouse gas emissions, as well as for climate change impacts and for achieving sustainable development. For example, the larger and longer an 'overshoot', the greater the reliance on practices or technologies that remove CO_2 from the atmosphere, on top of reducing the sources of emissions (mitigation). Such ideas for CO_2 removal have not been proven to work at scale and, therefore, run the risk of being less practical, effective or economical than assumed. There is also the risk that the use of CO_2 removal techniques ends up competing for land and water, and if these trade-offs are not appropriately managed, they can adversely affect sustainable development. Additionally, a larger and longer overshoot increases the risk for irreversible climate impacts, such as the onset of the collapse of polar ice shelves and accelerated sea level rise.

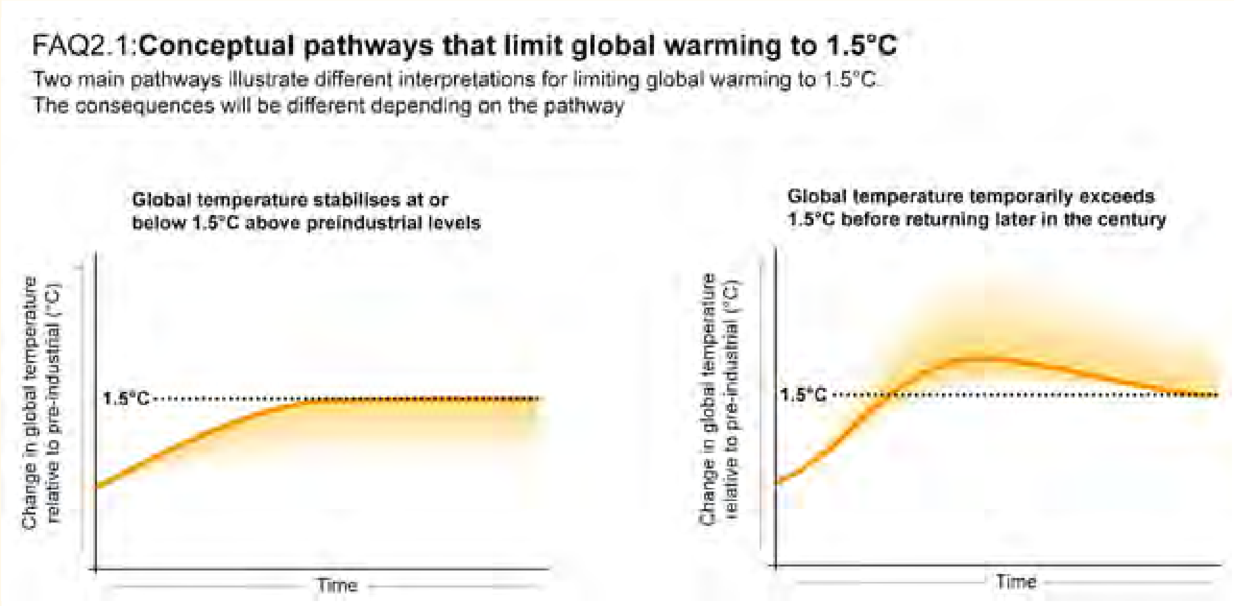
Countries that formally accept or 'ratify' the Paris Agreement submit pledges for how they intend to address climate change. Unique to each country, these pledges are known as Nationally Determined Contributions (NDCs). Different groups of researchers around the world have analysed the combined effect of adding up all the NDCs. Such analyses show that current pledges are not on track to limit global warming to 1.5°C above pre-industrial levels. If current pledges for 2030 are achieved but no more, researchers find very few (if any) ways to reduce emissions after 2030 sufficiently quickly to limit warming to 1.5°C. This, in turn, suggests that with the national pledges as they stand, warming would exceed 1.5°C, at least for a period of time, and practices and technologies that remove CO_2 from the atmosphere at a global scale would be required to return warming to 1.5°C at a later date.

A world that is consistent with holding warming to 1.5°C would see greenhouse gas emissions rapidly decline in the coming decade, with strong international cooperation and a scaling up of countries' combined ambition beyond current NDCs. In contrast, delayed action, limited international cooperation, and weak or fragmented policies that lead to stagnating or increasing greenhouse gas emissions would put the possibility of limiting global temperature rise to 1.5°C above pre-industrial levels out of reach.

(continued on next page)

2

FAQ 2.1 (continued)



FAQ 2.1, Figure 1 | Two main pathways for limiting global temperature rise to 1.5°C above pre-industrial levels are discussed in this Special Report. These are: stabilizing global temperature at, or just below, 1.5°C (left) and global temperature temporarily exceeding 1.5°C before coming back down later in the century (right). Temperatures shown are relative to pre-industrial but pathways are illustrative only, demonstrating conceptual not quantitative characteristics.

Frequently Asked Questions

FAQ 2.2 | What do Energy Supply and Demand have to do with Limiting Warming to 1.5°C?

Summary: *Limiting global warming to 1.5°C above pre-industrial levels would require major reductions in greenhouse gas emissions in all sectors. But different sectors are not independent of each other, and making changes in one can have implications for another. For example, if we as a society use a lot of energy, then this could mean we have less flexibility in the choice of mitigation options available to limit warming to 1.5°C. If we use less energy, the choice of possible actions is greater – for example, we could be less reliant on technologies that remove carbon dioxide (CO_2) from the atmosphere.*

To stabilize global temperature at any level, 'net' CO_2 emissions would need to be reduced to zero. This means the amount of CO_2 entering the atmosphere must equal the amount that is removed. Achieving a balance between CO_2 'sources' and 'sinks' is often referred to as 'net zero' emissions or 'carbon neutrality'. The implication of net zero emissions is that the concentration of CO_2 in the atmosphere would slowly decline over time until a new equilibrium is reached, as CO_2 emissions from human activity are redistributed and taken up by the oceans and the land biosphere. This would lead to a near-constant global temperature over many centuries.

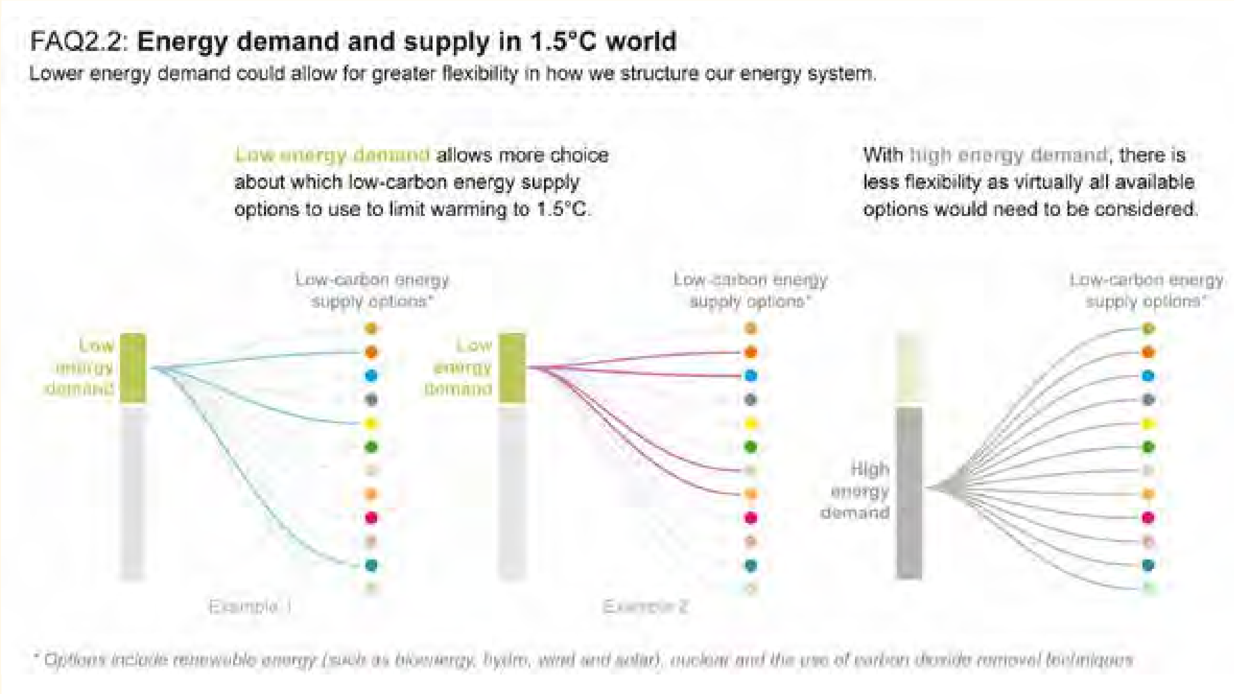
Warming will not be limited to 1.5°C or 2°C unless transformations in a number of areas achieve the required greenhouse gas emissions reductions. Emissions would need to decline rapidly across all of society's main sectors, including buildings, industry, transport, energy, and agriculture, forestry and other land use (AFOLU). Actions that can reduce emissions include, for example, phasing out coal in the energy sector, increasing the amount of energy produced from renewable sources, electrifying transport, and reducing the 'carbon footprint' of the food we consume.

The above are examples of 'supply-side' actions. Broadly speaking, these are actions that can reduce greenhouse gas emissions through the use of low-carbon solutions. A different type of action can reduce how much energy human society uses, while still ensuring increasing levels of development and well-being. Known as 'demand-side' actions, this category includes improving energy efficiency in buildings and reducing consumption of energy- and greenhouse-gas intensive products through behavioural and lifestyle changes, for example. Demand- and supply-side measures are not an either-or question, they work in parallel with each other. But emphasis can be given to one or the other.

Making changes in one sector can have consequences for another, as they are not independent of each other. In other words, the choices that we make now as a society in one sector can either restrict or expand our options later on. For example, a high demand for energy could mean we would need to deploy almost all known options to reduce emissions in order to limit global temperature rise to 1.5°C above pre-industrial levels, with the potential for adverse side-effects. In particular, a pathway with high energy demand would increase our reliance on practices and technologies that remove CO_2 from the atmosphere. As of yet, such techniques have not been proven to work on a large scale and, depending on how they are implemented, could compete for land and water. By leading to lower overall energy demand, effective demand-side measures could allow for greater flexibility in how we structure our energy system. However, demand-side measures are not easy to implement and barriers have prevented the most efficient practices being used in the past.

(continued on next page)

FAQ 2.2 (continued)



FAQ 2.2, Figure 1 | Having a lower energy demand increases the flexibility in choosing options for supplying energy. A larger energy demand means many more low carbon energy supply options would need to be used.

References

Ackerman, F. and E.A. Stanton, 2012: Climate Risks and Carbon Prices: Revising the Social Cost of Carbon. *Economics: The Open-Access, Open-Assessment E-Journal*, **6(2012-10)**, 1–25, doi:10.5018/economics-ejournal.ja.2012-10.

Adler, M.D. and N. Treich, 2015: Prioritarianism and Climate Change. *Environmental and Resource Economics*, **62(2)**, 279–308, doi:10.1007/s10640-015-9960-7.

Adler, M.D. et al., 2017: Priority for the worse-off and the social cost of carbon. *Nature Climate Change*, **7(6)**, 443–449, doi:10.1038/nclimate3298.

Akimoto, K., F. Sano, and T. Tomoda, 2017: GHG emission pathways until 2300 for the 1.5°C temperature rise target and the mitigation costs achieving the pathways. *Mitigation and Adaptation Strategies for Global Change*, 1–14, doi:10.1007/s11027-017-9762-z.

Alcalde, J. et al., 2018: Estimating geological CO_2 storage security to deliver on climate mitigation. *Nature Communications*, **9(1)**, 2201, doi:10.1038/s41467-018-04423-1.

Aldy, J.E. and R.N. Stavins, 2012: The Promise and Problems of Pricing Carbon. *The Journal of Environment & Development*, **21(2)**, 152–180, doi:10.1177/1070496512442508.

Aldy, J.E. et al., 2016: Economic tools to promote transparency and comparability in the Paris Agreement. *Nature Climate Change*, **6(11)**, 1000–1004, doi:10.1038/nclimate3106.

Allen, M.R. et al., 2009: Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature*, **458(7242)**, 1163–1166, doi:10.1038/nature08019.

Allen, M.R. et al., 2016: New use of global warming potentials to compare cumulative and short-lived climate pollutants. *Nature Climate Change*, **6(5)**, 1–5, doi:10.1038/nclimate2998.

Allen, M.R. et al., 2018: A solution to the misrepresentations of CO_2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. *npj Climate and Atmospheric Science*, **1(1)**, 16, doi:10.1038/s41612-018-0026-8.

Allwood, J.M., M.F. Ashby, T.G. Gutowski, and E. Worrell, 2013: Material efficiency: providing material services with less material production. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **371(1986)**, 20120496, doi:10.1098/rsta.2012.0496.

Anderson, K. and G. Peters, 2016: The trouble with negative emissions. *Science*, **354(6309)**, 182–183, doi:10.1126/science.aah4567.

Anenberg, S.C. et al., 2012: Global Air Quality and Health Co-benefits of Mitigating Near-Term Climate Change through Methane and Black Carbon Emission Controls. *Environmental Health Perspectives*, **120(6)**, 831–839, doi:10.1289/ehp.1104301.

Anthoff, D. and R.S.J. Tol, 2009: The impact of climate change on the balanced growth equivalent: An application of FUND. *Environmental and Resource Economics*, **43(3)**, 351–367, doi:10.1007/s10640-009-9269-5.

Armour, K.C., 2017: Energy budget constraints on climate sensitivity in light of inconstant climate feedbacks. *Nature Climate Change*, **7(5)**, 331–335, doi:10.1038/nclimate3278.

Arneth, A. et al., 2010: Terrestrial biogeochemical feedbacks in the climate system. *Nature Geoscience*, **3(8)**, 525–532, doi:10.1038/ngeo905.

Arroyo-Currás, T. et al., 2015: Carbon leakage in a fragmented climate regime: The dynamic response of global energy markets. *Technological Forecasting and Social Change*, **90**, 192–203, doi:10.1016/j.techfore.2013.10.002.

Bachu, S., 2015: Review of CO_2 storage efficiency in deep saline aquifers. *International Journal of Greenhouse Gas Control*, **40**, 188–202, doi:10.1016/j.ijggc.2015.01.007.

Bachu, S. et al., 2007a: *Phase II Final Report from the Task Force for Review and Identification of Standards for CO_2 Storage Capacity Estimation*. CSLF-T-2007-04, Task Force on CO_2 Storage Capacity Estimation for the Technical Group (TG) of the Carbon Sequestration Leadership Forum (CSLF), 43 pp.

Bachu, S. et al., 2007b: CO_2 storage capacity estimation: Methodology and gaps. *International Journal of Greenhouse Gas Control*, **1(4)**, 430–443, doi:10.1016/s1750-5836(07)00086-2.

Bajželj, B. et al., 2014: Importance of food-demand management for climate mitigation. *Nature Climate Change*, **4(10)**, 924–929, doi:10.1038/nclimate2353.

Banerjee, R. et al., 2012: Energy End-Use: Industry. In: *Global Energy Assessment – Toward a Sustainable Future* [Johansson, T.B., N. Nakicenovic, A. Patwardhan, and L. Gomez-Echeverri (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 513–574, doi:10.1017/cbo9780511793677.014.

Baranzini, A. et al., 2017: Carbon pricing in climate policy: seven reasons, complementary instruments, and political economy considerations. *Wiley Interdisciplinary Reviews: Climate Change*, **8(4)**, e462, doi:10.1002/wcc.462.

Bataille, C., H. Waisman, M. Colombier, L. Segafredo, and J. Williams, 2016a: The Deep Decarbonization Pathways Project (DDPP): insights and emerging issues. *Climate Policy*, **16(sup1)**, S1–S6, doi:10.1080/14693062.2016.1179620.

Bataille, C. et al., 2016b: The need for national deep decarbonization pathways for effective climate policy. *Climate Policy*, **16(sup1)**, S7–S26, doi:10.1080/14693062.2016.1173005.

Bauer, N. et al., 2017: Shared Socio-Economic Pathways of the Energy Sector – Quantifying the Narratives. *Global Environmental Change*, **42**, 316–330, doi:10.1016/j.gloenvcha.2016.07.006.

Bauer, N. et al., 2018: Global energy sector emission reductions and bioenergy use: overview of the bioenergy demand phase of the EMF-33 model comparison. *Climatic Change*, 1–16, doi:10.1007/s10584-018-2226-y.

Beck, S. and M. Mahony, 2017: The IPCC and the politics of anticipation. *Nature Climate Change*, **7(5)**, 311–313, doi:10.1038/nclimate3264.

Bentham, M., T. Mallows, J. Lowndes, and A. Green, 2014: CO_2 STORage evaluation database (CO_2 Stored). The UK's online storage atlas. *Energy Procedia*, **63**, 5103–5113, doi:10.1016/j.egypro.2014.11.540.

Benveniste, H. et al., 2018: Impacts of nationally determined contributions on 2030 global greenhouse gas emissions: Uncertainty analysis and distribution of emissions. *Environmental Research Letters*, **13(1)**, 014022, doi:10.1088/1748-9326/aaa0b9.

Berger, A. et al., 2017a: Nuclear energy and bio energy carbon capture and storage, keys for obtaining 1.5°C mean surface temperature limit. *International Journal of Global Energy Issues*, **40(3/4)**, 240–254, doi:10.1504/ijgei.2017.086622.

Berger, A. et al., 2017b: How much can nuclear energy do about global warming? *International Journal of Global Energy Issues*, **40(1/2)**, 43–78, doi:10.1504/ijgei.2017.080766.

Bertram, C. et al., 2015a: Carbon lock-in through capital stock inertia associated with weak near-term climate policies. *Technological Forecasting and Social Change*, **90(Part A)**, 62–72, doi:10.1016/j.techfore.2013.10.001.

Bertram, C. et al., 2015b: Complementing carbon prices with technology policies to keep climate targets within reach. *Nature Climate Change*, **5(3)**, 235–239, doi:10.1038/nclimate2514.

Bertram, C. et al., 2018: Targeted policies can compensate most of the increased sustainability risks in 1.5°C mitigation scenarios. *Environmental Research Letters*, **13(6)**, 064038, doi:10.1088/1748-9326/aac3ec.

Bindoff, N. et al., 2013: Detection and Attribution of Climate Change: from Global to Regional. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 867–952.

Blanco, G. et al., 2014: Drivers, Trends and Mitigation. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 351–412.

Boardman, A.E., D.H. Greenberg, A.R. Vining, and D.L. Weimer, 2006: *Cost-Benefit Analysis: Concepts and Practice (3rd edition)*. Pearson/Prentice Hall, Upper Saddle River, NJ, USA, 560 pp.

Bodirsky, B.L. et al., 2012: N_2O emissions from the global agricultural nitrogen cycle-current state and future scenarios. *Biogeosciences*, **9(10)**, 4169–4197, doi:10.5194/bg-9-4169-2012.

Bodirsky, B.L. et al., 2014: Reactive nitrogen requirements to feed the world in 2050 and potential to mitigate nitrogen pollution. *Nature Communications*, **5**, 3858, doi:10.1038/ncomms4858.

Bond, T.C. et al., 2013: Bounding the role of black carbon in the climate system: A scientific assessment. *Journal of Geophysical Research: Atmospheres*, **118(11)**, 5380–5552, doi:10.1002/jgrd.50171.

Bonsch, M. et al., 2014: Trade-offs between land and water requirements for large-scale bioenergy production. *GCB Bioenergy*, **8(1)**, 11–24, doi:10.1111/gcbb.12226.

Bosetti, V. and D.G. Victor, 2011: Politics and Economics of Second-Best Regulation of Greenhouse Gases: The Importance of Regulatory Credibility. *The Energy Journal*, **32(1)**, 1–24, www.jstor.org/stable/41323391.

Bosetti, V., C. Carraro, E. Massetti, and M. Tavoni, 2008: International energy R&D spillovers and the economics of greenhouse gas atmospheric stabilization. *Energy Economics*, **30(6)**, 2912–2929, doi:10.1016/j.eneco.2008.04.008.

Bosetti, V., C. Carraro, A. Sgobbi, and M. Tavoni, 2009: Delayed action and uncertain stabilisation targets. How much will the delay cost? *Climatic Change*, **96(3)**, 299–312, doi:10.1007/s10584-009-9630-2.

Bosetti, V., C. Carraro, M. Galeotti, E. Massetti, and M. Tavoni, 2006: WITCH – A World Induced Technical Change Hybrid Model. *The Energy Journal*, **27**, 13–37, www.jstor.org/stable/23297044.

Bosetti, V. et al., 2015: Sensitivity to energy technology costs: A multi-model comparison analysis. *Energy Policy*, **80**, 244–263, doi:10.1016/j.enpol.2014.12.012.

Boucher, O. and G.A. Folberth, 2010: New Directions: Atmospheric methane removal as a way to mitigate climate change? *Atmospheric Environment*, **44(27)**, 3343–3345, doi:10.1016/j.atmosenv.2010.04.032.

Bowen, A., E. Campiglio, and M. Tavoni, 2014: A macroeconomic perspective on climate change mitigation: Meeting the financing challenge. *Climate Change Economics*, **5(1)**, 1440005, doi:10.1142/s2010007814400053.

Bowerman, N.H.A., D.J. Frame, C. Huntingford, J.A. Lowe, and M.R. Allen, 2011: Cumulative carbon emissions, emissions floors and short-term rates of warming: implications for policy. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **369(1934)**, 45–66, doi:10.1098/rsta.2010.0288.

Bowerman, N.H.A. et al., 2013: The role of short-lived climate pollutants in meeting temperature goals. *Nature Climate Change*, **3(12)**, 1021–1024, doi:10.1038/nclimate2034.

Boysen, L.R., W. Lucht, and D. Gerten, 2017a: Trade-offs for food production, nature conservation and climate limit the terrestrial carbon dioxide removal potential. *Global Change Biology*, **23(10)**, 4303–4317, doi:10.1111/gcb.13745.

Boysen, L.R., W. Lucht, D. Gerten, and V. Heck, 2016: Impacts devalue the potential of large-scale terrestrial CO_2 removal through biomass plantations. *Environmental Research Letters*, **11(9)**, 1–10, doi:10.1088/1748-9326/11/9/095010.

Boysen, L.R. et al., 2017b: The limits to global-warming mitigation by terrestrial carbon removal. *Earth's Future*, **5(5)**, 463–474, doi:10.1002/2016ef000469.

Breyer, C. et al., 2017: On the role of solar photovoltaics in global energy transition scenarios. *Progress in Photovoltaics: Research and Applications*, **25(8)**, 727–745, doi:10.1002/pip.2885.

Brown, M.A. and Y. Li, 2018: Carbon pricing and energy efficiency: pathways to deep decarbonization of the US electric sector. *Energy Efficiency*, 1–19, doi:10.1007/s12053-018-9686-9.

Brown, P.T. and K. Caldeira, 2017: Greater future global warming inferred from Earth's recent energy budget. *Nature*, **552(7683)**, 45–50, doi:10.1038/nature24672.

Bruckner, T., I.A. Bashmakov, and Y. Mulugetta, 2014: Energy Systems. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 511–598.

Brunner, S. and K. Enting, 2014: Climate finance: A transaction cost perspective on the structure of state-to-state transfers. *Global Environmental Change*, **27**, 138–143, doi:10.1016/j.gloenvcha.2014.05.005.

Brynolf, S., M. Taljegard, M. Grahn, and J. Hansson, 2018: Electrofuels for the transport sector: A review of production costs. *Renewable and Sustainable Energy Reviews*, **81**, 1887–1905, doi:10.1016/j.rser.2017.05.288.

Buck, H.J., 2016: Rapid scale-up of negative emissions technologies: social barriers and social implications. *Climatic Change*, 1–13, doi:10.1007/s10584-016-1770-6.

Burke, E.J., I.P. Hartley, and C.D. Jones, 2012: Uncertainties in the global temperature change caused by carbon release from permafrost thawing. *Cryosphere*, **6(5)**, 1063–1076, doi:10.5194/tc-6-1063-2012.

Burke, E.J. et al., 2017: Quantifying uncertainties of permafrost carbon-climate feedbacks. *Biogeosciences*, **14(12)**, 3051–3066, doi:10.5194/bg-14-3051-2017.

Burns, W. and S. Nicholson, 2017: Bioenergy and carbon capture with storage (BECCS): the prospects and challenges of an emerging climate policy response. *Journal of Environmental Studies and Sciences*, **7(4)**, 527–534, doi:10.1007/s13412-017-0445-6.

Cadule, P., L. Bopp, and P. Friedlingstein, 2009: A revised estimate of the processes contributing to global warming due to climate-carbon feedback. *Geophysical Research Letters*, **36(14)**, L14705, doi:10.1029/2009gl038681.

Cai, Y., K.L. Judd, T.M. Lenton, T.S. Lontzek, and D. Narita, 2015: Environmental tipping points significantly affect the cost-benefit assessment of climate policies. *Proceedings of the National Academy of Sciences*, **112(15)**, 4606–4611, doi:10.1073/pnas.1503890112.

Calvin, K. et al., 2014: Trade-offs of different land and bioenergy policies on the path to achieving climate targets. *Climatic Change*, **123(3–4)**, 691–704, doi:10.1007/s10584-013-0897-y.

Calvin, K. et al., 2017: The SSP4: A world of deepening inequality. *Global Environmental Change*, **42**, 284–296, doi:10.1016/j.gloenvcha.2016.06.010.

Canadell, J.G. and M.R. Raupach, 2008: Managing Forests for Climate Change Mitigation. *Science*, **320(5882)**, 1456–1457, doi:10.1126/science.1155458.

Carslaw, K.S. et al., 2013: Large contribution of natural aerosols to uncertainty in indirect forcing. *Nature*, **503(7474)**, 67–71, doi:10.1038/nature12674.

Ceppi, P. and J.M. Gregory, 2017: Relationship of tropospheric stability to climate sensitivity and Earth's observed radiation budget. *Proceedings of the National Academy of Sciences*, **114(50)**, 13126–13131, doi:10.1073/pnas.1714308114.

Chan, S., P. Ellinger, and O. Widerberg, 2018: Exploring national and regional orchestration of non-state action for a <1.5°C world. *International Environmental Agreements: Politics, Law and Economics*, **18(1)**, 135–152, doi:10.1007/s10784-018-9384-2.

Chen, C. and M. Tavoni, 2013: Direct air capture of CO_2 and climate stabilization: A model based assessment. *Climatic Change*, **118(1)**, 59–72, doi:10.1007/s10584-013-0714-7.

Choi, Y.-S., D. Young, S. Nešić, and L.G.S. Gray, 2013: Wellbore integrity and corrosion of carbon steel in CO_2 geologic storage environments: A literature review. *International Journal of Greenhouse Gas Control*, **16**, S70–S77, doi:10.1016/j.ijggc.2012.12.028.

Clack, C.T.M. et al., 2017: Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar. *Proceedings of the National Academy of Sciences*, **114(26)**, 6722–6727, doi:10.1073/pnas.1610381114.

Clarke, L. et al., 2014: Assessing transformation pathways. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 413–510.

Collins, M. et al., 2013: Long-term Climate Change: Projections, Commitments and Irreversibility. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1029–1136.

Collins, W.J. et al., 2018: Increased importance of methane reduction for a 1.5 degree target. *Environmental Research Letters*, **13(5)**, 054003, doi:10.1088/1748-9326/aab89c.

Comyn-Platt, E. et al., 2018: Carbon budgets for 1.5 and 2°C targets lowered by natural wetland and permafrost feedbacks. *Nature Geoscience*, **11(8)**, 568–573, doi:10.1038/s41561-018-0174-9.

Cox, P.M., C. Huntingford, and M.S. Williamson, 2018: Emergent constraint on equilibrium climate sensitivity from global temperature variability. *Nature*, **553(7688)**, 319–322, doi:10.1038/nature25450.

Crespo Cuaresma, J., 2017: Income projections for climate change research: A framework based on human capital dynamics. *Global Environmental Change*, **42**, 226–236, doi:10.1016/j.gloenvcha.2015.02.012.

Creutzig, F., 2016: Evolving Narratives of Low-Carbon Futures in Transportation. *Transport Reviews*, **36(3)**, 341–360, doi:10.1080/01441647.2015.1079277.

Creutzig, F. et al., 2012: Reconciling top-down and bottom-up modelling on future bioenergy deployment. *Nature Climate Change*, **2(5)**, 320–327, doi:10.1038/nclimate1416.

Creutzig, F. et al., 2015: Bioenergy and climate change mitigation: an assessment. *GCB Bioenergy*, **7(5)**, 916–944, doi:10.1111/gcbb.12205.

Creutzig, F. et al., 2017: The underestimated potential of solar energy to mitigate climate change. *Nature Energy*, **2(9)**, 17140, doi:10.1038/nenergy.2017.140.

Davis, S.C. et al., 2013: Management swing potential for bioenergy crops. *GCB Bioenergy*, **5(6)**, 623–638, doi:10.1111/gcbb.12042.

Davis, S.J. and K. Caldeira, 2010: Consumption-based accounting of CO_2 emissions. *Proceedings of the National Academy of Sciences*, **107(12)**, 5687–92, doi:10.1073/pnas.0906974107.

de Richter, R., T. Ming, P. Davies, W. Liu, and S. Caillol, 2017: Removal of non-CO_2 greenhouse gases by large-scale atmospheric solar photocatalysis. *Progress in Energy and Combustion Science*, **60**, 68–96, doi:10.1016/j.pecs.2017.01.001.

de Vries, W., M. Posch, D. Simpson, and G.J. Reinds, 2017: Modelling long-term impacts of changes in climate, nitrogen deposition and ozone exposure on carbon sequestration of European forest ecosystems. *Science of The Total Environment*, **605–606**, 1097–1116, doi:10.1016/j.scitotenv.2017.06.132.

Dell, M., B.F. Jones, and B.A. Olken, 2014: What Do We Learn from the Weather? The New Climate–Economy Literature. *Journal of Economic Literature*, **52(3)**, 740–798, www.jstor.org/stable/24434109.

Dellink, R., J. Chateau, E. Lanzi, and B. Magné, 2017: Long-term economic growth projections in the Shared Socioeconomic Pathways. *Global Environmental Change*, **42**, 1–15, doi:10.1016/j.gloenvcha.2015.06.004.

Delponte, I., I. Pittaluga, and C. Schenone, 2017: Monitoring and evaluation of Sustainable Energy Action Plan: Practice and perspective. *Energy Policy*, **100**, 9–17, doi:10.1016/j.enpol.2016.10.003.

den Elzen, M.G.J., D.P. van Vuuren, and J. van Vliet, 2010: Postponing emission reductions from 2020 to 2030 increases climate risks and long-term costs. *Climatic Change*, **99(1)**, 313–320, doi:10.1007/s10584-010-9798-5.

den Elzen, M.G.J. et al., 2016: Contribution of the G20 economies to the global impact of the Paris agreement climate proposals. *Climatic Change*, **137(3–4)**, 655–665, doi:10.1007/s10584-016-1700-7.

Dennig, F., M.B. Budolfson, M. Fleurbaey, A. Siebert, and R.H. Socolow, 2015: Inequality, climate impacts on the future poor, and carbon prices. *Proceedings of the National Academy of Sciences*, **112(52)**, 15827–15832, doi:10.1073/pnas.1513967112.

Di, H.J. and K. Cameron, 2016: Inhibition of nitrification to mitigate nitrate leaching and nitrous oxide emissions in grazed grassland: A review. *Journal of Soils and Sediments*, **16**, 1401–1420, doi:10.1007/s11368-016-1403-8.

Doelman, J.C. et al., 2018: Exploring SSP land-use dynamics using the IMAGE model: Regional and gridded scenarios of land-use change and land-based climate change mitigation. *Global Environmental Change*, **48**, 119–135, doi:10.1016/j.gloenvcha.2017.11.014.

Dooley, J.J., 2013: Estimating the supply and demand for deep geologic CO_2 storage capacity over the course of the 21st century: A meta-analysis of the literature. *Energy Procedia*, **37**, 5141–5150, doi:10.1016/j.egypro.2013.06.429.

Dooley, K. and S. Kartha, 2018: Land-based negative emissions: risks for climate mitigation and impacts on sustainable development. *International Environmental Agreements: Politics, Law and Economics*, **18(1)**, 79–98, doi:10.1007/s10784-017-9382-9.

Duce, R.A. et al., 2008: Impacts of Atmospheric Anthropogenic Nitrogen on the Open Ocean. *Science*, **320(5878)**, 893–897, doi:10.1126/science.1150369.

EC, 2017: *High-Level Expert Group on Sustainable Finance interim report – Financing a sustainable European economy*. European Commission, Brussels, Belgium, 72 pp.

Edenhofer, O., J.C. Steckel, M. Jakob, and C. Bertram, 2018: Reports of coal's terminal decline may be exaggerated. *Environmental Research Letters*, **13(2)**, 024019, doi:10.1088/1748-9326/aaa3a2.

Erb, K.-H., H. Haberl, and C. Plutzar, 2012: Dependency of global primary bioenergy crop potentials in 2050 on food systems, yields, biodiversity conservation and political stability. *Energy Policy*, **47**, 260–269, doi:10.1016/j.enpol.2012.04.066.

Erb, K.-H. et al., 2016a: Biomass turnover time in terrestrial ecosystems halved by land use. *Nature Geoscience*, **9(9)**, 674–678, doi:10.1038/ngeo2782.

Erb, K.-H. et al., 2016b: Exploring the biophysical option space for feeding the world without deforestation. *Nature Communications*, **7**, 11382, doi:10.1038/ncomms11382.

Erb, K.-H. et al., 2018: Unexpectedly large impact of forest management and grazing on global vegetation biomass. *Nature*, **553**, 73–76, doi:10.1038/nature25138.

Erickson, P., S. Kartha, M. Lazarus, and K. Tempest, 2015: Assessing carbon lock-in. *Environmental Research Letters*, **10(8)**, 084023, doi:10.1088/1748-9326/10/8/084023.

Etminan, M., G. Myhre, E.J. Highwood, and K.P. Shine, 2016: Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. *Geophysical Research Letters*, **43(24)**, 12,614–12,623, doi:10.1002/2016gl071930.

Faehn, T. and E. Isaksen, 2016: Diffusion of Climate Technologies in the Presence of Commitment Problems. *The Energy Journal*, **37(2)**, 155–180, doi:10.5547/01956574.37.2.tfae.

Fankhauser, S., A. Sahni, A. Savvas, and J. Ward, 2016: Where are the gaps in climate finance? *Climate and Development*, **8(3)**, 203–206, doi:10.1080/17565529.2015.1064811.

FAOSTAT, 2018: Database Collection of the Food and Agriculture Organization of the United Nations. FAO. Retrieved from: www.fao.org/faostat.

Fawcett, A.A. et al., 2015: Can Paris pledges avert severe climate change? *Science*, **350(6265)**, 1168–1169, doi:10.1126/science.aad5761.

Forster, P.M., 2016: Inference of Climate Sensitivity from Analysis of Earth's Energy Budget. *Annual Review of Earth and Planetary Sciences*, **44(1)**, 85–106, doi:10.1146/annurev-earth-060614-105156.

Frank, S. et al., 2017: Reducing greenhouse gas emissions in agriculture without compromising food security? *Environmental Research Letters*, **12(10)**, 105004, doi:10.1088/1748-9326/aa8c83.

Frank, S. et al., 2018: Structural change as a key component for agricultural non-CO_2 mitigation efforts. *Nature Communications*, **9(1)**, 1060, doi:10.1038/s41467-018-03489-1.

Frankfurt School-UNEP Centre/BNEF, 2017: *Global Trends in Renewable Energy Investment 2017*. Frankfurt School of Finance & Management gGmbH, Frankfurt, Germany, 90 pp.

Fricko, O. et al., 2016: Energy sector water use implications of a 2°C climate policy. *Environmental Research Letters*, **11(3)**, 034011, doi:10.1088/1748-9326/11/3/034011.

Fricko, O. et al., 2017: The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. *Global Environmental Change*, **42**, 251–267, doi:10.1016/j.gloenvcha.2016.06.004.

Friedlingstein, P. et al., 2014a: Persistent growth of CO_2 emissions and implications for reaching climate targets. *Nature Geoscience*, **7(10)**, 709–715, doi:10.1038/ngeo2248.

Friedlingstein, P. et al., 2014b: Uncertainties in CMIP5 climate projections due to carbon cycle feedbacks. *Journal of Climate*, **27(2)**, 511–526, doi:10.1175/jcli-d-12-00579.1.

Frölicher, T.L. and F. Joos, 2010: Reversible and irreversible impacts of greenhouse gas emissions in multi-century projections with the NCAR global coupled carbon cycle-climate model. *Climate Dynamics*, **35(7)**, 1439–1459, doi:10.1007/s00382-009-0727-0.

Fuglestvedt, J.S. et al., 2010: Transport impacts on atmosphere and climate: Metrics. *Atmospheric Environment*, **44(37)**, 4648–4677, doi:10.1016/j.atmosenv.2009.04.044.

Fujimori, S., 2017: SSP3: AIM Implementation of Shared Socioeconomic Pathways. *Global Environmental Change*, **42**, 268–283, doi:10.1016/j.gloenvcha.2016.06.009.

Fujimori, S. et al., 2016: Implication of Paris Agreement in the context of long-term climate mitigation goals. *SpringerPlus*, **5(1)**, 1620, doi:10.1186/s40064-016-3235-9.

Fuss, S. et al., 2014: Betting on negative emissions. *Nature Climate Change*, **4(10)**, 850–853, doi:10.1038/nclimate2392.

Fuss, S. et al., 2016: Research priorities for negative emissions. *Environmental Research Letters*, **11(11)**, 115007, doi:10.1088/1748-9326/11/11/115007.

Fuss, S. et al., 2018: Negative emissions – Part 2: Costs, potentials and side effects. *Environmental Research Letters*, **13(6)**, 063002, doi:10.1088/1748-9326/aabf9f.

Geden, O., 2015: Policy: Climate advisers must maintain integrity. *Nature*, **521(7550)**, 27–28, doi:10.1038/521027a.

Geels, F.W., B.K. Sovacool, T. Schwanen, and S. Sorrell, 2017: Sociotechnical transitions for deep decarbonization. *Science*, **357(6357)**, 1242–1244, doi:10.1126/science.aao3760.

Gerber, P.J. et al., 2013: *Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities*. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, 115 pp.

Gernaat, D.E.H.J. et al., 2015: Understanding the contribution of non-carbon dioxide gases in deep mitigation scenarios. *Global Environmental Change*, **33**, 142–153, doi:10.1016/j.gloenvcha.2015.04.010.

Ghan, S.J. et al., 2013: A simple model of global aerosol indirect effects. *Journal of Geophysical Research: Atmospheres*, **118(12)**, 6688–6707, doi:10.1002/jgrd.50567.

Giannakidis, G., K. Karlsson, M. Labriet, and B. Ó Gallachóir (eds.), 2018: *Limiting Global Warming to Well Below 2°C: Energy System Modelling and Policy Development*. Springer International Publishing, Cham, Switzerland, 423 pp., doi:10.1007/978-3-319-74424-7.

Gillett, N.P., V.K. Arora, D. Matthews, and M.R. Allen, 2013: Constraining the Ratio of Global Warming to Cumulative CO_2 Emissions Using CMIP5 Simulations. *Journal of Climate*, **26(18)**, 6844–6858, doi:10.1175/jcli-d-12-00476.1.

Gillett, N.P., V.K. Arora, K. Zickfeld, S.J. Marshall, and W.J. Merryfield, 2011: Ongoing climate change following a complete cessation of carbon dioxide emissions. *Nature Geoscience*, **4(2)**, 83–87, doi:10.1038/ngeo1047.

Global CCS Institute, 2016: *The Global Status of CCS: 2016 Summary Report*. Global CCS Institute, Melbourne, Australia, 28 pp.

González-Eguino, M., A. Olabe, and T. Ribera, 2017: New Coal-Fired Plants Jeopardise Paris Agreement. *Sustainability*, **9(2)**, 168, doi:10.3390/su9020168.

Goodwin, P., S. Brown, I.D. Haigh, R.J. Nicholls, and J.M. Matter, 2018a: Adjusting Mitigation Pathways to Stabilize Climate at 1.5°C and 2.0°C Rise in Global Temperatures to Year 2300. *Earth's Future*, 0–3, doi:10.1002/2017ef000732.

Goodwin, P. et al., 2018b: Pathways to 1.5 and 2°C warming based on observational and geological constraints. *Nature Geoscience*, **11(1)**, 1–22, doi:10.1038/s41561-017-0054-8.

Gota, S., C. Huizenga, K. Peet, N. Medimorec, and S. Bakker, 2018: Decarbonising transport to achieve Paris Agreement targets. *Energy Efficiency*, 1–24, doi:10.1007/s12053-018-9671-3.

Gough, C. and P. Upham, 2011: Biomass energy with carbon capture and storage (BECCS or Bio-CCS). *Greenhouse Gases: Science and Technology*, **1(4)**, 324–334, doi:10.1002/ghg.34.

Goulder, L. and A. Schein, 2013: Carbon Taxes vs. Cap and Trade: A Critical Review. *Climate Change Economics*, **04(03)**, 1350010, doi:10.1142/s2010007813500103.

Grassi, G. et al., 2017: The key role of forests in meeting climate targets requires science for credible mitigation. *Nature Climate Change*, **7(3)**, 220–226, doi:10.1038/nclimate3227.

Greene, C.H. et al., 2017: Geoengineering, marine microalgae, and climate stabilization in the 21st century. *Earth's Future*, **5(3)**, 278–284, doi:10.1002/2016ef000486.

Gregory, J.M. and T. Andrews, 2016: Variation in climate sensitivity and feedback parameters during the historical period. *Geophysical Research Letters*, **43(8)**, 3911–3920, doi:10.1002/2016gl068406.

Gren, I.-M. and A.Z. Aklilu, 2016: Policy design for forest carbon sequestration: A review of the literature. *Forest Policy and Economics*, **70**, 128–136, doi:10.1016/j.forpol.2016.06.008.

Griscom, B.W. et al., 2017: Natural climate solutions. *Proceedings of the National Academy of Sciences*, **114(44)**, 11645–11650, doi:10.1073/pnas.1710465114.

Grubb, M., J.C. Hourcade, and K. Neuhoff, 2014: *Planetary economics: Energy, climate change and the three domains of sustainable development*. Routledge Earthscan, Abingdon, UK and New York, NY, USA, 520 pp.

Grubler, A. and C. Wilson (eds.), 2014: *Energy Technology Innovation: Learning from Historical Successes and Failures*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 400 pp., doi:10.1017/cbo9781139150880.

Grubler, A. et al., 2018: A low energy demand scenario for meeting the 1.5°C target and sustainable development goals without negative emission technologies. *Nature Energy*, **3(6)**, 515–527, doi:10.1038/s41560-018-0172-6.

Guivarch, C. and J. Rogelj, 2017: *Carbon price variations in 2°C scenarios explored*. Carbon Pricing Leadership Coalition (CPLC), 15 pp.

Güneralp, B. et al., 2017: Global scenarios of urban density and its impacts on building energy use through 2050. *Proceedings of the National Academy of Sciences*, **114(34)**, 8945–8950, doi:10.1073/pnas.1606035114.

Gupta, S. and J. Harnisch, 2014: Cross-cutting Investment and Finance Issues. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1207–1246.

Haberl, H., 2015: Competition for land: A sociometabolic perspective. *Ecological Economics*, **119**, 424–431, doi:10.1016/j.ecolecon.2014.10.002.

Haberl, H. et al., 2011: Global bioenergy potentials from agricultural land in 2050: Sensitivity to climate change, diets and yields. *Biomass and Bioenergy*, **35(12)**, 4753–4769, doi:10.1016/j.biombioe.2011.04.035.

Haberl, H. et al., 2013: Bioenergy: how much can we expect for 2050? *Environmental Research Letters*, **8(3)**, 031004, doi:10.1088/1748-9326/8/3/031004.

Harmes, A., 2011: The Limits of Carbon Disclosure: Theorizing the Business Case for Investor Environmentalism. *Global Environmental Politics*, **11(2)**, 98–119, doi:10.1162/glep_a_00057.

Hartmann, J. et al., 2013: Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification. *Reviews of Geophysics*, **51(2)**, 113–149, doi:10.1002/rog.20004.

Hauglustaine, D.A., Y. Balkanski, and M. Schulz, 2014: A global model simulation of present and future nitrate aerosols and their direct radiative forcing of climate. *Atmospheric Chemistry and Physics*, **14**, 11031–11063, doi:10.5194/acp-14-11031-2014.

Havlik, P. et al., 2013: Crop Productivity and the Global Livestock Sector: Implications for Land Use Change and Greenhouse Gas Emissions. *American Journal of Agricultural Economics*, **95(2)**, 442–448, doi:10.1093/ajae/aas085.

Havlík, P. et al., 2014: Climate change mitigation through livestock system transitions. *Proceedings of the National Academy of Sciences*, **111(10)**, 3709–3714, doi:10.1073/pnas.1308044111.

Heck, V., D. Gerten, W. Lucht, and L.R. Boysen, 2016: Is extensive terrestrial carbon dioxide removal a 'green' form of geoengineering? A global modelling study. *Global and Planetary Change*, **137**, 123–130, doi:10.1016/j.gloplacha.2015.12.008.

Heck, V., D. Gerten, W. Lucht, and A. Popp, 2018: Biomass-based negative emissions difficult to reconcile with planetary boundaries. *Nature Climate Change*, **8(2)**, 151–155, doi:10.1038/s41558-017-0064-y.

Hejazi, M. et al., 2014: Long-term global water projections using six socioeconomic scenarios in an integrated assessment modeling framework. *Technological Forecasting and Social Change*, **81**, 205–226, doi:10.1016/j.techfore.2013.05.006.

Herrero, M. et al., 2016: Greenhouse gas mitigation potentials in the livestock sector. *Nature Climate Change*, **6(5)**, 452–461, doi:10.1038/nclimate2925.

Herrington, T. and K. Zickfeld, 2014: Path independence of climate and carbon cycle response over a broad range of cumulative carbon emissions. *Earth System Dynamics*, **5**, 409–422, doi:10.5194/esd-5-409-2014.

Herzog, H., K. Caldeira, and J. Reilly, 2003: An Issue of Permanence: Assessing the Effectiveness of Temporary Carbon Storage. *Climatic Change*, **59(3)**, 293–310, doi:10.1023/a:1024801618900.

Hildingsson, R. and B. Johansson, 2016: Governing low-carbon energy transitions in sustainable ways: Potential synergies and conflicts between climate and environmental policy objectives. *Energy Policy*, **88**, 245–252, doi:10.1016/j.enpol.2015.10.029.

Hoesly, R.M. et al., 2018: Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS). *Geoscientific Model Development*, **11(1)**, 369–408, doi:10.5194/gmd-11-369-2018.

Hof, A.F. et al., 2017: Global and regional abatement costs of Nationally Determined Contributions (NDCs) and of enhanced action to levels well below 2°C and 1.5°C. *Environmental Science & Policy*, **71**, 30–40, doi:10.1016/j.envsci.2017.02.008.

Höglund-Isaksson, L. et al., 2017: Cost estimates of the Kigali Amendment to phase-down hydrofluorocarbons. *Environmental Science & Policy*, **75**, 138–147, doi:10.1016/j.envsci.2017.05.006.

Holz, C., S. Kartha, and T. Athanasiou, 2018a: Fairly sharing 1.5: national fair shares of a 1.5°C-compliant global mitigation effort. *International Environmental Agreements: Politics, Law and Economics*, **18(1)**, 117–134, doi:10.1007/s10784-017-9371-z.

Holz, C., L.S. Siegel, E. Johnston, A.P. Jones, and J. Sterman, 2018b: Ratcheting ambition to limit warming to 1.5°C – trade-offs between emission reductions and carbon dioxide removal. *Environmental Research Letters*, **13(6)**, 064028, doi:10.1088/1748-9326/aac0c1.

Honegger, M. and D. Reiner, 2018: The political economy of negative emissions technologies: consequences for international policy design. *Climate Policy*, **18(3)**, 306–321, doi:10.1080/14693062.2017.1413322.

Hong, S., C.J.A. Bradshaw, and B.W. Brook, 2015: Global zero-carbon energy pathways using viable mixes of nuclear and renewables. *Applied Energy*, **143**, 451–459, doi:10.1016/j.apenergy.2015.01.006.

Hope, C., 2006: The Marginal Impact of CO_2 from PAGE2002: An Integrated Assessment Model Incorporating the IPCC's Five Reasons for Concern. *The Integrated Assessment Journal*, **6(1)**, 19–56, http://journals.sfu.ca/int_assess/index.php/iaj/article/viewarticle/227.

Hristov, A.N. et al., 2015: An inhibitor persistently decreased enteric methane emission from dairy cows with no negative effect on milk production. *Proceedings of the National Academy of Sciences*, **112(34)**, 10663–8, doi:10.1073/pnas.1504124112.

Hsiang, S. et al., 2017: Estimating economic damage from climate change in the United States. *Science*, **356(6345)**, 1362–1369, doi:10.1126/science.aal4369.

Humpenöder, F. et al., 2014: Investigating afforestation and bioenergy CCS as climate change mitigation strategies. *Environmental Research Letters*, **9(6)**, 064029, doi:10.1088/1748-9326/9/6/064029.

Humpenöder, F. et al., 2018: Large-scale bioenergy production: how to resolve sustainability trade-offs? *Environmental Research Letters*, **13(2)**, 024011, doi:10.1088/1748-9326/aa9e3b.

Huntingford, C. and J. Lowe, 2007: "Overshoot" Scenarios and Climate Change. *Science*, **316(5826)**, 829, doi:10.1126/science.316.5826.829b.

IEA, 2014: *Energy Technology Perspectives 2014: Harnessing Electricity's Potential*. International Energy Agency (IEA), Paris, France, 382 pp.

IEA, 2015a: *Energy and Climate Change. World Energy Outlook Special Report*. International Energy Agency (IEA), Paris, France, 200 pp.

IEA, 2015b: *Energy Technology Perspectives 2015: Mobilising Innovation to Accelerate Climate Action*. International Energy Agency (IEA), Paris, France, 418 pp.

IEA, 2016a: *Energy Technology Perspectives 2016: Towards Sustainable Urban Energy Systems*. International Energy Agency (IEA), Paris, France, 418 pp.

IEA, 2016b: *World Energy Investment 2016*. International Energy Agency (IEA), Paris, France, 177 pp.

IEA, 2017a: *Energy Technology Perspectives 2017: Catalyzing Energy Technology Transformations*. International Energy Agency (IEA), Paris, France, 443 pp.

IEA, 2017b: *Renewables Information – Overview (2017 edition)*. International Energy Agency (IEA), Paris, 11 pp.

IEA, 2017c: *World Energy Investment 2017*. International Energy Agency (IEA), Paris, France, 191 pp.

IEA, 2017d: *World Energy Outlook 2017*. International Energy Agency (IEA), Paris, France, 782 pp.

IEA, 2017e: *World Energy Statistics 2017*. International Energy Agency (IEA). OECD Publishing, Paris, France, 847 pp., doi:10.1787/world_energy_stats-2017-en.

IEAGHG, 2006: *Near zero emission technology for CO_2 capture from power plant*. IEAGHG 2006/13, IEA Greenhouse Gas R&D Programme, Cheltenham, UK, 114 pp.

Ilyina, T., D. Wolf-Gladrow, G. Munhoven, and C. Heinze, 2013: Assessing the potential of calcium-based artificial ocean alkalinization to mitigate rising atmospheric CO_2 and ocean acidification. *Geophysical Research Letters*, **40(22)**, 5909–5914, doi:10.1002/2013gl057981.

IPCC, 2005: IPCC Special Report on Carbon Dioxide Capture and Storage. [Metz, B., O. Davidson, H.C. de Coninck, M. Loos, and L.A. Meyer (eds.)]. Prepared by Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp.

IPCC, 2013a: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC, 2013b: Climate Change 2013: The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC, 2014a: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Core Writing Team, R.K. Pachauri, and L.A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 151 pp.

IPCC, 2014b: Summary for Policymakers. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadne, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1–30.

IPCC/TEAP, 2005: Safeguarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbons and Perfluorocarbons. [Metz, B., L. Kuijpers, S. Solomon, S.O. Andersen, O. Davidson, J. Pons, D. Jager, T. Kestin, M. Manning, and L. Meyer (eds.)]. A Special Report of the Intergovernmental Panel on Climate Change (IPCC) and Technology and Economic Assessment Panel (TEAP). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 485 pp.

Irlam, L., 2017: *Global Costs of Carbon Capture and Storage*. Global CCS Institute, Melbourne, Australia, 14 pp.

IWG, 2016: *Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis - Under Executive Order 12866*. Interagency Working Group on Social Cost of Greenhouse Gases, United States, 35 pp.

Iyer, G.C. et al., 2015: Improved representation of investment decisions in assessments of CO_2 mitigation. *Nature Climate Change*, **5(5)**, 436–440, doi:10.1038/nclimate2553.

Jackson, R.B. et al., 2017: Warning signs for stabilizing global CO_2 emissions. *Environmental Research Letters*, **12(11)**, 110202, doi:10.1088/1748-9326/aa9662.

Jacobson, M.Z., 2002: Control of fossil-fuel particulate black carbon and organic matter, possibly the most effective method of slowing global warming. *Journal of Geophysical Research: Atmospheres*, **107(D19)**, 4410, doi:10.1029/2001jd001376.

Jacobson, M.Z., 2010: Short-term effects of controlling fossil-fuel soot, biofuel soot and gases, and methane on climate, Arctic ice, and air pollution health. *Journal of Geophysical Research: Atmospheres*, **115(D14)**, D14209, doi:10.1029/2009jd013795.

Jacobson, M.Z., 2017: Roadmaps to Transition Countries to 100% Clean, Renewable Energy for All Purposes to Curtail Global Warming, Air Pollution, and Energy Risk. *Earth's Future*, **5(10)**, 948–952, doi:10.1002/2017ef000672.

Jacobson, M.Z. et al., 2017: 100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World. *Joule*, **1(1)**, 108–121, doi:10.1016/j.joule.2017.07.005.

Jakob, M. and J.C. Steckel, 2016: Implications of climate change mitigation for sustainable development. *Environmental Research Letters*, **11(10)**, 104010, doi:10.1088/1748-9326/11/10/104010.

Jakob, M. et al., 2014: Feasible mitigation actions in developing countries. *Nature Climate Change*, **4(11)**, 961–968, doi:10.1038/nclimate2370.

Johnson, N. et al., 2015: Stranded on a low-carbon planet: Implications of climate policy for the phase-out of coal-based power plants. *Technological Forecasting and Social Change*, **90**, 89–102, doi:10.1016/j.techfore.2014.02.028.

Jones, A., J.M. Haywood, and C.D. Jones, 2018: Can reducing black carbon and methane below RCP2.6 levels keep global warming below 1.5°C? *Atmospheric Science Letters*, **19(6)**, e821, doi:10.1002/asl.821.

Jones, C.D. et al., 2016: Simulating the Earth system response to negative emissions. *Environmental Research Letters*, **11(9)**, 095012, doi:10.1088/1748-9326/11/9/095012.

Jones, D.G. et al., 2015: Developments since 2005 in understanding potential environmental impacts of CO_2 leakage from geological storage. *International Journal of Greenhouse Gas Control*, **40**, 350–377, doi:10.1016/j.ijggc.2015.05.032.

Joshi, V. and S. Kumar, 2015: Meat Analogues: Plant based alternatives to meat products – A review. *International Journal of Food Fermentation and Technology*, **5(2)**, 107–119, doi:10.5958/2277-9396.2016.00001.5.

Kandlikar, M., 1995: The relative role of trace gas emissions in greenhouse abatement policies. *Energy Policy*, **23(10)**, 879–883, doi:10.1016/0301-4215(95)00108-u.

KC, S. and W. Lutz, 2017: The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Global Environmental Change*, **42**, 181–192, doi:10.1016/j.gloenvcha.2014.06.004.

Kearns, J. et al., 2017: Developing a consistent database for regional geologic CO_2 storage capacity worldwide. *Energy Procedia*, **114**, 4697–4709, doi:10.1016/j.egypro.2017.03.1603.

Keith, D.W. and J.S. Rhodes, 2002: Bury, Burn or Both: A Two-for-One Deal on Biomass Carbon and Energy. *Climatic Change*, **54(3)**, 375–377, doi:10.1023/a:1016187420442.

Keith, D.W., M. Ha-Duong, and J.K. Stolaroff, 2006: Climate Strategy with CO_2 Capture from the Air. *Climatic Change*, **74(1–3)**, 17–45, doi:10.1007/s10584-005-9026-x.

Kheshgi, H.S., 1995: Sequestering atmospheric carbon dioxide by increasing ocean alkalinity. *Energy*, **20(9)**, 915–922, doi:10.1016/0360-5442(95)00035-f.

Kim, S.H., K. Wada, A. Kurosawa, and M. Roberts, 2014: Nuclear energy response in the EMF27 study. *Climatic Change*, **123(3–4)**, 443–460, doi:10.1007/s10584-014-1098-z.

Klein, D. et al., 2014: The value of bioenergy in low stabilization scenarios: An assessment using REMIND-MAgPIE. *Climatic Change*, **123(3–4)**, 705–718, doi:10.1007/s10584-013-0940-z.

Klimont, Z. et al., 2017: Global anthropogenic emissions of particulate matter including black carbon. *Atmospheric Chemistry and Physics*, **17(14)**, 8681–8723, doi:10.5194/acp-17-8681-2017.

Klinsky, S. and H. Winkler, 2018: Building equity in: strategies for integrating equity into modelling for a 1.5°C world. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376(2119)**, 20160461, doi:10.1098/rsta.2016.0461.

Knutti, R. and J. Rogelj, 2015: The legacy of our CO_2 emissions: a clash of scientific facts, politics and ethics. *Climatic Change*, **133(3)**, 361–373, doi:10.1007/s10584-015-1340-3.

Knutti, R., M.A.A. Rugenstein, and G.C. Hegerl, 2017: Beyond equilibrium climate sensitivity. *Nature Geoscience*, **10(10)**, 727–736, doi:10.1038/ngeo3017.

Kolstad, C. et al., 2014: Social, Economic and Ethical Concepts and Methods. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadne, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 207–282.

Krasting, J.P., J.P. Dunne, E. Shevliakova, and R.J. Stouffer, 2014: Trajectory sensitivity of the transient climate response to cumulative carbon emissions. *Geophysical Research Letters*, **41(7)**, 2520–2527, doi:10.1002/(issn)1944-8007.

Krause, A. et al., 2017: Global consequences of afforestation and bioenergy cultivation on ecosystem service indicators. *Biogeosciences*, **14(21)**, 4829–4850, doi:10.5194/bg-14-4829-2017.

Kraxner, F. et al., 2013: Global bioenergy scenarios – Future forest development, land-use implications, and trade-offs. *Biomass and Bioenergy*, **57**, 86–96, doi:10.1016/j.biombioe.2013.02.003.

Kreidenweis, U. et al., 2016: Afforestation to mitigate climate change: impacts on food prices under consideration of albedo effects. *Environmental Research Letters*, **11(8)**, 085001, doi:10.1088/1748-9326/11/8/085001.

Kretzschmar, J. et al., 2017: Comment on "Rethinking the Lower Bound on Aerosol Radiative Forcing". *Journal of Climate*, **30(16)**, 6579–6584, doi:10.1175/jcli-d-16-0668.1.

Krey, V., G. Luderer, L. Clarke, and E. Kriegler, 2014a: Getting from here to there – energy technology transformation pathways in the EMF27 scenarios. *Climatic Change*, **123**, 369–382, doi:10.1007/s10584-013-0947-5.

Krey, V. et al., 2014b: Annex II: Metrics & Methodology. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1281–1328.

Kriegler, E., O. Edenhofer, L. Reuster, G. Luderer, and D. Klein, 2013a: Is atmospheric carbon dioxide removal a game changer for climate change mitigation? *Climatic Change*, **118(1)**, 45–57, doi:10.1007/s10584-012-0681-4.

Kriegler, E. et al., 2012: The need for and use of socio-economic scenarios for climate change analysis: A new approach based on shared socio-economic pathways. *Global Environmental Change*, **22(4)**, 807–822, doi:10.1016/j.gloenvcha.2012.05.005.

Kriegler, E. et al., 2013b: What Does the 2°C Target Imply for a Global Climate Agreement in 2020? The Limits Study on Durban Platform Scenarios. *Climate Change Economics*, **4(4)**, 1340008, doi:10.1142/s2010007813400083.

Kriegler, E. et al., 2014a: A new scenario framework for climate change research: the concept of shared climate policy assumptions. *Climatic Change*, **122(3)**, 401–414, doi:10.1007/s10584-013-0971-5.

Kriegler, E. et al., 2014b: The role of technology for achieving climate policy objectives: Overview of the EMF 27 study on global technology and climate policy strategies. *Climatic Change*, **123(3–4)**, 353–367, doi:10.1007/s10584-013-0953-7.

Kriegler, E. et al., 2015a: Diagnostic indicators for integrated assessment models of climate policy. *Technological Forecasting and Social Change*, **90(Part A)**, 45–61, doi:10.1016/j.techfore.2013.09.020.

Kriegler, E. et al., 2015b: Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. *Technological Forecasting and Social Change*, **90(Part A)**, 24–44, doi:10.1016/j.techfore.2013.09.021.

Kriegler, E. et al., 2016: Will economic growth and fossil fuel scarcity help or hinder climate stabilization?: Overview of the RoSE multi-model study. *Climatic Change*, **136(1)**, 7–22, doi:10.1007/s10584-016-1668-3.

Kriegler, E. et al., 2017: Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century. *Global Environmental Change*, **42**, 297–315, doi:10.1016/j.gloenvcha.2016.05.015.

Kriegler, E. et al., 2018a: Short term policies to keep the door open for Paris climate goals. *Environmental Research Letters*, **13(7)**, 074022, doi:10.1088/1748-9326/aac4f1.

Kriegler, E. et al., 2018b: Pathways limiting warming to 1.5°C: a tale of turning around in no time? *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376(2119)**, 20160457, doi:10.1098/rsta.2016.0457.

Kuramochi, T. et al., 2017: Ten key short-term sectoral benchmarks to limit warming to 1.5°C. *Climate Policy*, **18(3)**, 1–19, doi:10.1080/14693062.2017.1397495.

Lamarque, J.-F. et al., 2011: Global and regional evolution of short-lived radiatively-active gases and aerosols in the Representative Concentration Pathways. *Climatic Change*, **109(1–2)**, 191–212, doi:10.1007/s10584-011-0155-0.

Lambin, E.F. and P. Meyfroidt, 2011: Global land use change, economic globalization, and the looming land scarcity. *Proceedings of the National Academy of Sciences*, **108(9)**, 3465–72, doi:10.1073/pnas.1100480108.

Le Quéré, C. et al., 2018: Global Carbon Budget 2017. *Earth System Science Data*, **10(1)**, 405–448, doi:10.5194/essd-10-405-2018.

Lehtilä, A. and T. Koljonen, 2018: Pathways to Post-fossil Economy in a Well Below 2°C World. In: *Limiting Global Warming to Well Below 2°C: Energy System Modelling and Policy Development* [Giannakidis, G., K. Karlsson, M. Labriet, and B. Gallachóir (eds.)]. Springer International Publishing, Cham, Switzerland, pp. 33–49, doi:10.1007/978-3-319-74424-7_3.

Leimbach, M., E. Kriegler, N. Roming, and J. Schwanitz, 2017: Future growth patterns of world regions – A GDP scenario approach. *Global Environmental Change*, **42**, 215–225, doi:10.1016/j.gloenvcha.2015.02.005.

Lemoine, D. and C. Traeger, 2014: Watch Your Step: Optimal Policy in a Tipping Climate. *American Economic Journal: Economic Policy*, **6(1)**, 137–166, doi:10.1257/pol.6.1.137.

Lenton, A., R.J. Matear, D.P. Keller, V. Scott, and N.E. Vaughan, 2018: Assessing carbon dioxide removal through global and regional ocean alkalinization under high and low emission pathways. *Earth System Dynamics*, **9(2)**, 339–357, doi:10.5194/esd-9-339-2018.

Lewis, N. and J.A. Curry, 2015: The implications for climate sensitivity of AR5 forcing and heat uptake estimates. *Climate Dynamics*, **45(3–4)**, 1009–1023, doi:10.1007/s00382-014-2342-y.

Lewis, N. and J. Curry, 2018: The impact of recent forcing and ocean heat uptake data on estimates of climate sensitivity. *Journal of Climate*, JCLI–D–17–0667.1, doi:10.1175/jcli-d-17-0667.1.

Liu, J., T.W. Hertel, F. Taheripour, T. Zhu, and C. Ringler, 2014: International trade buffers the impact of future irrigation shortfalls. *Global Environmental Change*, **29**, 22–31, doi:10.1016/j.gloenvcha.2014.07.010.

Liu, J.-Y. et al., 2018: Socioeconomic factors and future challenges of the goal of limiting the increase in global average temperature to 1.5°C. *Carbon Management*, 1–11, doi:10.1080/17583004.2018.1477374.

Löffler, K. et al., 2017: Designing a Model for the Global Energy System– GENeSYS – MOD: An Application of the Open-Source Energy Modeling System (OSeMOSYS). *Energies*, **10(10)**, 1468, doi:10.3390/en10101468.

Lontzek, T.S., Y. Cai, K.L. Judd, and T.M. Lenton, 2015: Stochastic integrated assessment of climate tipping points indicates the need for strict climate policy. *Nature Climate Change*, **5(5)**, 441–444, doi:10.1038/nclimate2570.

Lowe, J.A. and D. Bernie, 2018: The impact of Earth system feedbacks on carbon budgets and climate response. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376(2119)**, 20170263, doi:10.1098/rsta.2017.0263.

Lowe, J.A. et al., 2009: How difficult is it to recover from dangerous levels of global warming? *Environmental Research Letters*, **4(1)**, 014012, doi:10.1088/1748-9326/4/1/014012.

Lucon, O. et al., 2014: Buildings. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 671–738.

Luderer, G., C. Bertram, K. Calvin, E. De Cian, and E. Kriegler, 2016a: Implications of weak near-term climate policies on long-term mitigation pathways. *Climatic Change*, **136(1)**, 127–140, doi:10.1007/s10584-013-0899-9.

Luderer, G. et al., 2013: Economic mitigation challenges: how further delay closes the door for achieving climate targets. *Environmental Research Letters*, **8(3)**, 034033, doi:10.1088/1748-9326/8/3/034033.

Luderer, G. et al., 2014: The role of renewable energy in climate stabilization: results from the {EMF}27 scenarios. *Climatic Change*, **123(3–4)**, 427–441, doi:10.1007/s10584-013-0924-z.

Luderer, G. et al., 2016b: *Deep Decarbonisation towards 1.5°C – 2°C stabilization: Policy findings from the ADVANCE project*. The ADVANCE Consortium, 42 pp.

Luderer, G. et al., 2017: Assessment of wind and solar power in global low-carbon energy scenarios: An introduction. *Energy Economics*, **64**, 542–551, doi:10.1016/j.eneco.2017.03.027.

Luderer, G. et al., 2018: Residual fossil CO_2 emissions in 1.5–2°C pathways. *Nature Climate Change*, **8(7)**, 626–633, doi:10.1038/s41558-018-0198-6.

Lutz, W. and S. KC, 2011: Global Human Capital: Integrating Education and Population. *Science*, **333(6042)**, 587–592, doi:10.1126/science.1206964.

MacDougall, A.H., N.C. Swart, and R. Knutti, 2017: The Uncertainty in the Transient Climate Response to Cumulative CO 2 Emissions Arising from the Uncertainty in Physical Climate Parameters. *Journal of Climate*, **30(2)**, 813–827, doi:10.1175/jcli-d-16-0205.1.

MacDougall, A.H., K. Zickfeld, R. Knutti, and H.D. Matthews, 2015: Sensitivity of carbon budgets to permafrost carbon feedbacks and non-CO_2 forcings. *Environmental Research Letters*, **10(12)**, 125003, doi:10.1088/1748-9326/10/12/125003.

Madeira, M.S. et al., 2017: Microalgae as feed ingredients for livestock production and meat quality: A review. *Livestock Science*, **205**, 111–121, doi:10.1016/j.livsci.2017.09.020.

Mahowald, N.M. et al., 2017: Aerosol Deposition Impacts on Land and Ocean Carbon Cycles. *Current Climate Change Reports*, **3(1)**, 16–31, doi:10.1007/s40641-017-0056-z.

Malavelle, F.F. et al., 2017: Strong constraints on aerosol–cloud interactions from volcanic eruptions. *Nature*, **546(7659)**, 485–491, doi:10.1038/nature22974.

Marangoni, G. and M. Tavoni, 2014: The Clean Energy R&D Strategy for 2°C. *Climate Change Economics*, **5(1)**, 1440003, doi:10.1142/s201000781440003x.

Marangoni, G. et al., 2017: Sensitivity of projected long-term CO_2 emissions across the Shared Socioeconomic Pathways. *Nature Climate Change*, **7(1)**, 113–119, doi:10.1038/nclimate3199.

Marcucci, A., S. Kypreos, and E. Panos, 2017: The road to achieving the long-term Paris targets: Energy transition and the role of direct air capture. *Climatic Change*, **144(2)**, 181–193, doi:10.1007/s10584-017-2051-8.

Marten, A.L., E.A. Kopits, C.W. Griffiths, S.C. Newbold, and A. Wolverton, 2015: Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates. *Climate Policy*, **15(2)**, 272–298, doi:10.1080/14693062.2014.912981.

Marvel, K., G.A. Schmidt, R.L. Miller, and L.S. Nazarenko, 2016: Implications for climate sensitivity from the response to individual forcings. *Nature Climate Change*, **6(4)**, 386–389, doi:10.1038/nclimate2888.

Masui, T. et al., 2011: An emission pathway for stabilization at 6 W m^{-2} radiative forcing. *Climatic Change*, **109(1)**, 59–76, doi:10.1007/s10584-011-0150-5.

Matter, J.M. et al., 2016: Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions. *Science*, **352(6291)**, 1312–1314, doi:10.1126/science.aad8132.

Matthews, H.D. and K. Caldeira, 2008: Stabilizing climate requires near-zero emissions. *Geophysical Research Letters*, **35(4)**, 1–5, doi:10.1029/2007gl032388.

Matthews, H.D. and K. Zickfeld, 2012: Climate response to zeroed emissions of greenhouse gases and aerosols. *Nature Climate Change*, **2(5)**, 338–341, doi:10.1038/nclimate1424.

Matthews, H.D., N.P. Gillett, P.A. Stott, and K. Zickfeld, 2009: The proportionality of global warming to cumulative carbon emissions. *Nature*, **459(7248)**, 829–832, doi:10.1038/nature08047.

Matthews, H.D. et al., 2017: Estimating Carbon Budgets for Ambitious Climate Targets. *Current Climate Change Reports*, **3**, 69–77, doi:10.1007/s40641-017-0055-0.

Mazzotti, M. et al., 2005: Mineral carbonation and industrial uses of carbon dioxide. In: *IPCC Special Report on Carbon Dioxide Capture and Storage* [Metz, B., O. Davidson, H.C. de Coninck, M. Loos, and L.A. Meyer (eds.)]. Prepared by Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 319–338.

McCollum, D.L., V. Krey, and K. Riahi, 2011: An integrated approach to energy sustainability. *Nature Climate Change*, **1(9)**, 428–429, doi:10.1038/nclimate1297.

McCollum, D.L. et al., 2013: Energy Investments under Climate Policy: A Comparison of Global Models. *Climate Change Economics*, **4(4)**, 1340010, doi:10.1142/s2010007813400101.

McCollum, D.L. et al., 2017: Improving the behavioral realism of global integrated assessment models: An application to consumers' vehicle choices. *Transportation Research Part D: Transport and Environment*, **55**, 322–342, doi:10.1016/j.trd.2016.04.003.

McCollum, D.L. et al., 2018: Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. *Nature Energy*, **3(7)**, 589–599, doi:10.1038/s41560-018-0179-z.

McFarland, J.R., A.A. Fawcett, A.C. Morris, J.M. Reilly, and P.J. Wilcoxen, 2018: Overview of the EMF 32 Study on U.S. Carbon Tax Scenarios. *Climate Change Economics*, **9(1)**, 1840002, doi:10.1142/s201000781840002x.

McLeod, E. et al., 2011: A blueprint for blue carbon: Toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. *Frontiers in Ecology and the Environment*, **9(10)**, 552–560, doi:10.1890/110004.

Mehling, M. and E. Tvinnereim, 2018: Carbon Pricing and the 1.5°C Target: Near-Term Decarbonisation and the Importance of an Instrument Mix. *Carbon & Climate Law Review*, **12(1)**, 50–61, doi:10.21552/cclr/2018/1/9.

Meinshausen, M., S.C.B. Raper, and T.M.L. Wigley, 2011a: Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 1: Model description and calibration. *Atmospheric Chemistry and Physics*, **11(4)**, 1417–1456, doi:10.5194/acp-11-1417-2011.

Meinshausen, M. et al., 2009: Greenhouse-gas emission targets for limiting global warming to 2°C. *Nature*, **458(7242)**, 1158–1162, doi:10.1038/nature08017.

Meinshausen, M. et al., 2011b: The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic Change*, **109(1–2)**, 213–241, doi:10.1007/s10584-011-0156-z.

Méjean, A., C. Guivarch, J. Lefèvre, and M. Hamdi-Cherif, 2018: The transition in energy demand sectors to limit global warming to 1.5°C. *Energy Efficiency*, 1–22, doi:10.1007/s12053-018-9682-0.

Mengis, N., A.- Partanen, J. Jalbert, and H.D. Matthews, 2018: 1.5°C carbon budget dependent on carbon cycle uncertainty and future non-CO_2 forcing. *Scientific Reports*, **8(1)**, 5831, doi:10.1038/s41598-018-24241-1.

Michaelowa, A., M. Allen, and F. Sha, 2018: Policy instruments for limiting global temperature rise to 1.5°C – can humanity rise to the challenge? *Climate Policy*, **18(3)**, 275–286, doi:10.1080/14693062.2018.1426977.

Millar, R.J. and P. Friedlingstein, 2018: The utility of the historical record for assessing the transient climate response to cumulative emissions. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376(2119)**, 20160449, doi:10.1098/rsta.2016.0449.

Millar, R.J. et al., 2017: Emission budgets and pathways consistent with limiting warming to 1.5°C. *Nature Geoscience*, **10(10)**, 741–747, doi:10.1038/ngeo3031.

Minx, J.C., W.F. Lamb, M.W. Callaghan, L. Bornmann, and S. Fuss, 2017: Fast growing research on negative emissions. *Environmental Research Letters*, **12(3)**, 035007, doi:10.1088/1748-9326/aa5ee5.

Minx, J.C. et al., 2018: Negative emissions-Part 1: Research landscape and synthesis. *Environmental Research Letters*, **13(6)**, 063001, doi:10.1088/1748-9326/aabf9b.

Moore, F.C. and D.B. Diaz, 2015: Temperature impacts on economic growth warrant stringent mitigation policy. *Nature Climate Change*, **5(1)**, 127–132, doi:10.1038/nclimate2481.

Mouratiadou, I. et al., 2016: The impact of climate change mitigation on water demand for energy and food: An integrated analysis based on the Shared Socioeconomic Pathways. *Environmental Science & Policy*, **64**, 48–58, doi:10.1016/j.envsci.2016.06.007.

Muller, A. et al., 2017: Strategies for feeding the world more sustainably with organic agriculture. *Nature Communications*, **8(1)**, 1290, doi:10.1038/s41467-017-01410-w.

Mundaca, L. and A. Markandya, 2016: Assessing regional progress towards a Green Energy Economy. *Applied Energy*, **179**, 1372–1394, doi:10.1016/j.apenergy.2015.10.098.

Mundaca, L., M. Mansoz, L. Neij, and G. Timilsina, 2013: Transaction costs analysis of low-carbon technologies. *Climate Policy*, **13(4)**, 490–513, doi:10.1080/14693062.2013.781452.

Mundaca, L., L. Neij, A. Markandya, P. Hennicke, and J. Yan, 2016: Towards a Green Energy Economy? Assessing policy choices, strategies and transitional pathways. *Applied Energy*, **179**, 1283–1292, doi:10.1016/j.apenergy.2016.08.086.

Myhre, G. et al., 2013: Anthropogenic and Natural Radiative Forcing. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 659–740.

Myhre, G. et al., 2017: Multi-model simulations of aerosol and ozone radiative forcing due to anthropogenic emission changes during the period 1990-2015. *Atmospheric Chemistry and Physics*, **17(4)**, 2709–2720, doi:10.5194/acp-17-2709-2017.

Narayan, C., P.M. Fernandes, J. van Brusselen, and A. Schuck, 2007: Potential for CO_2 emissions mitigation in Europe through prescribed burning in the context of the Kyoto Protocol. *Forest Ecology and Management*, **251(3)**, 164–173, doi:10.1016/j.foreco.2007.06.042.

NASEM, 2016: *Assessment of Approaches to Updating the Social Cost of Carbon: Phase 1 Report on a Near-Term Update*. National Academies of Sciences, Engineering, and Medicine (NASEM). The National Academies Press, Washington DC, USA, 72 pp., doi:10.17226/21898.

NASEM, 2017: *Valuing Climate Damages: Updating estimation of the social costs of carbon dioxide*. National Academies of Sciences, Engineering, and Medicine (NASEM), The National Academies Press, Washington DC, USA, 262 pp., doi:10.17226/24651.

Naudts, K. et al., 2016: Europe's forest management did not mitigate climate warming. *Science*, **351(6273)**, 597–600, doi:10.1126/science.aad7270.

Nelson, G.C. et al., 2014: Climate change effects on agriculture: economic responses to biophysical shocks. *Proceedings of the National Academy of Sciences*, **111(9)**, 3274–9, doi:10.1073/pnas.1222465110.

Nemet, G.F. et al., 2018: Negative emissions – Part 3: Innovation and upscaling. *Environmental Research Letters*, **13(6)**, 063003, doi:10.1088/1748-9326/aabff4.

NETL, 2013: *Cost and performance of PC and IGCC plants for a range of carbon dioxide capture: Revision 1*. DOE/NETL-2011/1498, U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL), 500 pp.

NETL, 2015: *Carbon Storage Atlas – Fifth Edition (Atlas V)*. U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL), 114 pp.

Nicol, A. et al., 2013: Induced seismicity; observations, risks and mitigation measures at CO_2 storage sites. *Energy Procedia*, **37**, 4749–4756, doi:10.1016/j.egypro.2013.06.384.

Nohara, D. et al., 2015: Examination of a climate stabilization pathway via zero-emissions using Earth system models. *Environmental Research Letters*, **10(9)**, 095005, doi:10.1088/1748-9326/10/9/095005.

Nordhaus, W.D., 2007a: A Review of The Stern Review on the Economics of Climate Change. *Journal of Economic Literature*, **45(3)**, 686–702, www.jstor.org/stable/27646843.

Nordhaus, W.D., 2007b: To Tax or Not to Tax: Alternative Approaches to Slowing Global Warming. *Review of Environmental Economics and Policy*, **1(1)**, 26–44, doi:10.1093/reep/rem008.

Nordhaus, W.D., 2013: *The Climate Casino: Risk, Uncertainty, and Economics for a Warming World*. Yale University Press, New Haven, CT, USA, 392 pp.

Nordhaus, W.D., 2014: Estimates of the Social Cost of Carbon: Concepts and Results from the DICE-2013R Model and Alternative Approaches. *Journal of the Association of Environmental and Resource Economists*, **1(1–2)**, 273–312, doi:10.1086/676035.

Nordhaus, W.D., 2017: Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences*, **114(7)**, 1518–1523, doi:10.1073/pnas.1609244114.

Nordhaus, W.D. and J. Boyer, 2000: *Warming the World: Economic Models of Global Warming*. MIT Press, Cambridge, MA, USA and London, UK, 244 pp.

NRC, 2015: *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration*. National Research Council (NRC). The National Academies Press, Washington DC, USA, 140 pp., doi:10.17226/18805.

O'Neill, B.C. et al., 2014: A new scenario framework for climate change research: The concept of shared socioeconomic pathways. *Climatic Change*, **122(3)**, 387–400, doi:10.1007/s10584-013-0905-2.

O'Neill, B.C. et al., 2017: The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change*, **42**, 169–180, doi:10.1016/j.gloenvcha.2015.01.004.

Obersteiner, M. et al., 2001: Managing Climate Risk. *Science*, **294(5543)**, 786–787, doi:10.1126/science.294.5543.786b.

Obersteiner, M. et al., 2016: Assessing the land resource–food price nexus of the Sustainable Development Goals. *Science Advances*, **2(9)**, e1501499, doi:10.1126/sciadv.1501499.

Obersteiner, M. et al., 2018: How to spend a dwindling greenhouse gas budget. *Nature Climate Change*, **8(1)**, 7–10, doi:10.1038/s41558-017-0045-1.

OECD, 2017: *Investing in Climate, Investing in Growth*. OECD Publishing, Paris, France, 314 pp., doi:10.1787/9789264273528-en.

OECD/IEA and IRENA, 2017: *Perspectives for the Energy Transition: Investment Needs for a Low-Carbon Energy System*. OECD/IEA and IRENA, 204 pp.

Ogawa, T., S. Nakanishi, T. Shidahara, T. Okumura, and E. Hayashi, 2011: Saline-aquifer CO_2 sequestration in Japan-methodology of storage capacity assessment. *International Journal of Greenhouse Gas Control*, **5(2)**, 318–326, doi:10.1016/j.ijggc.2010.09.009.

Painter, T.H. et al., 2013: End of the Little Ice Age in the Alps forced by industrial black carbon. *Proceedings of the National Academy of Sciences*, **110(38)**, 15216–21, doi:10.1073/pnas.1302570110.

Patt, A., 2017: Beyond the tragedy of the commons: Reframing effective climate change governance. *Energy Research & Social Science*, **34**, 1–3, doi:10.1016/j.erss.2017.05.023.

Patterson, J.J. et al., 2018: Political feasibility of 1.5°C societal transformations: the role of social justice. *Current Opinion in Environmental Sustainability*, **31**, 1–9, doi:10.1016/j.cosust.2017.11.002.

Paustian, K. et al., 2016: Climate-smart soils. *Nature*, **532(7597)**, 49–57, doi:10.1038/nature17174.

Pawar, R.J. et al., 2015: Recent advances in risk assessment and risk management of geologic CO_2 storage. *International Journal of Greenhouse Gas Control*, **40**, 292–311, doi:10.1016/j.ijggc.2015.06.014.

Pehl, M. et al., 2017: Understanding future emissions from low-carbon power systems by integration of life-cycle assessment and integrated energy modelling. *Nature Energy*, **2(12)**, 939–945, doi:10.1038/s41560-017-0032-9.

Peters, G.P., 2016: The 'best available science' to inform 1.5°C policy choices. *Nature Climate Change*, **6(7)**, 646–649, doi:10.1038/nclimate3000.

Pietzcker, R.C. et al., 2017: System integration of wind and solar power in integrated assessment models: A cross-model evaluation of new approaches. *Energy Economics*, **64**, 583–599, doi:10.1016/j.eneco.2016.11.018.

Pikaar, I. et al., 2018: Decoupling Livestock from Land Use through Industrial Feed Production Pathways. *Environmental Science & Technology*, **52(13)**, 7351–7359, doi:10.1021/acs.est.8b00216.

Pindyck, R.S., 2013: Climate Change Policy: What Do the Models Tell Us? *Journal of Economic Literature*, **51(3)**, 1–23, doi:10.1257/jel.51.3.860.

Pizer, W. et al., 2014: Using and improving the social cost of carbon. *Science*, **346(6214)**, 1189–1190, doi:10.1126/science.1259774.

Popp, A., H. Lotze-Campen, and B. Bodirsky, 2010: Food consumption, diet shifts and associated non-CO_2 greenhouse gases from agricultural production. *Global Environmental Change*, **20(3)**, 451–462, doi:10.1016/j.gloenvcha.2010.02.001.

Popp, A. et al., 2014a: Land-use protection for climate change mitigation. *Nature Climate Change*, **4(12)**, 1095–1098, doi:10.1038/nclimate2444.

Popp, A. et al., 2014b: Land-use transition for bioenergy and climate stabilization: Model comparison of drivers, impacts and interactions with other land use based mitigation options. *Climatic Change*, **123(3–4)**, 495–509, doi:10.1007/s10584-013-0926-x.

Popp, A. et al., 2017: Land-use futures in the shared socio-economic pathways. *Global Environmental Change*, **42**, 331–345, doi:10.1016/j.gloenvcha.2016.10.002.

Post, M.J., 2012: Cultured meat from stem cells: Challenges and prospects. *Meat Science*, **92(3)**, 297–301, doi:10.1016/j.meatsci.2012.04.008.

Prestele, R. et al., 2016: Hotspots of uncertainty in land-use and land-cover change projections: a global-scale model comparison. *Global Change Biology*, **22(12)**, 3967–3983, doi:10.1111/gcb.13337.

Proistosescu, C. and P.J. Huybers, 2017: Slow climate mode reconciles historical and model-based estimates of climate sensitivity. *Science Advances*, **3(7)**, e1602821, doi:10.1126/sciadv.1602821.

Psarras, P. et al., 2017: Slicing the pie: how big could carbon dioxide removal be? *Wiley Interdisciplinary Reviews: Energy and Environment*, **6(5)**, e253, doi:10.1002/wene.253.

Purohit, P. and L. Höglund-Isaksson, 2017: Global emissions of fluorinated greenhouse gases 2005–2050 with abatement potentials and costs. *Atmospheric Chemistry and Physics*, **17(4)**, 2795–2816, doi:10.5194/acp-17-2795-2017.

Rao, S. et al., 2016: A multi-model assessment of the co-benefits of climate mitigation for global air quality. *Environmental Research Letters*, **11(12)**, 124013, doi:10.1088/1748-9326/11/12/124013.

Rao, S. et al., 2017: Future air pollution in the Shared Socio-economic Pathways. *Global Environmental Change*, **42**, 346–358, doi:10.1016/j.gloenvcha.2016.05.012.

Rau, G.H., 2011: CO_2 Mitigation via Capture and Chemical Conversion in Seawater. *Environmental Science & Technology*, **45(3)**, 1088–1092, doi:10.1021/es102671x.

Revesz, R. et al., 2014: Global warming: Improve economic models of climate change. *Nature*, **508(7495)**, 173–175, doi:10.1038/508173a.

Riahi, K. et al., 2011: RCP 8.5 – A scenario of comparatively high greenhouse gas emissions. *Climatic Change*, **109(1)**, 33, doi:10.1007/s10584-011-0149-y.

Riahi, K. et al., 2012: Energy Pathways for Sustainable Development. In: *Global Energy Assessment – Toward a Sustainable Future*. Cambridge, United Kingdom and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 1203–1306, doi:10.1017/cbo9780511793677.023.

Riahi, K. et al., 2015: Locked into Copenhagen pledges – Implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technological Forecasting and Social Change*, **90(Part A)**, 8–23, doi:10.1016/j.techfore.2013.09.016.

Riahi, K. et al., 2017: The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, **42**, 153–168, doi:10.1016/j.gloenvcha.2016.05.009.

Ricke, K.L., R.J. Millar, and D.G. MacMartin, 2017: Constraints on global temperature target overshoot. *Scientific Reports*, **7(1)**, 1–7, doi:10.1038/s41598-017-14503-9.

Riis, F. and E. Halland, 2014: CO_2 storage atlas of the Norwegian Continental shelf: Methods used to evaluate capacity and maturity of the CO_2 storage potential. *Energy Procedia*, **63**, 5258–5265, doi:10.1016/j.egypro.2014.11.557.

Rockström, J. et al., 2017: A roadmap for rapid decarbonization. *Science*, **355(6331)**, 1269–1271, doi:10.1126/science.aah3443.

Roelfsema, M., M. Harmsen, J.J.G. Olivier, A.F. Hof, and D.P. van Vuuren, 2018: Integrated assessment of international climate mitigation commitments outside the UNFCCC. *Global Environmental Change*, **48**, 67–75, doi:10.1016/j.gloenvcha.2017.11.001.

Rogelj, J., D.L. McCollum, B.C. O'Neill, and K. Riahi, 2013a: 2020 emissions levels required to limit warming to below 2 C. *Nature Climate Change*, **3(4)**, 405–412, doi:10.1038/nclimate1758.

Rogelj, J., M. Meinshausen, J. Sedláček, and R. Knutti, 2014a: Implications of potentially lower climate sensitivity on climate projections and policy. *Environmental Research Letters*, **9(3)**, 031003, doi:10.1088/1748-9326/9/3/031003.

Rogelj, J., D.L. McCollum, A. Reisinger, M. Meinshausen, and K. Riahi, 2013b: Probabilistic cost estimates for climate change mitigation. *Nature*, **493(7430)**, 79–83, doi:10.1038/nature11787.

Rogelj, J., M. Meinshausen, M. Schaeffer, R. Knutti, and K. Riahi, 2015a: Impact of short-lived non-CO_2 mitigation on carbon budgets for stabilizing global warming. *Environmental Research Letters*, **10(7)**, 075001, doi:10.1088/1748-9326/10/7/075001.

Rogelj, J. et al., 2011: Emission pathways consistent with a 2°C global temperature limit. *Nature Climate Change*, **1(8)**, 413–418, doi:10.1038/nclimate1258.

Rogelj, J. et al., 2014b: Disentangling the effects of CO_2 and short-lived climate forcer mitigation. *Proceedings of the National Academy of Sciences*, **111(46)**, 16325–16330, doi:10.1073/pnas.1415631111.

Rogelj, J. et al., 2015b: Energy system transformations for limiting end-of-century warming to below 1.5°C. *Nature Climate Change*, **5(6)**, 519–527, doi:10.1038/nclimate2572.

Rogelj, J. et al., 2015c: Mitigation choices impact carbon budget size compatible with low temperature goals. *Environmental Research Letters*, **10(7)**, 075003, doi:10.1088/1748-9326/10/7/075003.

Rogelj, J. et al., 2015d: Zero emission targets as long-term global goals for climate protection. *Environmental Research Letters*, **10(10)**, 105007, doi:10.1088/1748-9326/10/10/105007.

Rogelj, J. et al., 2016a: Paris Agreement climate proposals need a boost to keep warming well below 2°C. *Nature*, **534(7609)**, 631–639, doi:10.1038/nature18307.

Rogelj, J. et al., 2016b: Differences between carbon budget estimates unravelled. *Nature Climate Change*, **6(3)**, 245–252, doi:10.1038/nclimate2868.

Rogelj, J. et al., 2017: Understanding the origin of Paris Agreement emission uncertainties. *Nature Communications*, **8**, 15748, doi:10.1038/ncomms15748.

Rogelj, J. et al., 2018: Scenarios towards limiting global mean temperature increase below 1.5°C. *Nature Climate Change*, **8(4)**, 325–332, doi:10.1038/s41558-018-0091-3.

Rose, S.K., 2012: The role of the social cost of carbon in policy. *Wiley Interdisciplinary Reviews: Climate Change*, **3(2)**, 195–212, doi:10.1002/wcc.163.

Rose, S.K., D.B. Diza, and G.J. Blanford, 2017a: Understanding the Social Cost of Carbon: A Model diagnostic and Inter-comparison Study. *Climate Change Economics*, **8(2)**, 1750009, doi:10.1142/s2010007817500099.

Rose, S.K., R. Richels, G. Blanford, and T. Rutherford, 2017b: The Paris Agreement and next steps in limiting global warming. *Climatic Change*, **142(1–2)**, 1–16, doi:10.1007/s10584-017-1935-y.

Rose, S.K. et al., 2014a: Bioenergy in energy transformation and climate management. *Climatic Change*, **123(3–4)**, 477–493, doi:10.1007/s10584-013-0965-3.

Rose, S.K. et al., 2014b: Non-Kyoto radiative forcing in long-run greenhouse gas emissions and climate change scenarios. *Climatic Change*, **123(3–4)**, 511–525, doi:10.1007/s10584-013-0955-5.

Rugenstein, M.A.A. et al., 2016: Multiannual Ocean-Atmosphere Adjustments to Radiative Forcing. *Journal of Climate*, **29(15)**, 5643–5659, doi:10.1175/jcli-d-16-0312.1.

Samset, B.H. et al., 2016: Fast and slow precipitation responses to individual climate forcers: A PDRMIP multimodel study. *Geophysical Research Letters*, **43(6)**, 2782–2791, doi:10.1002/2016gl068064.

Samset, B.H. et al., 2018: Climate impacts from a removal of anthropogenic aerosol emissions. *Geophysical Research Letters*, **45(2)**, 1020–1029, doi:10.1002/2017gl076079.

Sand, M. et al., 2015: Response of Arctic temperature to changes in emissions of short-lived climate forcers. *Nature Climate Change*, **6(3)**, 286–289, doi:10.1038/nclimate2880.

Sanderson, B.M., B.C. O'Neill, and C. Tebaldi, 2016: What would it take to achieve the Paris temperature targets? *Geophysical Research Letters*, **43(13)**, 7133–7142, doi:10.1002/2016gl069563.

Sands, R.D., 2018: U.S. Carbon Tax Scenarios and Bioenergy. *Climate Change Economics*, **9(1)**, 1840010, doi:10.1142/s2010007818400109.

Sarofim, M.C., S.T. Waldhoff, and S.C. Anenberg, 2017: Valuing the Ozone-Related Health Benefits of Methane Emission Controls. *Environmental and Resource Economics*, **66(1)**, 45–63, doi:10.1007/s10640-015-9937-6.

Saunders, H.D., 2015: Recent Evidence for Large Rebound: Elucidating the Drivers and their Implications for Climate Change Models. *The Energy Journal*, **36(1)**, 23–48, doi:10.5547/01956574.36.1.2.

Schädel, C. et al., 2014: Circumpolar assessment of permafrost C quality and its vulnerability over time using long-term incubation data. *Global Change Biology*, **20(2)**, 641–652, doi:10.1111/gcb.12417.

Schädel, C. et al., 2016: Potential carbon emissions dominated by carbon dioxide from thawed permafrost soils. *Nature Climate Change*, **6(10)**, 950–953, doi:10.1038/nclimate3054.

Schleussner, C.-F. et al., 2016: Science and policy characteristics of the Paris Agreement temperature goal. *Nature Climate Change*, **6(7)**, 827–835, doi:10.1038/nclimate3096.

Schmidt, M.G.W., H. Held, E. Kriegler, and A. Lorenz, 2013: Climate Policy Under Uncertain and Heterogeneous Climate Damages. *Environmental and Resource Economics*, **54(1)**, 79–99, doi:10.1007/s10640-012-9582-2.

Schmitz, C. et al., 2012: Trading more food: Implications for land use, greenhouse gas emissions, and the food system. *Global Environmental Change*, **22(1)**, 189–209, doi:10.1016/j.gloenvcha.2011.09.013.

Schneider, T. et al., 2017: Climate goals and computing the future of clouds. *Nature Climate Change*, **7(1)**, 3–5, doi:10.1038/nclimate3190.

Schneider von Deimling, T. et al., 2012: Estimating the near-surface permafrost-carbon feedback on global warming. *Biogeosciences*, **9(2)**, 649–665, doi:10.5194/bg-9-649-2012.

Schneider von Deimling, T. et al., 2015: Observation-based modelling of permafrost carbon fluxes with accounting for deep carbon deposits and thermokarst activity. *Biogeosciences*, **12(11)**, 3469–3488, doi:10.5194/bg-12-3469-2015.

Schuiling, R.D. and P. Krijgsman, 2006: Enhanced Weathering: An Effective and Cheap Tool to Sequester CO_2. *Climatic Change*, **74(1–3)**, 349–354, doi:10.1007/s10584-005-3485-y.

Schurer, A.P. et al., 2018: Interpretations of the Paris climate target. *Nature Geoscience*, **11(4)**, 220–221, doi:10.1038/s41561-018-0086-8.

Schuur, E.A.G. et al., 2015: Climate change and the permafrost carbon feedback. *Nature*, **520(7546)**, 171–179, doi:10.1038/nature14338.

Scott, C.E. et al., 2018: Substantial large-scale feedbacks between natural aerosols and climate. *Nature Geoscience*, **11(1)**, 44–48, doi:10.1038/s41561-017-0020-5.

Scott, V., R.S. Haszeldine, S.F.B. Tett, and A. Oschlies, 2015: Fossil fuels in a trillion tonne world. *Nature Climate Change*, **5(5)**, 419–423, doi:10.1038/nclimate2578.

Searle, S.Y. and C.J. Malins, 2014: Will energy crop yields meet expectations? *Biomass and Bioenergy*, **65**, 3–12, doi:10.1016/j.biombioe.2014.01.001.

Séférian, R., M. Rocher, C. Guivarch, and J. Colin, 2018: Constraints on biomass energy deployment in mitigation pathways: the case of water limitation. *Environmental Research Letters*, 1–32, doi:10.1088/1748-9326/aabcd7.

Seto, K.C. et al., 2016: Carbon Lock-In: Types, Causes, and Policy Implications. *Annual Review of Environment and Resources*, **41(1)**, 425–452, doi:10.1146/annurev-environ-110615-085934.

Shah, N., M. Wei, V. Letschert, and A. Phadke, 2015: *Benefits of Leapfrogging to Superefficiency and Low Global Warming Potential Refrigerants in Room Air Conditioning*. LBNL-1003671, Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA, USA, 58 pp.

Shearer, C., N. Mathew-Shah, L. Myllyvirta, A. Yu, and T. Nace, 2018: *Boom and Bust 2018: Tracking the Global Coal Plant Pipeline*. CoalSwarm, Greenpeace USA, and Sierra Club, 16 pp.

Shell International B.V., 2018: *Shell Scenarios: Sky – Meeting the Goals of the Paris Agreement*. Shell International B.V. 36 pp.

Sherwood, S.C., S. Bony, and J.-L. Dufresne, 2014: Spread in model climate sensitivity traced to atmospheric convective mixing. *Nature*, **505(7481)**, 37–42, doi:10.1038/nature12829.

Shindell, D.T., 2015: The social cost of atmospheric release. *Climatic Change*, **130(2)**, 313–326, doi:10.1007/s10584-015-1343-0.

Shindell, D.T. and G. Faluvegi, 2010: The net climate impact of coal-fired power plant emissions. *Atmospheric Chemistry and Physics*, **10(7)**, 3247–3260, doi:10.5194/acp-10-3247-2010.

Shindell, D.T., Y. Lee, and G. Faluvegi, 2016: Climate and health impacts of US emissions reductions consistent with 2°C. *Nature Climate Change*, **6(5)**, 503–507, doi:10.1038/nclimate2935.

Shindell, D.T., J.S. Fuglestvedt, and W.J. Collins, 2017a: The social cost of methane: theory and applications. *Faraday Discussions*, **200**, 429–451, doi:10.1039/c7fd00009j.

Shindell, D.T., G. Faluvegi, L. Rotstayn, and G. Milly, 2015: Spatial patterns of radiative forcing and surface temperature response. *Journal of Geophysical Research: Atmospheres*, **120(11)**, 5385–5403, doi:10.1002/2014jd022752.

Shindell, D.T., G. Faluvegi, K. Seltzer, and C. Shindell, 2018: Quantified, localized health benefits of accelerated carbon dioxide emissions reductions. *Nature Climate Change*, **8(4)**, 291–295, doi:10.1038/s41558-018-0108-y.

Shindell, D.T. et al., 2012: Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security. *Science*, **335(6065)**, 183–189, doi:10.1126/science.1210026.

Shindell, D.T. et al., 2017b: A climate policy pathway for near- and long-term benefits. *Science*, **356(6337)**, 493–494, doi:10.1126/science.aak9521.

Shukla, P.R. and V. Chaturvedi, 2012: Low carbon and clean energy scenarios for India: Analysis of targets approach. *Energy Economics*, **34(sup3)**, S487–S495, doi:10.1016/j.eneco.2012.05.002.

Siegmeier, J. et al., 2018: The fiscal benefits of stringent climate change mitigation: an overview. *Climate Policy*, **18(3)**, 352–367, doi:10.1080/14693062.2017.1400943.

Silva, R.A. et al., 2016: The effect of future ambient air pollution on human premature mortality to 2100 using output from the ACCMIP model ensemble. *Atmospheric Chemistry and Physics*, **16(15)**, 9847–9862, doi:10.5194/acp-16-9847-2016.

Sims, R. et al., 2014: Transport. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadne, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 599–670.

Smith, C.J. et al., 2018: FAIR v1.3: a simple emissions-based impulse response and carbon cycle model. *Geoscientific Model Development*, **11(6)**, 2273–2297, doi:10.5194/gmd-11-2273-2018.

Smith, L.J. and M.S. Torn, 2013: Ecological limits to terrestrial biological carbon dioxide removal. *Climatic Change*, **118(1)**, 89–103, doi:10.1007/s10584-012-0682-3.

Smith, P., 2016: Soil carbon sequestration and biochar as negative emission technologies. *Global Change Biology*, **22(3)**, 1315–1324, doi:10.1111/gcb.13178.

Smith, P. and M. Bustamante, 2014: Agriculture, Forestry and Other Land Use (AFOLU). In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 811–922.

Smith, P. et al., 2013: How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? *Global Change Biology*, **19(8)**, 2285–2302, doi:10.1111/gcb.12160.

Smith, P. et al., 2015: Biophysical and economic limits to negative CO_2 emissions. *Nature Climate Change*, **6(1)**, 42–50, doi:10.1038/nclimate2870.

Snopkowski, K., M.C. Towner, M.K. Shenk, and H. Colleran, 2016: Pathways from education to fertility decline: a multi-site comparative study. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **371(1692)**, 20150156, doi:10.1098/rstb.2015.0156.

Socolow, R. et al., 2011: *Direct Air Capture of CO_2 with Chemicals: A Technology Assessment for the APS Panel on Public Affairs*. American Physical Society (APS), College Park, MD, USA, 100 pp.

Somanthan, E. et al., 2014: National and Sub-national Policies and Institutions. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1141–1206.

Sonnenschein, J., R. Van Buskirk, J.L. Richter, and C. Dalhammar, 2018: Minimum energy performance standards for the 1.5°C target: an effective complement to carbon pricing. *Energy Efficiency*, 1–16, doi:10.1007/s12053-018-9669-x.

Spencer, T., R. Pierfederici, H. Waisman, and M. Colombier, 2015: *Beyond the Numbers. Understanding the Transformation Induced by INDCs*. Study N°05/15, MILES Project Consortium, Paris, France, 80 pp.

Springmann, M., H.C.J. Godfray, M. Rayner, and P. Scarborough, 2016: Analysis and valuation of the health and climate change cobenefits of dietary change. *Proceedings of the National Academy of Sciences*, **113(15)**, 4146–4151, doi:10.1073/pnas.1523119113.

Steckel, J.C., O. Edenhofer, and M. Jakob, 2015: Drivers for the renaissance of coal. *Proceedings of the National Academy of Sciences*, **112(29)**, E3775–E3781, doi:10.1073/pnas.1422722112.

Stehfest, E. et al., 2009: Climate benefits of changing diet. *Climatic Change*, **95(1–2)**, 83–102, doi:10.1007/s10584-008-9534-6.

Stern, N., 2007: *The Economics of Climate Change: The Stern Review*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 692 pp., doi:10.1017/cbo9780511817434.

Stern, N., 2013: The Structure of Economic Modeling of the Potential Impacts of Climate Change: Grafting Gross Underestimation of Risk onto Already Narrow Science Models. *Journal of Economic Literature*, **51(3)**, 838–859, doi:10.1257/jel.51.3.838.

Stern, N., 2016: Current climate models are grossly misleading. *Nature*, **530**, 407–409, doi:10.1038/530407a.

Stevanović, M. et al., 2017: Mitigation Strategies for Greenhouse Gas Emissions from Agriculture and Land-Use Change: Consequences for Food Prices. *Environmental Science & Technology*, **51(1)**, 365–374, doi:10.1021/acs.est.6b04291.

Stiglitz, J.E. et al., 2017: *Report of the High-Level Commission on Carbon Prices*. Carbon Pricing Leadership Coalition (CPLC), 68 pp.

Stocker, T.F. et al., 2013: Technical Summary. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 33–115.

Stohl, A. et al., 2015: Evaluating the climate and air quality impacts of short-lived pollutants. *Atmospheric Chemistry and Physics*, **15(18)**, 10529–10566, doi:10.5194/acp-15-10529-2015.

Strapasson, A. et al., 2017: On the global limits of bioenergy and land use for climate change mitigation. *GCB Bioenergy*, **9(12)**, 1721–1735, doi:10.1111/gcbb.12456.

Strefler, J., T. Amann, N. Bauer, E. Kriegler, and J. Hartmann, 2018a: Potential and costs of carbon dioxide removal by enhanced weathering of rocks. *Environmental Research Letters*, **13(3)**, 034010, doi:10.1088/1748-9326/aaa9c4.

Strefler, J. et al., 2018b: Between Scylla and Charybdis: Delayed mitigation narrows the passage between large-scale CDR and high costs. *Environmental Research Letters*, **13(4)**, 044015, doi:10.1088/1748-9326/aab2ba.

Su, X. et al., 2017: Emission pathways to achieve 2.0°C and 1.5°C climate targets. *Earth's Future*, **5(6)**, 592–604, doi:10.1002/2016ef000492.

Subbarao, G. et al., 2013: Potential for biological nitrification inhibition to reduce nitrification and N_2O emissions in pasture crop–livestock systems. *Animal*, **7(s2)**, 322–332, doi:10.1017/s1751731113000761.

Subharat, S. et al., 2016: Vaccination of Sheep with a Methanogen Protein Provides Insight into Levels of Antibody in Saliva Needed to Target Ruminal Methanogens. *PLOS ONE*, **11(7)**, e0159861, doi:10.1371/journal.pone.0159861.

Szulczewski, M.L., C.W. MacMinn, and R. Juanes, 2014: Theoretical analysis of how pressure buildup and CO_2 migration can both constrain storage capacity in deep saline aquifers. *International Journal of Greenhouse Gas Control*, **23**, 113–118, doi:10.1016/j.ijggc.2014.02.006.

Tachiiri, K., T. Hajima, and M. Kawamiya, 2015: Increase of uncertainty in transient climate response to cumulative carbon emissions after stabilization of atmospheric CO_2 concentration. *Environmental Research Letters*, **10(12)**, 125018, doi:10.1088/1748-9326/10/12/125018.

2

Tan, I., T. Storelvmo, and M.D. Zelinka, 2016: Observational constraints on mixed-phase clouds imply higher climate sensitivity. *Science*, **352(6282)**, 224–227, doi:10.1126/science.aad5300.

Tavoni, M. and R.S.J. Tol, 2010: Counting only the hits? The risk of underestimating the costs of stringent climate policy. *Climatic Change*, **100(3–4)**, 769–778, doi:10.1007/s10584-010-9867-9.

The Royal Society, 2009: *Geoengineering the climate: science, governance and uncertainty*. RS Policy document 10/09, The Royal Society, London, UK, 82 pp.

Thomson, A.M. et al., 2011: RCP4.5: a pathway for stabilization of radiative forcing by 2100. *Climatic Change*, **109(1–2)**, 77–94, doi:10.1007/s10584-011-0151-4.

Tilman, D. and M. Clark, 2014: Global diets link environmental sustainability and human health. *Nature*, **515(7528)**, 518–522, doi:10.1038/nature13959.

Tokarska, K.B. and N.P. Gillett, 2018: Cumulative carbon emissions budgets consistent with 1.5°C global warming. *Nature Climate Change*, **8(4)**, 296–299, doi:10.1038/s41558-018-0118-9.

Tokarska, K.B., N.P. Gillett, V.K. Arora, W.G. Lee, and K. Zickfeld, 2018: The influence of non-CO_2 forcings on cumulative carbon emissions budgets. *Environmental Research Letters*, **13(3)**, 034039, doi:10.1088/1748-9326/aaafdd.

Tol, R.S.J., 1999: Spatial and Temporal Efficiency in Climate Policy: Applications of FUND. *Environmental and Resource Economics*, **14(1)**, 33–49, doi:10.1023/a:1008314205375.

Tol, R.S.J., 2017: The structure of the climate debate. *Energy Policy*, **104**, 431–438, doi:10.1016/j.enpol.2017.01.005.

Tuomisto, H.L. and M.J. Teixeira de Mattos, 2011: Environmental Impacts of Cultured Meat Production. *Environmental Science & Technology*, **45(14)**, 6117–6123, doi:10.1021/es200130u.

UNEP, 2015: *Aligning the Financial System with Sustainable Development: Pathways to Scale*. Inquiry: Design of a Sustainable Financial System and United Nations Environment Programme (UNEP), Geneva, Switzerland, 25 pp.

UNEP, 2016: *The Emissions Gap Report 2016: A UNEP Synthesis Report*. United Nations Environment Programme (UNEP), Nairobi, Kenya, 85 pp.

UNEP, 2017: *The Emissions Gap Report 2017: A UN Environment Synthesis Report*. United Nations Environment Programme (UNEP), Nairobi, Kenya, 116 pp.

UNFCCC, 2016: *Aggregate effect of the intended nationally determined contributions: an update*. FCCC/CP/2016/2, The Secretariat of the United Nations Framework Convention on Climate Change (UNFCCC), Bonn, Germany, 75 pp.

Unruh, G.C. and J. Carrillo-Hermosilla, 2006: Globalizing carbon lock-in. *Energy Policy*, **34(10)**, 1185–1197, doi:10.1016/j.enpol.2004.10.013.

Unruh, J.D., 2011: Tree-Based Carbon Storage in Developing Countries: Neglect of the Social Sciences. *Society & Natural Resources*, **24(2)**, 185–192, doi:10.1080/08941920903410136.

US EPA, 2013: *Global Mitigation of Non-CO_2 Greenhouse Gases: 2010–2030. Report No. EPA-430-R-13-011*. United States Environmental Protection Agency (US EPA), Washington DC, USA, 410 pp.

Valin, H. et al., 2013: Agricultural productivity and greenhouse gas emissions: trade-offs or synergies between mitigation and food security? *Environmental Research Letters*, **8(3)**, 035019, doi:10.1088/1748-9326/8/3/035019.

van den Bergh, J.C.J.M., 2017: Rebound policy in the Paris Agreement: instrument comparison and climate-club revenue offsets. *Climate Policy*, **17(6)**, 801–813, doi:10.1080/14693062.2016.1169499.

van Sluisveld, M.A.E., S.H. Martínez, V. Daioglou, and D.P. van Vuuren, 2016: Exploring the implications of lifestyle change in 2°C mitigation scenarios using the IMAGE integrated assessment model. *Technological Forecasting and Social Change*, **102**, 309–319, doi:10.1016/j.techfore.2015.08.013.

van Soest, H.L. et al., 2017: Low-emission pathways in 11 major economies: comparison of cost-optimal pathways and Paris climate proposals. *Climatic Change*, **142(3–4)**, 491–504, doi:10.1007/s10584-017-1964-6.

van Vuuren, D.P. and K. Riahi, 2011: The relationship between short-term emissions and long-term concentration targets. *Climatic Change*, **104(3)**, 793–801, doi:10.1007/s10584-010-0004-6.

van Vuuren, D.P., A.F. Hof, M.A.E. van Sluisveld, and K. Riahi, 2017a: Open discussion of negative emissions is urgently needed. *Nature Energy*, **2(12)**, 902–904, doi:10.1038/s41560-017-0055-2.

van Vuuren, D.P. et al., 2007: Stabilizing greenhouse gas concentrations at low levels: An assessment of reduction strategies and costs. *Climatic Change*, **81(2)**, 119–159, doi:10.1007/s10584-006-9172-9.

van Vuuren, D.P. et al., 2011a: The representative concentration pathways: An overview. *Climatic Change*, **109(1)**, 5–31, doi:10.1007/s10584-011-0148-z.

van Vuuren, D.P. et al., 2011b: RCP2.6: Exploring the possibility to keep global mean temperature increase below 2°C. *Climatic Change*, **109(1)**, 95–116, doi:10.1007/s10584-011-0152-3.

van Vuuren, D.P. et al., 2015: Pathways to achieve a set of ambitious global sustainability objectives by 2050: Explorations using the IMAGE integrated assessment model. *Technological Forecasting and Social Change*, **98**, 303–323, doi:10.1016/j.techfore.2015.03.005.

van Vuuren, D.P. et al., 2016: Carbon budgets and energy transition pathways. *Environmental Research Letters*, **11(7)**, 075002, doi:10.1088/1748-9326/11/7/075002.

van Vuuren, D.P. et al., 2017b: Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. *Global Environmental Change*, **42**, 237–250, doi:10.1016/j.gloenvcha.2016.05.008.

van Vuuren, D.P. et al., 2018: Alternative pathways to the 1.5°C target reduce the need for negative emission technologies. *Nature Climate Change*, **8(5)**, 391–397, doi:10.1038/s41558-018-0119-8.

Vangkilde-Pedersen, T. et al., 2009: Assessing European capacity for geological storage of carbon dioxide-the EU GeoCapacity project. *Energy Procedia*, **1(1)**, 2663–2670, doi:10.1016/j.egypro.2009.02.034.

Veland, S. et al., 2018: Narrative matters for sustainability: the transformative role of storytelling in realizing 1.5°C futures. *Current Opinion in Environmental Sustainability*, **31**, 41–47, doi:10.1016/j.cosust.2017.12.005.

Velders, G.J.M., D.W. Fahey, J.S. Daniel, S.O. Andersen, and M. McFarland, 2015: Future atmospheric abundances and climate forcings from scenarios of global and regional hydrofluorocarbon (HFC) emissions. *Atmospheric Environment*, **123**, 200–209, doi:10.1016/j.atmosenv.2015.10.071.

Vogt-Schilb, A. and S. Hallegatte, 2017: Climate policies and nationally determined contributions: reconciling the needed ambition with the political economy. *Wiley Interdisciplinary Reviews: Energy and Environment*, **6(6)**, 1–23, doi:10.1002/wene.256.

Voigt, C. et al., 2017a: Warming of subarctic tundra increases emissions of all three important greenhouse gases – carbon dioxide, methane, and nitrous oxide. *Global Change Biology*, **23(8)**, 3121–3138, doi:10.1111/gcb.13563.

Voigt, C. et al., 2017b: Increased nitrous oxide emissions from Arctic peatlands after permafrost thaw. *Proceedings of the National Academy of Sciences*, **114(24)**, 6238–6243, doi:10.1073/pnas.1702902114.

von Stechow, C. et al., 2015: Integrating Global Climate Change Mitigation Goals with Other Sustainability Objectives: A Synthesis. *Annual Review of Environment and Resources*, **40(1)**, 363–394, doi:10.1146/annurev-environ-021113-095626.

von Stechow, C. et al., 2016: 2°C and SDGs: united they stand, divided they fall? *Environmental Research Letters*, **11(3)**, 034022, doi:10.1088/1748-9326/11/3/034022.

Vrontisi, Z. et al., 2018: Enhancing global climate policy ambition towards a 1.5°C stabilization: a short-term multi-model assessment. *Environmental Research Letters*, **13(4)**, 044039, doi:10.1088/1748-9326/aab53e.

Wachsmuth, J. and V. Duscha, 2018: Achievability of the Paris targets in the EU-the role of demand-side-driven mitigation in different types of scenarios. *Energy Efficiency*, 1–19, doi:10.1007/s12053-018-9670-4.

Walsh, M.J. et al., 2016: Algal food and fuel coproduction can mitigate greenhouse gas emissions while improving land and water-use efficiency. *Environmental Research Letters*, **11(11)**, 114006, doi:10.1088/1748-9326/11/11/114006.

Wang, X. et al., 2016: Taking account of governance: Implications for land-use dynamics, food prices, and trade patterns. *Ecological Economics*, **122**, 12–24, doi:10.1016/j.ecolecon.2015.11.018.

Warwick, P.D., M.K. Verma, P.A. Freeman, M.D. Corum, and S.H. Hickman, 2014: U.S. geological survey carbon sequestration – geologic research and assessments. *Energy Procedia*, **63**, 5305–5309, doi:10.1016/j.egypro.2014.11.561.

Wedlock, D.N., P.H. Janssen, S.C. Leahy, D. Shu, and B.M. Buddle, 2013: Progress in the development of vaccines against rumen methanogens. *Animal*, **7(s2)**, 244–252, doi:10.1017/s1751731113000682.

Wei, N. et al., 2013: A preliminary sub-basin scale evaluation framework of site suitability for onshore aquifer-based CO_2 storage in China. *International Journal of Greenhouse Gas Control*, **12**, 231–246, doi:10.1016/j.ijggc.2012.10.012.

Weindl, I. et al., 2015: Livestock in a changing climate: production system transitions as an adaptation strategy for agriculture. *Environmental Research Letters*, **10(9)**, 094021, doi:10.1088/1748-9326/10/9/094021.

Weindl, I. et al., 2017: Livestock and human use of land: Productivity trends and dietary choices as drivers of future land and carbon dynamics. *Global and Planetary Change*, **159**, 1–10, doi:10.1016/j.gloplacha.2017.10.002.

Weitzman, M.L., 2014: Can Negotiating a Uniform Carbon Price Help to Internalize the Global Warming Externality? *Journal of the Association of Environmental and Resource Economists*, **1(1/2)**, 29–49, doi:10.1086/676039.

Werner, C., H.-P. Schmidt, D. Gerten, W. Lucht, and C. Kammann, 2018: Biogeochemical potential of biomass pyrolysis systems for limiting global warming to 1.5°C. *Environmental Research Letters*, **13(4)**, 044036, doi:10.1088/1748-9326/aabb0e.

West, J.J. et al., 2013: Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health. *Nature Climate Change*, **3(10)**, 885–889, doi:10.1038/nclimate2009.

Weyant, J., 2017: Some Contributions of Integrated Assessment Models of Global Climate Change. *Review of Environmental Economics and Policy*, **11(1)**, 115–137, doi:10.1093/reep/rew018.

Weyant, J.P., F.C. Chesnaye, and G.J. Blanford, 2006: Overview of EMF-21: Multigas Mitigation and Climate Policy. *The Energy Journal*, **27**, 1–32, doi:10.5547/issn0195-6574-ej-volsi2006-nosi3-1.

Wiebe, K. et al., 2015: Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios. *Environmental Research Letters*, **10(8)**, 085010, doi:10.1088/1748-9326/10/8/085010.

Wigley, T.M.L., R. Richels, and J. Edmonds, 2007: Overshoot Pathways to CO_2 stabilization in a multi-gas context. In: *Human Induced Climate Change: An Interdisciplinary Perspective* [Schlesinger, M.E., H.S. Kheshgi, J. Smith, F.C. de la Chesnaye, J.M. Reilly, T. Wilson, and C. Kolstad (eds.)]. Cambridge University Press, Cambridge, pp. 84–92, doi:10.1017/cbo9780511619472.009.

Williams, P.J. and L.M.L. Laurens, 2010: Microalgae as biodiesel & biomass feedstocks: Review & analysis of the biochemistry, energetics & economics. *Energy & Environmental Science*, **3(5)**, 554–590, doi:10.1039/b924978h.

Williamson, P., 2016: Emissions reduction: Scrutinize CO_2 removal methods. *Nature*, **530(153)**, 153–155, doi:10.1038/530153a.

Williamson, P. and R. Bodle, 2016: *Update on Climate Geoengineering in Relation to the Convention on Biological Diversity: Potential Impacts and Regulatory Framework*. CBD Technical Series No. 84, Secretariat of the Convention on Biological Diversity, Montreal, QC, Canada, 158 pp.

Wise, M., K. Calvin, P. Kyle, P. Luckow, and J. Edmonds, 2014: Economic and physical modeling of land use in GCAM 3.0 and an application to agricultural productivity, land, and terrestrial carbon. *Climate Change Economics*, **5(2)**, 1450003, doi:10.1142/s2010007814500031.

Woolf, D., J.E. Amonette, F.A. Street-Perrott, J. Lehmann, and S. Joseph, 2010: Sustainable biochar to mitigate global climate change. *Nature Communications*, **1(5)**, 1–9, doi:10.1038/ncomms1053.

Xiao, X.-J. and K. Jiang, 2018: China's nuclear power under the global 1.5°C target: Preliminary feasibility study and prospects. *Advances in Climate Change Research*, **9(2)**, 138–143, doi:10.1016/j.accre.2018.05.002.

Xu, Y. and V. Ramanathan, 2017: Well below 2°C: Mitigation strategies for avoiding dangerous to catastrophic climate changes. *Proceedings of the National Academy of Sciences*, **114(39)**, 10315–10323, doi:10.1073/pnas.1618481114.

Yeh, S. et al., 2016: Detailed assessment of global transport-energy models' structures and projections. *Transportation Research Part D: Transport and Environment*, **55**, 294–309, doi:10.1016/j.trd.2016.11.001.

Zeman, F.S. and K. Lackner, 2004: Capturing Carbon Dioxide directly from the Atmosphere. *World Resource Review*, **16(2)**, 157–172.

Zeman, F.S. and D.W. Keith, 2008: Carbon Neutral Hydrocarbons. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **366(1882)**, 3901–3918, doi:10.1098/rsta.2008.0143.

Zhai, C., J.H. Jiang, and H. Su, 2015: Long-term cloud change imprinted in seasonal cloud variation: More evidence of high climate sensitivity. *Geophysical Research Letters*, **42(20)**, 8729–8737, doi:10.1002/2015gl065911.

Zhang, R., S. Fujimori, and T. Hanaoka, 2018: The contribution of transport policies to the mitigation potential and cost of 2°C and 1.5°C goals. *Environmental Research Letters*, **13(5)**, 054008, doi:10.1088/1748-9326/aabb0d.

Zickfeld, K. and T. Herrington, 2015: The time lag between a carbon dioxide emission and maximum warming increases with the size of the emission. *Environmental Research Letters*, **10(3)**, 031001, doi:10.1088/1748-9326/10/3/031001.

Zickfeld, K., A.H. MacDougall, and H.D. Matthews, 2016: On the proportionality between global temperature change and cumulative CO_2 emissions during periods of net negative CO_2 emissions. *Environmental Research Letters*, **11(5)**, 055006, doi:10.1088/1748-9326/11/5/055006.

Zickfeld, K., M. Eby, H.D. Matthews, and A.J. Weaver, 2009: Setting cumulative emissions targets to reduce the risk of dangerous climate change. *Proceedings of the National Academy of Sciences*, **106(38)**, 16129–16134, doi:10.1073/pnas.0805800106.

Zomer, R.J., D.A. Bossio, R. Sommer, and L.V. Verchot, 2017: Global Sequestration Potential of Increased Organic Carbon in Cropland Soils. *Scientific Reports*, **7(1)**, 15554, doi:10.1038/s41598-017-15794-8.

Zomer, R.J. et al., 2016: Global Tree Cover and Biomass Carbon on Agricultural Land: The contribution of agroforestry to global and national carbon budgets. *Scientific Reports*, **6**, 29987, doi:10.1038/srep29987.

2SM

Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development

Supplementary Material

Authors:
Piers Forster (UK), Daniel Huppmann (Austria), Elmar Kriegler (Germany), Luis Mundaca (Sweden/Chile), Chris Smith (UK), Joeri Rogelj (Austria/Belgium), Roland Séférian (France)

This chapter supplementary material should be cited as:
Forster, P., D. Huppmann, E. Kriegler, L. Mundaca, C. Smith, J. Rogelj, and R. Séférian, 2018: Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development Supplementary Material. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. Available from https://www.ipcc.ch/sr15

Table of Contents

2.SM.1 Part 1

2.SM.1.1 Geophysical Relationships and Constraints

2.SM.1.1.1 Reduced-complexity climate models

The 'Model for the Assessment of Greenhouse Gas Induced Climate Change' (MAGICC6, Meinshausen et al., 2011a), is a reduced-complexity carbon cycle, atmospheric composition and climate model that has been widely used in prior IPCC Assessments and policy literature. This model is used with its parameter set as identical to that employed in AR5 for backwards compatibility. This model has been shown to match temperature trends very well compared to CMIP5 models (Collins et al., 2013; Clarke et al., 2014).

The 'Finite Amplitude Impulse Response' (FAIRv1.3, Smith et al., 2018) model is similar to MAGICC but has even simpler representations of the carbon cycle and some atmospheric chemistry. Its parameter sets are based on AR5 physics with updated methane radiative forcing (Etminan et al., 2016). The FAIR model is a reasonable fit to CMIP5 models for lower emissions pathways but underestimates the temperature response compared to CMIP5 models for RCP8.5 (Smith et al., 2018). It has been argued that its near-term temperature trends are more realistic than MAGICC (Leach et al., 2018).

The MAGICC model is used in this report to classify the different pathways in terms of temperature thresholds and its results are averaged with the FAIR model to support the evaluation of the non-CO_2 forcing contribution to the remaining carbon budget. The FAIR model is less established in the literature but can be seen as being more up to date in regards to its radiative forcing treatment. It is used in this report to help assess uncertainty in the pathway classification approach and to support the carbon budget evaluation (Chapter 2, Section 2.2 and 2.SM.1.1.2).

This section analyses geophysical differences between FAIR and MAGICC to help provide confidence in the assessed climate response findings of the main report (Sections 2.2 and 2.3).

There are structural choices in how the models relate emissions to concentrations and effective radiative forcing. There are also differences in their ranges of climate sensitivity, their choice of carbon cycle parameters, and how they are constrained, even though both models are consistent with AR5 ranges. Overall, their temperature trends are similar for the range of emission trajectories (Figure 2.1 of the main report). However, differences exist in their near-term trends, with MAGICC exhibiting stronger warming trends than FAIR (see Figure 2.SM.1). Leach et al. (2018) also note that that MAGICC warms more strongly than current warming rates. By adjusting FAIR parameters to match those in MAGICC, more than half the difference in mean near-term warming trends can be traced to parameter choices. The remaining differences are due to choices regarding model structure (Figure 2.SM.1).

A structural difference exists in the way the models transfer from the historical period to the future. The setup of MAGICC used for AR5 uses a parametrization that is constrained by observations of hemispheric temperatures and ocean heat uptake, as well as assessed ranges of radiative forcing consistent with AR4 (Meinshausen et al., 2009). From 1765 to 2005 the setup used for AR5 bases forcing on observed concentrations and uses emissions from 2006. It also ramps down the magnitude of volcanic forcing from 1995 to 2000 to give zero forcing in future scenarios, and solar forcing is fixed at 2009 values in the future. In contrast, FAIR produces a constrained set of parameters from emissions runs over the historic period (1765–2017) using both natural and anthropogenic forcings, and then uses this set to run the emissions model with only anthropogenic emissions for the full period of analysis (1765–2110). Structural choices in how aerosol, CH_4 and N_2O are implemented in the model are apparent (see Figure 2.SM.2). MAGICC has a weaker CH_4 radiative forcing, but a stronger total aerosol effective radiative forcing that is close to the AR4 best estimate of -1.2 Wm^{-2} for the total aerosol radiative forcing (Forster et al., 2007). As a result, its forcing is larger than either FAIR or the AR5 best estimate (Figure 2.SM.2), although its median aerosol forcing is well within the IPCC range (Myhre et al., 2013). The difference in N_2O forcings between the models result both from a slightly downwards-revised radiative forcing estimate for N_2O in Etminan et al. (2016) and the treatment of how the models account for natural emissions and atmospheric lifetime of N_2O. The stronger aerosol forcing and its stronger recovery in MAGICC has the largest effect on near-term trends, with CH_4 and N_2O also contributing to stronger warming trends in the MAGICC model.

The transient climate response to cumulative carbon emissions (TCRE) differences between the models are an informative illustration of their parametric differences (Figure 2.SM.3). In the setups used in this report, FAIR has a TCRE median of 0.38°C (5–95% range of 0.25°C to 0.57°C) per 1000 GtO_2 and MAGICC a TCRE median of 0.47°C (5–95% range of 0.13°C to 1.02°C) per 1000 $GtCO_2$. When directly used for the estimation of carbon budgets, this would make the remaining carbon budgets considerably larger in FAIR compared to MAGICC. As a result, rather than to use their budgets directly, this report bases its budget estimate on the AR5 TCRE *likely* (greater than 16–84%) range of 0.2°C to 0.7°C per 1000 $GtCO_2$ (Collins et al., 2013) (see Section 2.SM.1.1.2).

The summary assessment is that both models exhibit plausible temperature responses to emissions. It is too premature to say that either model may be biased. As MAGICC is more established in the literature than FAIR and has been tested against CMIP5 models, the classification of scenarios used in this report is based on MAGICC temperature projections. There is *medium confidence* in this classification and the likelihoods used at the boundaries could prove to underestimate the probability of staying below given temperatures thresholds if near-term temperatures in the applied setup of MAGICC turn out to be warming too strongly. However, neither model accounts for possible permafrost melting in their setup used for this report (although MAGICC does have a setting that would allow this to be included (Schneider von Deimling et al., 2012, 2015)), so biases in MAGICC could cancel in terms of their effect on long-term temperature targets. The veracity of these reduced-complexity climate models is a substantial knowledge gap in the overall assessment of pathways and their temperature thresholds.

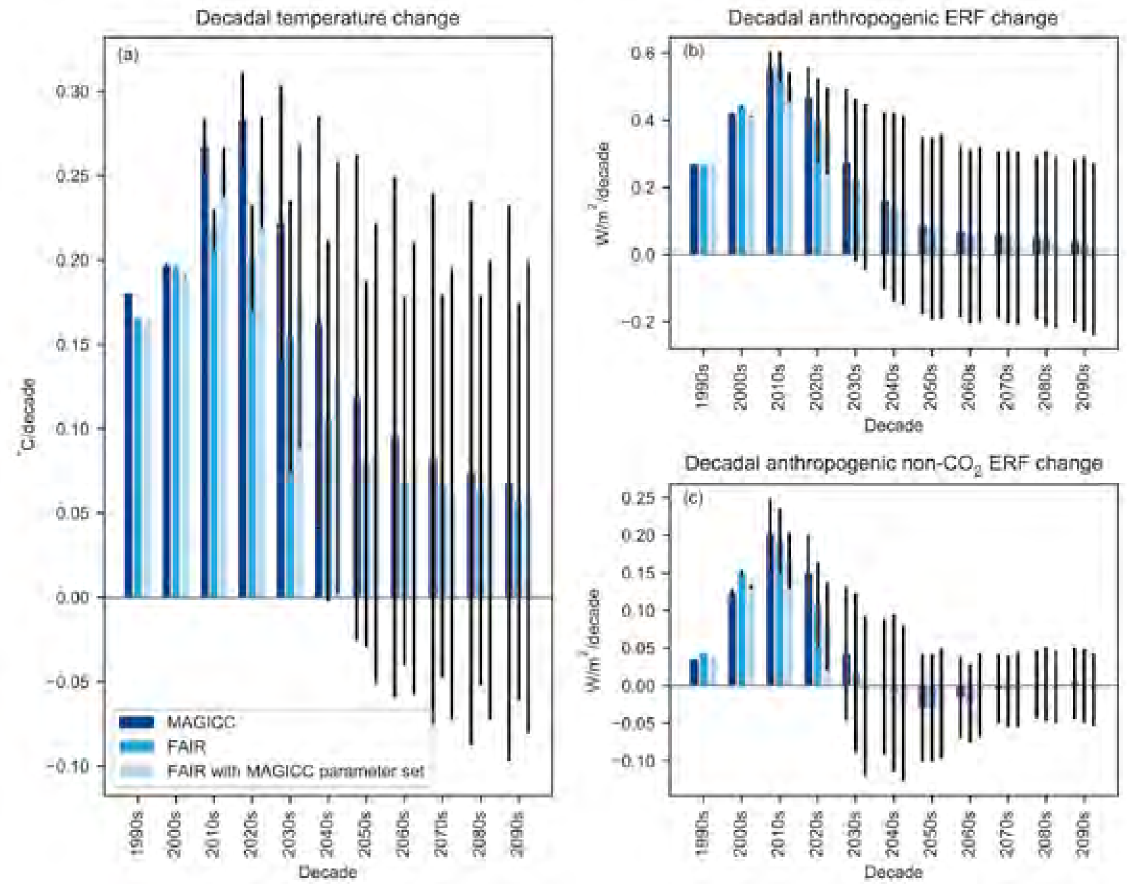


Figure 2.SM.1 | Warming rates per decade for MAGICC (dark blue), FAIR (sky blue) and FAIR matching the MAGICC parameter set (light blue) for the scenario dataset used in this report. These bars represent the mean of regression slopes taken over each decade (years 0 to 9) for scenario median temperature changes, over all scenarios. The black bars show the standard deviation over the set of scenarios.

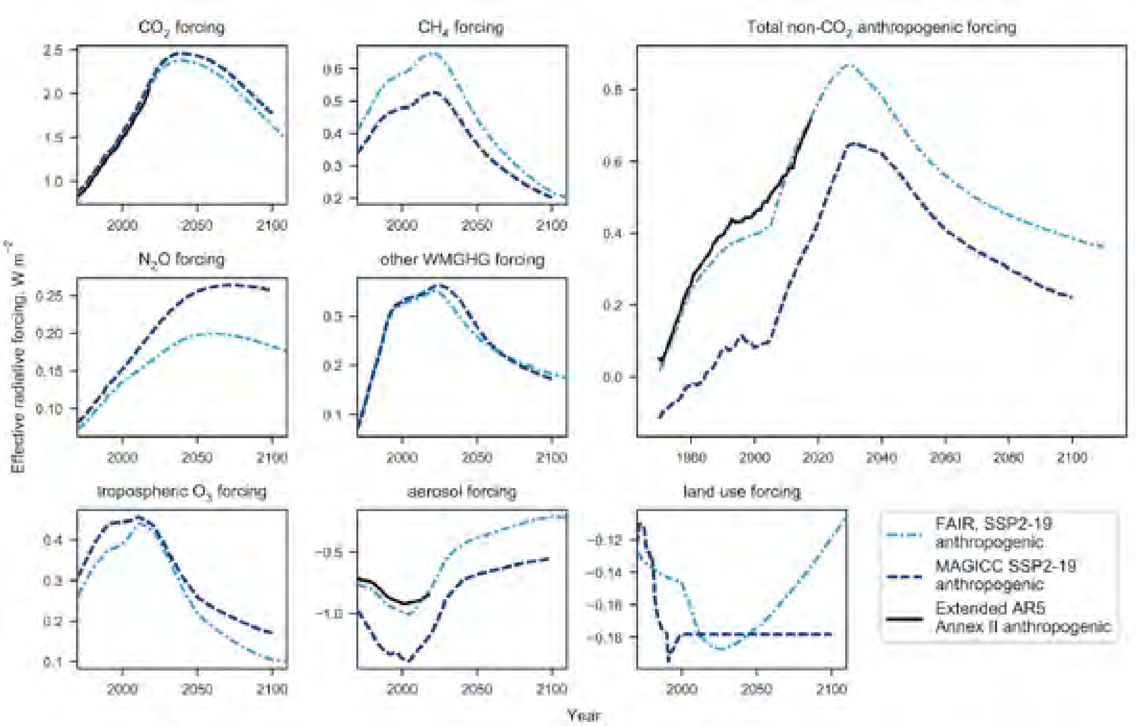


Figure 2.SM.2 | Time series of MAGICC (dark blue dashed) and FAIR (sky blue dash-dotted) effective radiative forcing for an example emission scenario for the main forcing agents where the models exhibit differences. AR5 data is from Myhre et al. (2013), extended from 2011 until the end of 2017 with greenhouse gas data from NOAA/ESRL (www.esrl.noaa.gov/gmd/ccgg/trends/), updated radiative forcing approximations for greenhouse gases (Etminan et al., 2016) and extended aerosol forcing following (Myhre et al., 2017).

The differences between FAIR and MAGICC have a substantial effect on their remaining carbon budgets (see Figure 2.SM.3), and the strong near-term warming in the specific MAGICC setup applied here (Leach et al., 2018) may bias its results to smaller remaining budgets (green line on Figure 2.SM.3). Likewise, the relatively small TCRE in FAIR (compared to AR5) might bias its results to higher remaining budgets (orange line on Figure 2.SM.3). Rather than using the entire model response, only the contribution of non-CO_2 warming from each model is used, using the method discussed next.

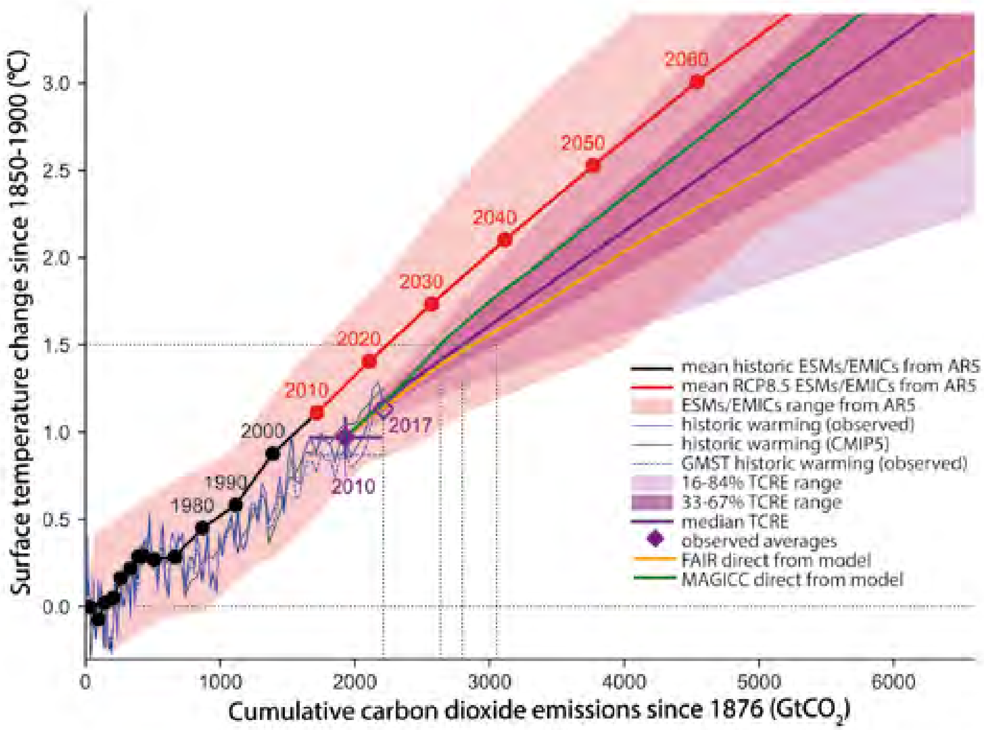


Figure 2.SM.3 | This figure follows Figure 2.3 of the main report but with two extra lines showing FAIR (orange) and MAGICC (green) results separately. These additional lines show the full model response averaged across all scenarios and geophysical parameters.

2.SM.1.1.2 Methods for Assessing Remaining Carbon Budgets

First, the basis for the median remaining carbon budget estimate is described based on MAGICC and FAIR non-CO_2 warming contributions. This is then compared to a simple analysis approach. Lastly, the uncertainty analysis is detailed.

2.SM.1.1.2.1 Median remaining carbon budget basis

This assessment employs historical net cumulative CO_2 emissions reported by the Global Carbon Project (Le Quéré et al., 2018). They report 2170 ± 240 $GtCO_2$ emitted between 1 January 1876 and 31 December 2016. Annual CO_2 emissions for 2017 are estimated at about 42 ± 3 GtCO2 yr^{-1} (Le Quéré et al., 2018; version 1.3 accessed 22 May 2018). From 1 Jan 2011 until 31 December 2017, an additional 290 $GtCO_2$ (270–310 $GtCO_2$, 1σ range) have been emitted (Le Quéré et al., 2018).

In WG1 AR5, TCRE was assessed to have a likely range of 0.22°C to 0.68°C per 1000 $GtCO_2$. The middle of this range (0.45°C per 1000 $GtCO_2$) is taken to be the best estimate, although no best estimate was explicitly defined (Collins et al., 2013; Stocker et al., 2013).

TCRE is diagnosed from integrations of climate models forced with CO_2 emissions only. However, the influence of other climate forcers on global temperatures should also be taken into account (see Figure 3 in Knutti and Rogelj (2015).

The reference non-CO_2 temperature contribution (RNCTC) is defined as the median future warming due to non-CO_2 radiative forcing until the time of net zero CO_2 emissions. The RNCTC is then removed from predefined levels of future peak warming (ΔT_{peak}) between 0.3°C and 1.2°C. The CO_2-only carbon budget is subsequently computed for this revised set of warming levels (ΔT_{peak}–RNCTC).

In FAIR, the RNCTC is defined as the difference in temperature between two experiments, one where all anthropogenic emissions are included and one where only CO_2 emissions are included, using the constrained parameter set. Parallel integrations with matching physical parameters are performed for the suite of 205 scenarios in which CO_2 emissions become net zero during the 21st century. The non-CO_2 warming from a 2006–2015 average baseline is evaluated at the time in which CO_2 emissions become net zero. A linear regression between peak temperature relative to 2006–2015 and non-CO_2 warming relative to 2006–2015 at the time of net zero emissions is performed over the set of 205 scenarios (Figure 2.SM.4). The RNCTC acts to reduce the ΔT_{peak} by an amount of warming caused by non-CO_2 agents, which also takes into account warming effects of non-CO_2 forcing on the carbon cycle response. In the MAGICC model the non-CO_2 temperature contribution is computed from the non-CO_2 effective radiative forcing time series for the same 205 scenarios, using the AR5 impulse response function (Myhre et al., 2013). As in FAIR, the RNCTC is then calculated from a linear regression of non-CO_2 temperature change against peak temperature.

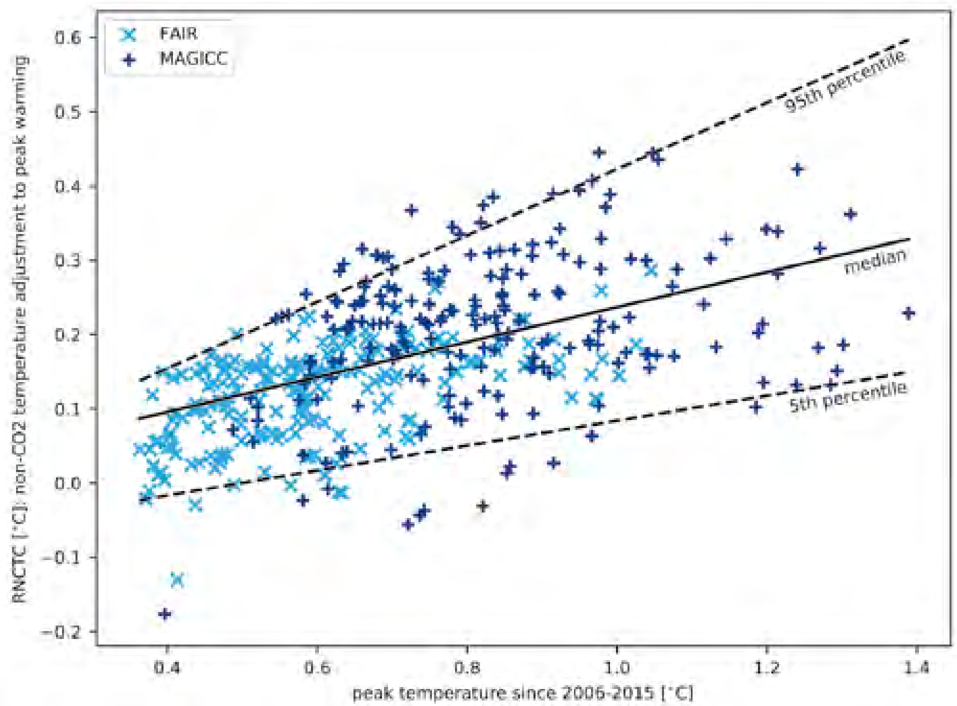


Figure 2.SM.4 | Relationship of RNCTC with peak temperature in the FAIR and MAGICC models. The black line is the linear regression relationship between peak temperature and RNCTC. The dashed lines show the quantile regressions at the 5th and 95th percentile.

Table 2.SM.1 presents the CO_2-only budgets for different levels of future warming assuming both a normal and a log-normal TCRE distribution, where the overall distribution matches the AR5 likely TCRE range of 0.2°C to 0.7°C per 1000 $GtCO_2$. Table 2.SM.2 presents the RNCTC values for different levels of future warming and how they affect the remaining carbon budget for the individual models assuming the normal distribution of TCRE. These are then averaged and rounded to give the numbers presented in the main chapter (Table 2.2). The budgets are taken with respect to the 2006–2015 baseline for temperature and from 1 January 2018 for cumulative emissions. In the main report (Section 2.2), as well as in Table 2.SM.1, the estimates account for cumulative CO_2 emissions between the start of 2011 and the end of 2017 of about 290 $GtCO_2$.

2.SM.1.1.2.2 Checks on approach

A simple approach to infer the carbon budget contribution from non-CO_2 forcers has been proposed based on global warming potential and is found to hold for a wide range of mitigation scenarios (Allen et al., 2018). This is based on an empirical relationship between peak temperature, TCRE, cumulative CO_2 emissions (G_{CO2}), non-CO_2 forcing ($\Delta F_{non\text{-}CO2}$) and the Absolute Global Warming Potential of CO_2 ($AGWP_H(CO_2)$) over time horizon H, taken to be 100 years:

$$\Delta T_{peak} \approx \mathrm{TCRE} \times (G_{CO2}+\Delta F_{non\text{-}CO2} \times (H/\mathrm{AGWP}_H(CO_2)) \qquad (2.SM.1)$$

This method reduces the budget by an amount proportional to the change in non-CO_2 forcing. To determine this non-CO_2 forcing contribution, a reference non-CO_2 forcing contribution (RNCFC) is estimated from the MAGICC and FAIR runs. The RNCFC is defined as $\Delta F_{non\text{-}CO2}$ in Equation 2.SM.1, which is a watts-per-metre-squared difference in the non-CO_2 effective radiative forcing between the 20 years before peak temperature is reached and 1996–2015. This provides an estimate of the non-CO_2 forcing contribution to the change in carbon budget. A similar calculation was performed for aerosol forcing in isolation (ΔF_{aer}) and the results showed that the weakening aerosol forcing is the largest contributor to the smaller carbon budget, compared to the CO_2-only budget. $AGWP_{100}$ values are taken from AR5 (Myhre et al., 2013) and the resultant remaining carbon budgets are given in Table 2.SM.3. This method reduces the remaining carbon budget by 1091 $GtCO_2$ per Wm^{-2} of non-CO_2 effective radiative forcing (with a 5% to 95% range of 886 to 1474 $GtCO_2$). These results show good agreement to those computed with the RNCTC method from Table 2.SM.2, adding confidence to both methods. The RNCFC method is approximate and the choice of periods to use for averaging forcing is somewhat subjective, so the RNCTC is preferred over the RNCFC for this assessment.

Table 2.SM.1 | Remaining CO_2-only budget in $GtCO_2$ from 1 January 2018 for different levels of warming from 2006–2015 for normal and log-normal distributions of TCRE based on the AR5 likely range. 290 $GtCO_2$ have been removed to account for emissions between the start of 2011 and the end of 2017. The assessed warming from 1850–1900 to 2006–2015 is about 0.87°C with 1 standard deviation uncertainty range of ±0.12°C.

	Normal Distribution			Log-Normal Distribution		
CO_2-only Remaining Budgets ($GtCO_2$)	TCRE 0.35°C per 1000 $GtCO_2$	TCRE 0.45°C per 1000 $GtCO_2$	TCRE 0.55°C per 1000 $GtCO_2$	TCRE 0.30°C per 1000 $GtCO_2$	TCRE 0.38°C per 1000 $GtCO_2$	TCRE 0.50°C per 1000 $GtCO_2$
Additional warming from 2005–2015 °C	TCRE 33%	TCRE 50%	TCRE 67%	TCRE 33%	TCRE 50%	TCRE 67%
0.3	571	376	253	709	487	315
0.4	859	598	434	1042	746	517
0.5	1146	820	615	1374	1005	718
0.6	1433	1042	796	1707	1265	920
0.7	1720	1264	977	2040	1524	1122
0.8	2007	1486	1158	2373	1783	1323
0.9	2294	1709	1339	2706	2042	1525
1	2581	1931	1520	3039	2301	1726
1.1	2868	2153	1701	3372	2560	1928
1.2	3156	2375	1882	3705	2819	2130

Table 2.SM.2 | Remaining carbon dioxide budget from 1 January 2018 reduced by the effect of non-CO_2 forcers. Budgets are for different levels of warming from 2006–2015 for a normal distribution of TCRE based on the AR5 likely range of 0.2°C to 0.7°C per 1000 $GtCO_2$. 290 $GtCO_2$ have been removed to account for emissions between the start of 2011 and the end of 2017. This method employed the RNCTC estimates of non-CO_2 temperature change until the time of net zero CO_2 emissions.

		MAGICC				FAIR		
Remaining Carbon Budgets ($GtCO_2$) Additional warming from 2006–2015 °C	**MAGICC RNCTC** (°C)	TCRE 33%	TCRE 50%	TCRE 67%	**FAIR RNCTC** (°C)	TCRE 33%	TCRE 50%	TCRE 67%
0.3	0.14	184	77	9	0.06	402	245	146
0.4	0.15	434	270	166	0.08	629	421	289
0.5	0.16	681	461	322	0.10	856	596	433
0.6	0.18	930	654	480	0.12	1083	772	576
0.7	0.19	1177	845	635	0.14	1312	949	720
0.8	0.20	1427	1038	793	0.16	1539	1125	863
0.9	0.22	1674	1229	948	0.18	1766	1300	1006
1	0.23	1924	1422	1106	0.20	1993	1476	1149
1.1	0.24	2171	1613	1262	0.22	2223	1653	1294
1.2	0.26	2421	1806	1419	0.25	2449	1829	1437

Table 2.SM.3 | Remaining carbon dioxide budgets from 1 January 2018 reduced by the effect of non-CO_2 forcers calculated by using a simple empirical approach based on non-CO_2 forcing (RNCFC) computed by the FAIR model. Budgets are for different levels of warming from 2006–2015 and for a normal distribution of TCRE based on the AR5 likely range of 0.2°C to 0.7°C per 1000 $GtCO_2$. 290 $GtCO_2$ have been removed to account for emissions between the start of 2011 and the end of 2017.

		FAIR		
Remaining Carbon Budgets ($GtCO_2$) Additional warming from 2006–2015 °C	**FAIR RNCFC** (Wm^{-2})	TCRE 33%	TCRE 50%	TCRE 67%
0.3	0.191	363	168	45
0.4	0.211	629	368	204
0.5	0.232	893	568	362
0.6	0.253	1157	767	521
0.7	0.273	1423	967	680
0.8	0.294	1687	1166	838
0.9	0.314	1952	1366	997
1	0.335	2216	1566	1155
1.1	0.356	2481	1765	1314
1.2	0.376	2746	1965	1473

2.SM.1.1.2.3 Uncertainties

Uncertainties are explored across several lines of evidence and summarized in Table 2.2 of the main report. Expert judgement is used to estimate the overall uncertainty and to estimate the amount of 100 $GtCO_2$ that is removed to account for possible missing permafrost and wetlands feedbacks (see Section 2.2). Irrespective of the metric used to estimate global warming, the uncertainty in global warming since pre-industrial levels (1850–1900) up to the 2006–2015 reference period as estimated in Chapter 1 is of the order of ±0.1°C (*likely* range). This uncertainty affects how close warming since pre-industrial levels is to the 1.5°C and 2°C limits. To illustrate this impact, the remaining carbon budgets for a range of future warming thresholds between 0.3°C and 1.2°C above present-day are analysed. The uncertainty in 2006–2015 warming compared to 1850–1900 relates to a ±250 $GtCO_2$ uncertainty in carbon budgets for a best-estimate TCRE.

A measure of the uncertainty due to variations in the consistent level of non-CO_2 mitigation at the time that net zero CO_2 emissions are reached in pathways is analysed by a quantile regression of each pathway's median peak temperature against its corresponding median RNCTC (evaluated with the FAIR model), for the 5th, median and 95th percentiles of scenarios. A variation of approximately ±0.1°C around the median RNCTC is observed for median peak temperatures between 0.3° and 1.2°C above the 2006–2015 mean. This variation is equated to a ±250 $GtCO_2$ uncertainty in carbon budgets for a median TCRE estimate of about 0.45°C per 1000 $GtCO_2$. An uncertainty of –400 to +200 $GtCO_2$ is associated with the non-CO_2 forcing and response. This is analysed from a regression of 5th and 95th percentile RNCTC against 5th and 95th percentile peak temperature calculated with FAIR, compared to the median RNCTC response. These uncertainty contributions are shown in Table 2.2 in the main chapter.

The effects of uncertainty in the TCRE distribution were gauged by repeating the remaining budget estimate for a log-normal distribution of the AR5 *likely* range. This reduces the median TCRE from 0.45°C per 1000 $GtCO_2$ to 0.38°C per 1000 $GtCO_2$ (see Table 2.SM.1.1). Table 2.SM.1.4 presents these remaining budgets and shows that around 200 $GtCO_2$ would be added to the budget by assuming a log-normal *likely* range. The assessment and evidence supporting either distribution is discussed in the main chapter.

Uncertainties in past CO_2 emissions ultimately impact estimates of the remaining carbon budgets for 1.5°C or 2°C. Uncertainty in CO_2 emissions induced by past land-use and land-cover changes contribute most, representing about 240 $GtCO_2$ from 1870 to 2017. Yet this uncertainty is substantially reduced when deriving cumulative CO_2 emissions from a recent period. The cumulative emissions from the 2006–2015 reference period to 2017 used in this report are approximately 290 $GtCO_2$ with an uncertainty of about 20 $GtCO_2$.

Table 2.SM.4 | Remaining carbon dioxide budget from 1 January 2018 reduced by the effect of non-CO_2 forcers. Numbers are differences between estimates of the remaining budget made with the log-normal distribution compared to that estimated with a normal distribution of TCRE based on the AR5 likely range (see Table 2.A.1). 290 $GtCO_2$ have been removed to account for emissions between the start of 2011 and the end of 2017. This method employed the FAIR model RNCTC estimates of non-CO_2 temperature response.

	Log-Normal Minus Normal TCRE Distribution		
Remaining Budgets ($GtCO_2$) Additional warming from 2006–2015 °C	TCRE 33%	TCRE 50%	TCRE 67%
0.3	110	89	50
0.4	146	118	66
0.5	183	148	82
0.6	219	177	99
0.7	255	207	115
0.8	291	236	131
0.9	328	265	148
1	364	294	164
1.1	400	324	180
1.2	436	353	197

2.SM.1.2 Integrated Assessment Models

The set of process-based integrated assessment models (IAMs) that provided input to this assessment is not fundamentally different from those underlying the IPCC AR5 assessment of transformation pathways (Clarke et al., 2014), and an overview of these integrated modelling tools can be found there. However, there have been a number of model developments since AR5, in particular improving the sectoral detail of IAMs (Edelenbosch et al., 2017b), the representation of solar and wind energy (Creutzig et al., 2017; Johnson et al., 2017; Luderer et al., 2017; Pietzcker et al., 2017), the description of bioenergy and food production and associated sustainability trade-offs (Havlík et al., 2014; Weindl et al., 2017; Bauer et al., 2018; Frank et al., 2018), the representation of a larger portfolio of carbon dioxide removal (CDR) technologies (Chen and Tavoni, 2013; Marcucci et al., 2017; Strefler et al., 2018b), the accounting of behavioural change (van Sluisveld et al., 2016; McCollum et al., 2017; van Vuuren et al., 2018) and energy demand developments (Edelenbosch et al., 2017a, c; Grubler et al., 2018), and the modelling of sustainable development implications (van Vuuren et al., 2015; Bertram et al., 2018), for example, relating to water use (Bonsch et al., 2014; Hejazi et al., 2014; Fricko et al., 2016; Mouratiadou et al., 2016, 2018), access to clean water and sanitation (Parkinson et al., 2019), materials use (Pauliuk et al., 2017), energy access (Cameron et al., 2016), air quality (Rao et al., 2017), and bioenergy use and food security (Frank et al., 2017; Humpenöder et al., 2018). Furthermore, since AR5, a harmonized model documentation of IAMs and underlying assumptions has been established within the framework of the EU ADVANCE project, which is available at www.iamcdocumentation.eu

2.SM.1.2.1 Short Introduction to the Scope, Use and Limitations of Integrated Assessment Modelling

IAMs are characterized by a dynamic representation of coupled systems, including energy, land, agricultural, economic and climate systems (Weyant, 2017). They are global in scope and typically cover sufficient sectors and sources of greenhouse gas emissions to project anthropogenic emissions and climate change. This allows them to identify the consistency of different pathways with long-term goals of limiting warming to specific levels (Clarke et al., 2014). IAMs can be applied in a forward-looking manner to explore internally consistent socio-economic–climate futures, often extrapolating current trends under a range of assumptions or using counterfactual "no policy" assumptions to generate baselines for subsequent climate policy analysis. They can also be used in a back-casting mode to explore the implications of climate policy goals and climate targets for systems transitions and near-to-medium-term action. In most IAM-based studies, both applications of IAMs are used concurrently (Clarke et al., 2009; Edenhofer et al., 2010; Luderer et al., 2012; Kriegler et al., 2014, 2015b, 2016; Riahi et al., 2015; Tavoni et al., 2015). Sometimes the class of IAMs is defined more narrowly as the subset of integrated pathway models with an economic core and equilibrium assumptions on supply and demand, although non-equilibrium approaches to integrated assessment modelling exist (Guivarch et al., 2011; Mercure et al., 2018). IAMs with an economic core describe consistent price–quantity relationships, where the "shadow price" of a commodity generally reflects its scarcity in the given setting. To this end, the price of greenhouse gas emissions emerging in IAMs reflects the restriction of future emissions imposed by a warming limit (Cross-Chapter Box 5 in Chapter 2, Section 2.SM.1.2.2). Such a price needs to be distinguished from suggested levels of emissions pricing in multidimensional policy contexts that are adapted to existing market environments and often include a portfolio of policy instruments (Chapter 2, Section 2.5.2) (Stiglitz et al., 2017).

Detailed-process IAMs that describe energy–land transitions on a process level are critically different from stylized cost–benefit IAMs that aggregate such processes into stylized abatement cost and climate damage relationships to identify cost-optimal responses to climate change (Weyant, 2017). A key component of cost–benefit IAMs is the representation of climate damages, which has been debated in the recent literature (Revesz et al., 2014; Cai et al., 2015; Lontzek et al., 2015; Burke et al., 2016; Stern, 2016). In the meantime, new approaches and estimates for improving the representation of climate damages are emerging (Dell et al., 2014; Burke et al., 2015, 2018; Hsiang et al., 2017) (Chapter 3, Box 3.6). A detailed discussion of the strengths and weaknesses of cost-benefit IAMs is provided in AR5 (Clarke et al., 2014; Kolstad et al., 2014; Kunreuther et al., 2014) (see also Cross-Chapter Box 5 in Chapter 2). The assessment of 1.5°C-consistent pathways in Chapter 2 relies entirely on detailed-process IAMs. These IAMs have so far rarely attempted a full representation of climate damages on socio-economic systems, mainly for three reasons: a focus on the implications of mitigation goals for transition pathways (Clarke et al., 2014); the computational challenge to represent, estimate and integrate the complete range of climate impacts on a process level (Warszawski et al., 2014); and ongoing fundamental research on measuring the breadth and depth of how biophysical climate impacts can affect societal welfare (Dennig et al., 2015; Adler et al., 2017; Hallegatte and Rozenberg, 2017). While some detailed-process IAMs account for climate impacts in selected sectors, such as agriculture (Stevanović et al., 2016), these IAMs do not take into account climate impacts as a whole in their pathway modelling. The 1.5°C and 2°C-consistent pathways available to this report hence do not reflect climate impacts and adaptation challenges below 1.5°C and 2°C, respectively. Pathway modelling to date is also not able to identify socio-economic benefits of avoided climate damages between 1.5°C-consistent pathways and pathways leading to higher warming levels. These limitations are important knowledge gaps (Chapter 2, Section 2.6) and are a subject of active research. Due to these limitations, the use of the integrated pathway literature in this report is concentrated on the assessment of mitigation action to limit warming to 1.5°C, while the assessment of impacts and adaptation challenges in 1.5°C-warmer worlds relies on a different body of literature (see Chapters 3 to 5).

The use of IAMs for climate policy assessments has been framed in the context of solution-oriented assessments (Edenhofer and Kowarsch, 2015; Beck and Mahony, 2017). This approach emphasizes the exploratory nature of integrated assessment modelling to produce scenarios of internally consistent, goal-oriented futures. They describe a range of pathways that achieve long-term policy goals, and at the same time highlight trade-offs and opportunities associated with different courses of action. This literature has noted, however, that such exploratory knowledge generation about future pathways cannot be completely isolated from societal discourse, value formation and decision making and therefore needs to be reflective of its performative character (Edenhofer and Kowarsch, 2015; Beck and Mahony, 2017). This suggests an interactive approach which engages societal values and user perspectives in the pathway production process. It also requires transparent documentation of IAM frameworks and applications to enable users to contextualize pathway results in the assessment process. Integrated assessment modelling results assessed in AR5 were documented in Annex II of AR5 (Krey et al., 2014b), and this Supplementary Material aims to document the IAM frameworks that fed into the assessment of 1.5°C-consistent pathways in Chapter 2 of this report. It draws upon increased efforts to extend and harmonize IAM documentations (Section 2.SM.1.2.5). Another important aspect for the use of IAMs in solution-oriented assessments is building trust in their applicability and validity. The literature has discussed approaches to IAM evaluation (Schwanitz, 2013; Wilson et al., 2017), including model diagnostics (Kriegler et al., 2015a; Wilkerson et al., 2015; Craxton et al., 2017) and comparison with historical developments (Wilson et al., 2013; van Sluisveld et al., 2015).

2.SM.1.2.2 Economics and Policy Assumptions in IAMs

Experiments with IAMs most often create scenarios under idealized policy conditions which assume that climate change mitigation measures are undertaken where and when they are the most effective (Clarke et al., 2014). Such 'idealized implementation' scenarios assume that a global price on GHG emissions is implemented across all countries and all economic sectors, and rises over time through 2100 in a way that will minimize discounted economic costs. The emissions price reflects marginal abatement costs and is often used as a proxy of climate policy costs (see Chapter 2, Section 2.5.2). Scenarios developed under these assumptions are often referred to as 'least-cost' or 'cost-effective' scenarios because they result in the lowest aggregate global mitigation costs when assuming that global markets and economies operate in a frictionless, idealized way (Clarke et al., 2014; Krey et al., 2014b). However, in practice, the feasibility (see Cross-Chapter Box 3 in Chapter 1) of a global carbon pricing mechanism deserves careful consideration (see Chapter 4, Section 4.4). Scenarios from idealized conditions provide benchmarks for policymakers, since deviations from the idealized approaches capture important challenges for socio-technical and economic systems and resulting climate outcomes.

Model experiments diverging from idealized policy assumptions aim to explore the influence of policy barriers to implementation of globally cost-effective climate change mitigation, particularly in the near term. Such scenarios are often referred to as 'second-best' scenarios. They include, for instance, (i) fragmented policy regimes in which some regions champion immediate climate mitigation action (e.g., by 2020) while other regions join this effort with a delay of one or more decades (Clarke et al., 2009; Blanford et al., 2014; Kriegler et al., 2015b), (ii) prescribed near-term mitigation efforts (until 2020 or 2030) after which a global climate target is adopted (Luderer et al., 2013, 2016; Rogelj et al., 2013b; Riahi et al., 2015), or (iii) variations in technology preferences in mitigation portfolios (Edenhofer et al., 2010; Luderer et al., 2012; Tavoni et al., 2012; Krey et al., 2014a; Kriegler et al., 2014; Riahi et al., 2015; Bauer et al., 2017, 2018). Energy transition governance adds a further layer of potential deviations from cost-effective mitigation pathways and has been shown to lead to potentially different mitigation outcomes (Trutnevyte et al., 2015; Chilvers et al., 2017; Li and Strachan, 2017). Governance factors are usually not explicitly accounted for in IAMs.

Pricing mechanisms in IAMs are often augmented by assumptions about regulatory and behavioural climate policies in the near- to mid-term (Bertram et al., 2015; van Sluisveld et al., 2016; Kriegler et al., 2018). The choice of GHG price trajectory to achieve a pre-defined climate goal varies across IAMs and can affect the shape of mitigation pathways. For example, assuming exponentially increasing CO_2 pricing to stay within a limited CO_2 emissions budget is consistent with efficiency considerations in an idealized economic setting but can lead to temporary overshoot of the carbon budget if carbon dioxide removal (CDR) technologies are available. The pricing of non-CO_2 greenhouse gases is often pegged to CO_2 pricing using their global warming potentials (mostly GWP100) as exchange rates (see Cross-Chapter Box 2 in Chapter 1). This leads to stringent abatement of non-CO_2 gases in the medium- to long-term.

The choice of economic discount rate is usually reflected in the increase of GHG pricing over time and thus also affects the timing of emissions reductions. For example, the deployment of capital-intensive abatement options like renewable energy can be pushed back by higher discount rates. IAMs make different assumptions about the discount rate, with many of them assuming a social discount rate of ca. 5% per year (Clarke et al., 2014). In a survey of modelling teams contributing scenarios to the database for this assessment to which 13 out of 19 teams responded, discount rate assumptions varied between 2% yr^{-1} and 8% yr^{-1} depending on whether social welfare considerations or the representation of market actor behaviour is given larger weight. Some IAMs assume fixed charge rates that can vary by sector, taking into account the fact that private actors require shorter time horizons to amortize their investment. The impact of the choice of discount rate on mitigation pathways is underexplored in the literature. In general, the choice of discount rate is expected to have a smaller influence on low-carbon technology deployment schedules for tighter climate targets, as they leave less flexibility in the timing of emissions reductions. However, the introduction of large-scale CDR options might increase sensitivity again. It was shown, for example, that if a long-term CDR option like direct air capture with CCS (DACCS) is introduced in the mitigation portfolio, lower discount rates lead to more early abatement and less CDR deployment (Chen and Tavoni, 2013). If discount rates vary across regions, with higher costs of capital in developing countries, industrialized countries mitigate more and developing countries less, resulting in higher overall mitigation costs compared to a case with globally uniform discounting (Iyer et al., 2015). More work is also needed to study the sensitivity of the deployment schedule of low-carbon technologies to the choice of the discount rate. However, as overall emissions reductions need to remain consistent with the choice of climate goal, mitigation pathways from detailed process-based IAMs are still less sensitive to the choice of discount rate than cost-optimal pathways from cost-benefit IAMs (see Box 6.1 in Clarke et al., 2014) which have to balance near-term mitigation with long-term climate damages across time (Nordhaus, 2007; Dietz and Stern, 2008; Kolstad et al., 2014; Pizer et al., 2014) (see Cross-Chapter Box 5 in Chapter 2).

2.SM.1.2.3 Technology Assumptions and Transformation Modelling

Although model-based assessments project drastic near-, medium- and long-term transformations in 1.5°C scenarios, projections also often struggle to capture a number of hallmarks of transformative change, including disruption, innovation, and non-linear change in human behaviour (Rockström et al., 2017). Regular revisions and adjustments are standard for expert and model projections, for example, to account for new information such as the adoption of the Paris Agreement. Costs and deployment of mitigation technologies will differ in reality from the values assumed in the full-century trajectories of the model results. CCS and nuclear provide examples of where real-world costs have been higher than anticipated (Grubler, 2010; Rubin et al., 2015), while solar PV is an example where real-world costs have been lower (Creutzig et al., 2017; Figueres et al., 2017; Haegel et al., 2017). Such developments will affect the low-carbon transition for achieving stringent mitigation targets. This shows the difficulty of adequately estimating social and technological transitions and illustrates the challenges of producing scenarios consistent with a quickly evolving market (Sussams and Leaton, 2017).

Behavioural and institutional frameworks affect the market uptake of mitigation technologies and socio-technical transitions (see Chapter 4, Section 4.4). These aspects co-evolve with technology change and determine, among others, the adoption and use of low-carbon technologies (Clarke et al., 2014), which in turn can affect both the design and performance of policies (Kolstad et al., 2014; Wong-Parodi et al., 2016). Predetermining technological change in models can preclude the examination of policies that aim to promote disruptive technologies (Stanton et al., 2009). In addition, knowledge creation, networks, business strategies, transaction costs, microeconomic decision-making processes and institutional capacities influence (no-regret) actions, policy portfolios and innovation processes (and vice versa) (Mundaca et al., 2013; Lucon et al., 2014; Patt, 2015; Wong-Parodi et al., 2016; Geels et al., 2017); however, they are difficult to capture in equilibrium or cost-minimization model-based frameworks (Laitner et al., 2000; Wilson and Dowlatabadi, 2007; Ackerman et al., 2009; Ürge-Vorsatz et al., 2009; Mundaca et al., 2010; Patt et al., 2010; Brunner and Enting, 2014; Grubb et al., 2014; Patt, 2015; Turnheim et al., 2015; Geels et al., 2017; Rockström et al., 2017). It is argued that assessments that consider greater end-user heterogeneity, realistic market behaviour, and end-use technology details can address a more realistic and varied mix of policy instruments, innovation processes and transitional pathways (Ürge-Vorsatz et al., 2009; Mundaca et al., 2010; Wilson et al., 2012; Lucon et al., 2014; Li et al., 2015; Trutnevyte et al., 2015; Geels et al., 2017; McCollum et al., 2017). So-called 'rebound' effects in which behavioural changes partially offset policies, such as consumers putting less effort into demand reduction when efficiency is improved, are captured to a varying, and in many cases only limited, degree in IAMs.

There is also substantial variation in mitigation options represented in IAMs (see Section 2.SM.1.2.6) which depend on the one hand on the constraints of individual modelling frameworks and on the other hand on model development decisions influenced by modellers' beliefs and preferences (Chapter 2, Section 2.3.1.2). Further limitations can arise on the system level. For example, trade-offs between material use for energy versus other uses are not fully captured in many IAMs (e.g., petroleum for plastics, biomass for material substitution). An important consideration for the analysis of mitigation potential is the choice of (alternative) baseline(s). For example, IAMs often assume, in line with historical experience, that economic growth leads to a reduction in local air pollution as populations become richer (i.e., an environmental Kuznets curve) (Rao et al., 2017). In such cases, the mitigation potential is small because reference emissions that take into account this economic development effect are already low in scenarios that see continued economic development over their modelling time horizon. Assumptions about reference emissions are important because high reference emissions lead to high perceived mitigation potentials and potential overestimates of the actual benefit, while low reference emissions lead to low perceived benefits of mitigation measures and thus less incentive to address these important climate- and air-pollutants (Gschrey et al., 2011; Shindell et al., 2012; Amann et al., 2013; Rogelj et al., 2014; Shah et al., 2015; Velders et al., 2015).

2.SM.1.2.4 Land Use and Bioenergy Modelling in IAMs

The IAMs used in the land-use assessment in this chapter are based on the SSPs (Popp et al., 2017; Riahi et al., 2017) and all include an explicit land model. These land models calculate the supply of food, feed, fibre, forestry, and bioenergy products (see also Chapter 2, Box 2.1). The supply depends on the amount of land allocated to the particular good, as well as the yield for the good. Different IAMs have different means of calculating land allocation and different assumptions about yield, which is typically assumed to increase over time, reflecting technological progress in the agricultural sector (see Popp et al., 2014 for examples). In these models, the supply of bioenergy (including BECCS) depends on the price and yield of bioenergy, the policy environment (e.g., any taxes or subsidies affecting bioenergy profits), and the demand for land for other purposes. Dominant bioenergy feedstocks assumed in IAMs are woody and grassy energy crops (second-generation biomass) in addition to residues. Some models implement a "food first" approach, where food demands are met before any land is allocated to bioenergy. Other models use an economic land allocation approach, where bioenergy competes with other land uses depending on profitability. Competition between land uses depends strongly on socio-economic drivers such as population growth and food demand, and are typically varied across scenarios. When comparing global bioenergy yields from IAMs with the bottom-up literature, care must be taken that assumptions are comparable. An in-depth assessment of the land-use components of IAMs is outside the scope of this Special Report.

In all IAMs that include a land model, the land-use change emissions associated with these changes in land allocation are explicitly calculated. Most IAMs use an accounting approach to calculating land-use change emissions, similar to Houghton et al. (2012). These models calculate the difference in carbon content of land due to the conversion from one type to another and then allocate that difference across time in some manner. For example, increases in forest cover will increase terrestrial carbon stock, but that increase may take decades to accumulate. If forestland is converted to bioenergy, however, those emissions will enter the atmosphere more quickly.

IAMs often account for carbon flows and trade flows related to bioenergy separately. That is, IAMs may treat bioenergy as "carbon neutral" in the energy system, in that the carbon price does not affect the cost of bioenergy. However, these models will account for any land-use change emissions associated with the land conversions needed to produce bioenergy. Additionally, some models will separately track

Table 2.SM.5 | Land-use type descriptions as reported in pathways (adapted from the SSP database: https://tntcat.iiasa.ac.at/SspDb/)

Land Use Type	Description/Examples
Energy crops	Land dedicated to second-generation energy crops. (e.g., switchgrass, *Miscanthus*, fast-growing wood species)
Other crops	Food and feed/fodder crops
Pasture	Pasture land. All categories of pasture land – not only high-quality rang land. Based on FAO definition of "permanent meadows and pastures"
Managed forest	Managed forests producing commercial wood supply for timber or energy but also afforestation (note: woody energy crops are reported under "energy crops")
Natural forest	Undisturbed natural forests, modified natural forests and regrown secondary forests
Other natural land	Unmanaged land (e.g., grassland, savannah, shrubland, rock ice, desert), excluding forests

the carbon uptake from growing bioenergy and the emissions from combusting bioenergy (assuming it is not combined with CCS).

2.SM.1.2.5 Contributing Modelling Framework Reference Cards

For each of the contributing modelling frameworks a reference card has been created highlighting the key features of the model. These reference cards are either based on information received from contributing modelling teams upon submission of scenarios to the SR1.5 database, or alternatively drawn from the ADVANCE IAM wiki documentation, available at www.iamcdocumentation.eu (last accessed on 15 May 2018) and updated. These reference cards are provided in part 2 of this Supplementary Material.

2.SM.1.2.6 Overview of Mitigation Measures in Contributed IAM Scenarios

Table 2.SM.6 | Overview of the representation of mitigation measures in the integrated pathway literature, as submitted to the database supporting this report. Levels of inclusion have been elicited directly from contributing modelling teams by means of a questionnaire. The table shows the reported data. Dimensions of inclusion are explicit versus implicit, and endogenous or exogenous. An implicit level of inclusion is assigned when a mitigation measure is represented by a proxy like a marginal abatement cost curve in the agriculture forestry and other land-use (AFOLU) sector without modelling individual technologies or activities. An exogenous level of inclusion is assigned when a mitigation measure is not part of the dynamics of the modelling framework but can be explored through alternative scenarios.

Levels of Inclusion

	Explicit	Implicit
Endogenous	A	C
Exogenous	B	D
E	Not represented by model	

Levels of Inclusion	AIM	BET	COPPE-COFFEE	C-ROADS	DNE21+	GCAM 4.2	GEM-E3 3.0	GENESYSmod 1.0	GRAPE 1.0	IEA ETP	IEA WEM	IMACLIM 1.1	IMACLIM NL	IMAGE 3.0	MERGE-ETL 6.0	MESSAGE-GLOBIOM	MESSAGEix-GLOBIOM	POLES	REMIND-MAgPIE	Shell WEM v1	WITCH
Demand Side Measures																					
Energy efficiency improvements in energy end uses (e.g., appliances in buildings, engines in transport, industrial processes)	**A**	**A**	C	D	B	D	B	D	B	**A**	**A**	**A**	**A**	**A**	C	C	B	C	C	B	C
Electrification of transport demand (e.g., electric vehicles, electric rail)	**A**	**A**	**A**	D	**A**	**A**	B	**A**	**A**	**A**	**A**	**A**	**A**	**A**	C	**A**	**A**	**A**	**A**	B	**A**
Electrification of energy demand for buildings (e.g., heat pumps, electric/induction stoves)	**A**	**A**	**A**	D	**A**	**A**	B	**A**	D	**A**	**A**	C	C	**A**	C	**A**	**A**	**A**	C	B	C
Electrification of industrial energy demand (e.g., electric arc furnace, heat pumps, electric boilers, conveyor belts, extensive use of motor control, induction heating, industrial use of microwave heating)	**A**	**A**	C	D	**A**	C	D	**A**	D	**A**	**A**	C	C	**A**	C	**A**	**A**	C	C	B	C
CCS in industrial process applications (cement, pulp and paper, iron steel, oil and gas refining, chemicals)	**A**	E	**A**	D	D	**A**	E	E	C	**A**	**A**	E	E	**A**	E	**A**	**A**	E	**A**	B	C
Higher share of useful energy in final energy (e.g., insulation of buildings, lighter weight vehicles, combined heat and power generation, district heating, etc)	C	E	C	D	**A**	C	D	D	C	B	B	D	D	**A**	C	**A**	**A**	**A**	C	D	C
Reduced energy and service demand in **industry** (e.g., process innovations, better control)	C	C	C	D	C	C	C	D	D	B	B	C	C	B	C	C	B	B	C	C	C
Reduced energy and service demand in **buildings** (e.g., via behavioural change, reduced material and floor space demand, infrastructure and buildings configuration)	C	C	C	D	C	C	C	D	D	C	C	D	D	C	C	C	B	B	C	C	C
Reduced energy and service demand in **transport** (e.g., via behavioural change, new mobility business models, modal shift in individual transportation, eco-driving, car/bike-sharing schemes)	C	C	C	D	C	**A**	B	D	B	B	C	C	C	C	C	C	B	B	C	C	C
Reduced energy and service demand in **international transport** (international shipping and aviation)	**A**	E	**A**	D	D	**A**	C	E	B	B	B	C	C	C	C	B	B	**A**	D	C	C
Reduced material demand via higher resource efficiency, structural change, behavioural change and material substitution (e.g., steel and cement substitution, use of locally available building materials)	**A**	E	E	D	D	D	C	E	D	B	B	E	E	B	E	D	B	E	C	C	C
Urban form (including integrated on-site energy, influence of avoided transport and building energy demand)	E	E	E	D	D	E	E	D	E	B	E	D	D	E	E	E	B	E	E	C	E
Switch from traditional biomass and solid fuel use in the residential sector to modern fuels, or enhanced combustion practices, avoiding wood fuel	D	**A**	**A**	D	D	B	E	**A**	**A**	**A**	**A**	E	E	**A**	E	**A**	**A**	B	D	C	**A**
Dietary changes, reducing meat consumption	**A**	E	E	D	D	**A**	E	E	B	E	E	E	B	B	E	B	B	B	B	E	E
Substitution of livestock-based products with plant-based products (cultured meat, algae-based fodder)	C	E	E	D	E	E	E	E	E	E		E	B	B	E	E	E	E	E	E	E
Food processing (e.g., use of renewable energies, efficiency improvements, storage or conservation)	C	E	E	D	E	E	E	E	E	C	C	E	E	E	E	B	B	E	D	E	E
Reduction of food waste (including reuse of food processing refuse for fodder)	B	E	E	D	E	D	E	E	E	E	E	E	D	B	E	B	B	E	B	E	E
Supply Side Measures																					
Decarbonisation of Electricity:																					
Solar PV	**A**	**A**	**A**	D	**A**	**A**	B	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**
Solar CSP	E	E	**A**	D	E	**A**	E	**A**	E	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**

Table 2.SM.6 (continued)

Levels of Inclusion

	Explicit	Implicit
Endogenous	A	C
Exogenous	B	D
E	Not represented by model	

Levels of Inclusion / Model Names	AIM	BET	COPPE-COFFEE	C-ROADS	DNE21+	GCAM 4.2	GEM-E3 3.0	GENESYSmod 1.0	GRAPE 1.0	IEA ETP	IEA WEM	IMACLIM 1.1	IMACLIM NL	IMAGE 3.0	MERGE-ETL 6.0	MESSAGE-GLOBIOM	MESSAGEix-GLOBIOM	POLES	REMIND-MAgPIE	Shell WEM v1	WITCH
Supply Side Measures																					
Decarbonisation of Electricity:																					
Wind (on-shore and off-shore)	A	A	A	D	A	A	B	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Hydropower	A	A	A	D	A	A	B	A	A	A	A	A	A	B	A	A	A	A	A	A	A
Bio-electricity, including biomass co-firing	A	A	A	D	A	A	B	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Nuclear energy	A	A	A	D	A	A	B	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Advanced, small modular nuclear reactor designs (SMR)	E	E	A	D	E	A	E	E	E	C	C	E	E	E	A	E	E	E	E	C	E
Fuel cells (hydrogen)	E	E	A	D	A	A	E	A	A	A	A	E	E	A	A	A	A	A	A	A	A
CCS at coal and gas-fired power plants	A	A	A	D	A	A	B	E	A	A	A	A	A	A	A	A	E	A	A	B	A
Ocean energy (including tidal and current energy)	E	E	E	D	E	E	D	A	E	A	A	E	E	E	E	E	E	A	E	A	E
High-temperature geothermal heat	A	B	A	D	A	A	D	E	A	A	A	E	E	B	E	A	A	A	E	C	E
Decarbonisation of Non-Electric Fuels:																					
Hydrogen from biomass or electrolysis	E	A	A	D	A	A	E	A	A	A	C	E	E	A	A	A	A	A	A	A	E
First generation biofuels	A	E	A	D	A	A	B	E	A	A	A	C	A	A	A	B	B	A	B	A	A
Second generation biofuels (grassy or woody biomass to liquids)	A	A	A	D	A	A	B	A	A	A	A	E	A	A	A	A	A	A	A	A	A
Algae biofuels	E	E	A	D	E	E	E	C	E	E	C	E	E	E	E	E	E	E	E	A	E
Power-to-gas, methanisation, synthetic fuels	E	C	A	D	A	E	E	A	E	E	B	E	E	E	A	A	A	E	E	E	E
Solar and geothermal heating	E	E	A	D	E	E	B	A	E	A	A	E	E	E	E	A	A	A	A	A	E
Nuclear process heat	E	E	E	D	E	E	E	E	E	A	A	E	E	E	E	A	A	E	E	C	E
Other Processes:																					
Fuel switching and replacing fossil fuels by electricity in end-use sectors (partially a demand-side measure)	A	A	C	D	A	A	B	A	A	A	A	C	C	A	C	A	A	A	A	A	A
Substitution of halocarbons for refrigerants and insulation	C	E	E	D	E	C	C	E	E	E	E	E	E	A	E	A	A	A	D	E	C
Reduced gas flaring and leakage in extractive industries	C	E	A	D	D	C	C	E	E	E	A	E	E	C	E	B	B	A	C	D	D
Electrical transmission efficiency improvements, including smartgrids	B	E	C	D	A	E	E	E	E	B	B	E	E	B	C	E	E	E	E	B	E
Grid integration of intermittent renewables	E	E	C	D	A	C	E	C	D	A	A	E	E	C	C	C	C	A	A	D	C
Electricity storage	E	E	A	D	A	C	E	A	E	A	C	E	E	C	C	A	A	A	A	E	C
AFOLU Measures																					
Reduced deforestation, forest protection, avoided forest conversion	A	E	A	D	B	A	E	E	B	D	D	E	B	B	E	A	A	B	A	D	C
Forest management	C	E	E	D	E	C	E	E	C	D	D	E	B	B	E	A	A	B	E	D	C
Reduced land degradation, and forest restoration	C	E	D	D	E	E	E	E	C	D	D	E	E	B	E	E	E	B	E	D	E
Agroforestry and silviculture	E	E	D	D	E	E	E	E	E	D	D	E	E	E	E	E	E	E	E	E	E
Urban and peri-urban agriculture and forestry	E	E	E	D	E	E	E	E	E	D	D	E	E	E	E	E	E	E	E	E	E
Fire management and (ecological) pest control	C	E	D	D	E	C	E	E	E	D	D	E	E	E	E	E	E	E	E	E	E
Changing agricultural practices that enhance soil carbon	C	E	E	D	E	E	E	E	E	D	D	E	E	E	E	E	E	B	E	D	E
Conservation agriculture	E	E	E	D	E	E	E	E	E	D	D	E	E	E	E	A	A	E	E	E	C
Increasing agricultural productivity	A	E	A	D	A	B	E	E	B	D	D	E	A	B	E	A	A	E	A	D	C
Methane reductions in rice paddies	C	E	C	D	C	C	C	E	C	D	D	E	C	C	E	A	A	B	C	D	C
Nitrogen pollution reductions (e.g., by fertilizer reduction, increasing nitrogen fertilizer efficiency, sustainable fertilizers)	C	E	C	D	C	C	C	E	E	D	D	E	A	C	E	A	A	B	C	D	C
Livestock and grazing management, for example, methane and ammonia reductions in ruminants through feeding management or feed additives, or manure management for local biogas production to replace traditional biomass use	C	E	C	D	C	C	C	E	C	D	D	E	A	C	E	A	A	B	C	D	C
Manure management	C	E	C	D	C	C	C	E	C	D	D	E	C	C	E	A	A	E	C	E	C
Influence on land albedo of land use change	E	E	E	D	E	E	E	E	E	D	D	E	E	E	E	E	E	E	D	D	E

Table 2.SM.6 (continued)

Levels of Inclusion

	Explicit	Implicit
Endogenous	A	C
Exogenous	B	D
E	Not represented by model	

Levels of Inclusion	AIM	BET	COPPE-COFFEE	C-ROADS	DNE21+	GCAM 4.2	GEM-E3 3.0	GENESYSmod 1.0	GRAPE 1.0	IEA ETP	IEA WEM	IMACLIM 1.1	IMACLIM NL	IMAGE 3.0	MERGE-ETL 6.0	MESSAGE-GLOBIOM	MESSAGEix-GLOBIOM	POLES	REMIND-MAgPIE	Shell WEM v1	WITCH
Carbon Dioxide (Greenhouse Gas) Removal																					
Biomass use for energy production with carbon capture and sequestration (BECCS) (through combustion, gasification, or fermentation)	A	A	A	D	A	A	E	E	A	A	A	A	A	A	A	A	E	A	A	B	A
Direct air capture and sequestration (DACS) of CO_2 using chemical solvents and solid absorbents, with subsequent storage	E	E	E	D	E	E	E	E	E	E	E	E	E	E	A	E	E	E	A	E	E
Mineralization of atmospheric CO_2 through enhanced weathering of rocks	E	E	E	D	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
Afforestation/Reforestation	A	E	A	C	A	A	E	E	A	E	E	E	B	B	E	A	A	B	A	D	A
Restoration of wetlands (e.g., coastal and peat-land restoration, blue carbon)	E	E	E	D	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
Biochar	E	E	E	D	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
Soil carbon enhancement, enhancing carbon sequestration in biota and soils, e.g. with plants with high carbon sequestration potential (also AFOLU measure)	E	E	E	D	E	E	E	E	E	E	E	E	D	E	E	A	A	B	C	E	E
Carbon capture and usage (CCU); bioplastics (bio-based materials replacing fossil fuel uses as feedstock in the production of chemicals and polymers), carbon fibre	E	E	E	D	E	C	E	E	E	A	B	E	E	A	E	E	E	E	E	A	E
Material substitution of fossil CO_2 with bio-CO_2 in industrial application (e.g. the beverage industry)	E	E	E	D	E	C	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
Ocean iron fertilization	E	E	E	D	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
Ocean alcanization	E	E	E	D	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
Removing CH_4, N_2O and halocarbons via photocatalysis from the atmosphere	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E

2.SM.1.3 Overview of SR1.5 Scenario Database Collected for the Assessment in the Chapter

The scenario ensemble collected in the context of this report represents an ensemble of opportunity based on available published studies. The submitted scenarios cover a wide range of scenario types and thus allow exploration of a wide range of questions. For this to be possible, however, critical scenario selection based on scenario assumptions and setup is required. For example, as part of the SSP framework, a structured exploration of 1.5°C pathways was carried out under different future socioeconomic developments (Rogelj et al., 2018). This facilitates determining the fraction of successful (feasible) scenarios per SSPs (Table 2.SM.7), an assessment which cannot be carried out with a more arbitrary ensemble of opportunity.

Table 2.SM.7 | Summary of models (with scenarios in the database) attempting to create scenarios with an end-of-century forcing of 1.9W m^{-2}, consistent with limiting warming to below 1.5°C in 2100, and related shared policy assumptions (SPAs). Notes: 1 = successful scenario consistent with modelling protocol; 0 = unsuccessful scenario; x = not modelled; 0* = not attempted because scenarios for a 2.6 W m^{-2} target were already found to be unachievable in an earlier study. The SSP3-SPA3 scenario for a more stringent 1.9 W m^{-2} radiative forcing target has thus not been attempted anew by many modelling teams. Marker implementations for all forcing targets within each SSP have been selected for representing a specific SSP particularly adequately, and are indicated in blue. Source: Rogelj et al., 2018.

Model	Methodology	Reported scenario				
		SSP1-SPA1	SSP2-SPA2	SSP3-SPA3	SSP4-SPA4	SSP5-SPA5
AIM	General equilibrium (GE)	1	1	0*	0	0
GCAM4	Partial equilibrium (PE)	1	1	X	0	1
IMAGE	Hybrid (system dynamic models and GE for agriculture)	1	0	0*	X	X
MESSAGE-GLOBIOM	Hybrid (systems engineering PE model)	1	1	0*	X	X
REMIND-MAgPIE	General equilibrium (GE)	1	1	X	X	1
WITCH-GLOBIOM	General equilibrium (GE)	1	0	0	1	0

2.SM.1.3.1 Configuration of SR1.5 Scenario Database

The Integrated Assessment Modelling Consortium (IAMC), as part of its ongoing cooperation with Working Group III of the IPCC, issued a call for submissions of scenarios of 1.5°C global warming and related scenarios to facilitate the assessment of mitigation pathways in this special report. This database is hosted by the International Institute for Applied Systems Analysis (IIASA) at https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/. Upon approval of this report, the database of scenarios underlying this assessment will also be published. Computer scripts and tools used to conduct the analysis and generate figures will also be available for download from that website.

2.SM.1.3.1.1 Criteria for submission to the scenario database

Scenarios submitted to the database were required to either aim at limiting warming to 1.5°C or 2°C in the long term, or to provide context for such scenarios, for example, corresponding Nationally Determined Contribution (NDC) and baseline scenarios without climate policy. Model results should constitute an emissions trajectory over time, with underlying socio-economic development until at least the year 2050 generated by a formal model such as a dynamic systems, energy–economy, partial or general equilibrium or integrated assessment model.

The end of the 21st century is referred to as "long term" in the context of this scenario compilation. For models with time horizons shorter than 2100, authors and/or submitting modelling teams were asked to explain how they evaluated their scenario as being consistent with 1.5°C in the long term. Ultimately, scenarios that only covered part of the 21st century could only be integrated into the assessment to a very limited degree, as they lacked the longer-term perspective. Submissions of emissions scenarios for individual regions and specific sectors were possible, but no such scenarios were received.

Each scenario submission required a supporting publication in a peer-reviewed journal that was accepted by 15 May 2018. Alternatively, the scenario must have been published by the same date in a report that has been determined by IPCC to be eligible grey literature (see Table 2.SM.9). As part of the submission process, the authors of the underlying modelling team agreed to the publication of their model results in this scenario database.

2.SM.1.3.1.2 Historical consistency analysis of submitted scenarios

Submissions to the scenario database were compared to the following data sources for historical periods to identify reporting issues.

Historical emissions database (CEDS)
Historical emissions imported from the *Community Emissions Data System (CEDS) for Historical Emissions* (http://www.globalchange.umd.edu/ceds/) have been used as a reference and for use in figures (van Marle et al., 2017; Hoesly et al., 2018). Historical N_2O emissions, which are not included in the CEDS database, are compared against the RCP database (http://tntcat.iiasa.ac.at/RcpDb/).

Historical IEA World Energy Balances and Statistics
Aggregated historical time series of the energy system from the IEA World Energy Balances and Statistics (revision 2017) were used as a reference for validation of submitted scenarios and for use in figures.

2.SM.1.3.1.3 Verification of completeness and harmonization for climate impact assessment

Categorizing scenarios according to their long-term warming impact requires reported emissions time series until the end of the century of the following species: CO_2 from energy and industrial processes, methane, nitrous oxide and sulphur. The long-term climate impact could not be assessed for scenarios not reporting these species, and these scenarios were hence not included in any subsequent analysis.

For the diagnostic assessment of the climate impact of each submitted scenario, reported emissions were harmonized to historical values (base year 2010) as provided in the RCP database by applying an additive offset, which linearly decreased until 2050. For non-CO_2 emissions where this method resulted in negative values, a multiplicative offset was used instead. Emissions other than the required species that were not reported explicitly in the submitted scenario were filled from RCP2.6 (Meinshausen et al., 2011b; van Vuuren et al., 2011) to provide complete emissions profiles to MAGICC and FAIR (see Section 2.SM.1.1).

The harmonization and completion of non-reported emissions was only applied to the diagnostic assessment as input for the climate impact using MAGICC and FAIR. All figures and analysis used in the chapter analysis are based on emissions as reported by the modelling teams, except for column "Cumulative CO_2 emissions, harmonized" in Table 2.SM.12.

2.SM.1.3.1.4 Validity assessment of historical emissions for aggregate Kyoto greenhouse gases

The AR5 WGIII report assessed Kyoto greenhouse gases (GHG) in 2010 to fall in the range of 44.5–53.5 $GtCO_2e\ yr^{-1}$ using the GWP_{100} metric from the IPCC Second Assessment Report (SAR). As part of the diagnostics, the Kyoto GHG aggregation was recomputed using GWP_{100} according to SAR, AR4 and AR5 for all scenarios that provided sufficient level of detail for their emissions. A total of 33 scenarios from three modelling frameworks showed recomputed Kyoto GHG outside the year-2010 range assessed by the AR5 WGIII report. These scenarios were excluded from all analysis of near-term emissions evolutions, in particular in Figures 2.6, 2.7 and 2.8, and Table 2.4.

2.SM.1.3.1.5 Plausibility assessment of near-term development

Submitted scenarios were assessed for the plausibility of their near-term development across a number of dimensions. One issue identified were drastic reductions of CO_2 emissions from the land-use sector by 2020. Given recent trends, this was considered implausible and all scenarios from the ADVANCE and EMF33 studies reporting negative CO_2 emissions from the land-use sector in 2020 were excluded from the analysis throughout this chapter.

2.SM.1.3.1.6 Missing carbon price information

Out of the 132 scenarios limiting global warming to 2°C throughout the century (see Table 2.SM.8), a total of twelve scenarios submitted by three modelling teams reported carbon prices of zero or missing values in at least one year. These scenarios were excluded from the analysis in Section 2.5 and Figure 2.26 in Chapter 2.

2.SM.1.3.2 Contributions to the SR1.5 Database by Modelling Framework

In total, 19 modelling frameworks submitted 529 individual scenarios-based manuscripts that were published or accepted for publication by 15 May 2018 (Table 2.SM.8).

Table 2.SM.8 | Overview of submitted scenarios by modelling framework, including the categorization according to the climate impact (cf. Section 2.SM.1.4) and outcomes of validity and near-term plausibility assessment of pathways (cf. Section 2.SM.1.3.1).

	Below-1.5°C	1.5°C Return with Low OS	1.5°C Return with High OS	Lower 2°C	Higher 2°C	Above 2°C	Scenarios Assessed	Not Full Century	Missing Emissions Species for Assessment	Negative CO_2 Emissions (AFOLU) in 2020	Scenarios Submitted
AIM		6	1	24	10	49	**90**				**90**
BET									16		**16**
C-ROADS	2	1	2			1	**6**				**6**
DNE21+									21		**21**
FARM									13		**13**
GCAM		1	2	1	3	16	**23**			24	**47**
GEM-E3								4			**4**
GENeSYS-MOD								1			**1**
GRAPE									18		**18**
IEA ETP								1			**1**
IEA World Energy Model					1		**1**				**1**
IMACLIM								7	12		**19**
IMAGE		7	4	6	9	35	**61**				**61**
MERGE		1			1	1	**3**				**3**
MESSAGE		6	6	11	13	22	**58**				**58**
POLES	4	7	5	9	3	9	**37**				**37**
REMIND/REMIND–MAgPIE	2	11	17	16	16	31	**93**				**93**
Shell World Energy Model								1			**1**
WITCH	1	4		7	2	25	**39**				**39**
Total	**9**	**44**	**37**	**74**	**58**	**189**	**411**	**14**	**80**	**24**	**529**

2.SM.1.3.3 Overview and Scope of Studies Available in SR1.5 Database

Table 2.SM.9 | Recent studies included in the scenario database that this chapter draws upon and their key foci indicating which questions can be explored by the scenarios of each study. The difference between "Scenarios Submitted" and "Scenarios Assessed" is due to criteria described in Section 2.SM.1.3.1. The numbers between brackets indicate the modelling frameworks assessed.

Study/Model Name	Key Focus	Reference Papers	Modelling Frameworks	Scenarios Submitted	Scenarios Assessed
Multimodel Studies					
SSPx-1.9	Development of new community scenarios based on the full SSP framework limiting end-of-century radiative forcing to 1.9 W m^{-2}.	Riahi et al. (2017) Rogelj et al. (2018)	6	126	126
ADVANCE	Aggregate effect of the INDCs, comparison to optimal 2°C/1.5°C scenarios ratcheting up after 2020.	Vrontisi et al. (2018)	9 (6)	74	55
	Decarbonization bottlenecks and the effects of following the INDCs until 2030 as opposed to ratcheting up to optimal ambition levels after 2020 in terms of additional emissions locked in. Constraint of 400 $GtCO_2$ emissions from energy and industry over 2011–2100.	Luderer et al. (2018)			
CD-LINKS	Exploring interactions between climate and sustainable development policies, with the aim to identify robust integral policy packages to achieve all objectives.	McCollum et al. (2018)	8 (6)	36	36
	Evaluating implications of short-term policies on the mid-century transition in 1.5°C pathways linking the national to the global scale. Constraint of 400 $GtCO_2$ emissions over 2011–2100.				
EMF-33	Study of the bioenergy contribution in deep mitigation scenarios. Constraint of 400 $GtCO_2$ emissions from energy and industry over 2011–2100.	Bauer et al. (2018)	11 (5)	183	86

Table 2.SM.9 (continued)

Study/Model Name	Key Focus	Reference Papers	Modelling Frameworks	Scenarios Submitted	Scenarios Assessed
Single-Model Studies					
IMAGE 1.5	Understanding the dependency of 1.5°C pathways on negative emissions.	van Vuuren et al. (2018)		8	8
IIASA LED (MESSAGEix)	A global scenario of low energy demand (LED) for sustainable development below 1.5°C without negative emission technologies.	Grubler et al. (2018)		1	1
GENeSYS-MOD	Application of the open-source energy modelling system to the question of 1.5°C and 2°C pathways.	Löffler et al. (2017)		1	0
IEA WEO	World Energy Outlook.	OECD/IEA and IRENA (2017)		1	1
OECD/IEA ETP	Energy Technology Perspectives.	IEA (2017)		1	0
PIK CEMICS (REMIND)	Study of CDR requirements and portfolios in 1.5°C pathways.	Strefler et al. (2018a)		7	7
PIK PEP (REMIND-MAgPIE)	Exploring short-term policies as entry points to global 1.5°C pathways.	Kriegler et al. (2018)		13	13
PIK SD (REMIND-MAgPIE)	Targeted policies to compensate risk to sustainable development in 1.5°C scenarios.	Bertram et al. (2018)		12	12
AIM SFCM	Socio-economic factors and future challenges of the goal of limiting the increase in global average temperature to 1.5°C.	Liu et al. (2017)		33	33
C-Roads	Interactions between emissions reductions and carbon dioxide removal.	Holz et al. (2018)		6	6
PIK EMC (REMIND)	Exploring how delay closes the door to achieve various temperature targets, including limiting warming to 1.5°C	Luderer et al. (2013)		8	8
MESSAGE GEA	Exploring the relative importance of technological, societal, geophysical and political uncertainties for limiting warming to 1.5°C and 2°C.	Rogelj et al. (2013a, 2013b, 2015)		10	10
AIM TERL	The contribution of transport policies to the mitigation potential and cost of 2 °C and 1.5 °C goals	Zhang et al. (2018)		6	6
MERGE-ETL	The role of direct air capture and storage (DACS) in 1.5°C pathways.	Marcucci et al. (2017)		3	3
Shell SKY	A technically possible, but challenging pathway for society to achieve the goals of the Paris Agreement.	Shell International B.V. (2018)		1	0

2.SM.1.3.4 Data Collected

A reporting template was developed to facilitate the collection of standardized scenario results. The template was structured in nine categories, and each category was divided into four priority levels: "Mandatory", "High priority (Tier 1)", "Medium priority (Tier 2)", and "Other". In addition, one category was included to collect input assumptions on capital costs to facilitate the comparison across engineering-based models. An overview and definitions of all variables will be made available as part of the database publication.

Table 2.SM.10 | Number of variables (time series of scenario results) per category and priority level.

Category	Description	Mandatory (Tier 0)	High Priority (Tier 1)	Medium Priority (Tier 2)	Other	Total
Energy	Configuration of the energy system (for the full conversion chain of energy supply from primary energy extraction, electricity capacity, to final energy use)	19	91	83	0	193
Investment	Energy system investment expenditure	0	4	22	17	43
Emissions	Emissions by species and source	4	19	55	25	103
CCS	Carbon capture and sequestration	3	10	11	8	32
Climate	Radiative forcing and warming	0	11	2	8	21
Economy	GDP, prices, policy costs	2	15	25	7	49
SDG	Indicators on sustainable development goals achievement	1	9	11	1	22
Land	Agricultural production & demand	0	14	10	5	29
Water	Water consumption & withdrawal	0	0	16	1	17
Capital costs	Major electricity generation and other energy conversion technologies	0	0	0	31	31
Total		**29**	**173**	**235**	**103**	**540**

2SM

2.SM.1.4 Scenario Classification

A total of 529 scenarios were submitted to the scenario database. Of these, 14 scenarios did not report results until the end of the century and an additional 80 scenarios did not report the required emissions species. During the validation and diagnostics, 24 scenarios were excluded because of negative CO_2 emissions from the land-use sector by 2020 (see Section 2.SM.1.3). Therefore, the analysis in this report is based on 411 scenarios, of which 90 scenarios are consistent with 1.5°C at the end of the century and 132 remain below 2°C throughout the century (not including the 90 scenarios that are deemed consistent with 1.5°C). Table 2.SM.11 provides an overview of the number of scenarios per class. Table 2.SM.12 provides an overview of geophysical characteristics per class.

Table 2.SM.11 | Overview of pathway class specifications

Pathway Group	Class Name	Short Name Combined Classes	MAGICC Exceedance Probability Filter	Number of Scenarios
1.5°C	Below 1.5°C	-	P(1.5°C) ≤ 0.34	0
	Below 1.5°C	Below-1.5°C	0.34 < P(1.5°C) ≤ 0.5	9
	1.5°C Return with low overshoot (OS)	1.5°C-low-OS	0.5 < P(1.5°C) ≤ 0.67 AND P(1.5°C in 2100) ≤ 0.34	34
			0.5 < P(1.5°C) ≤ 0.67 AND 0.34 < P(1.5°C in 2100) ≤ 0.5	10
	1.5°C Return with high OS	1.5°C-high-OS	0.67 < P(1.5°C) AND P(1.5°C in 2100) ≤ 0.34	19
			0.67 < P(1.5°C) AND 0.34 < P(1.5°C in 2100) ≤ 0.5	18
2°C	Lower 2°C	Lower-2°C	P(2°C) ≤ 0.34 (excluding above)	74
	Higher 2°C	Higher-2°C	0.34 < P(2°C) ≤ 0.5 (excluding above)	58
Above 2°C	Above 2°C	-	0.5 < P(2°C)	189

As noted in the chapter text, scenario classification was based on probabilistic temperature outcomes assessed using the AR5 assessment of composition, forcing and climate response. These were represented within the MAGICC model (Meinshausen et al., 2009, 2011a) which was used in the same setup as AR5 WGIII analyses. As discussed in Chapter 2, Section 2.2, updates in geophysical understanding would alter such results were they incorporated within MAGICC, though central outcomes would remain well within the probability distribution of the setup used here (see Section 2.SM.1.1).

2.SM.1.5 Mitigation and SDG Pathway Synthesis

The Chapter 2 synthesis assessment (see Figure 2.28) of interactions between 1.5°C mitigation pathways and sustainable development or Sustainable Development Goals (SDGs) is based on the assessment of interactions between mitigation measures and SDGs carried out by Chapter 5 (Section 5.4). To derive a synthesis assessment of the interactions between 1.5°C mitigation pathways and SDGs, a set of clear and transparent steps are followed, as described below.

- Table 5.2 is at the basis of all interactions considered between mitigation measures and SDGs.
- A condensed set of mitigation measures, selecting and combining mitigation measures from Table 5.2, is defined (see Table 2.SM.13).
- If a measure in the condensed Chapter 2 set is a combination of multiple mitigation measures from Table 5.2, the main interaction (synergies, synergy or trade-off, trade-off) is based on all interactions with three-star (★★★) and four-star (★★★★) confidence ratings in Table 5.2. If no three-star or four-star interactions are available, lower confidence interactions are considered if available.
- The resulting interaction is defined by the interaction of the majority of cells.
- If one cell shows a diverging interaction and this interaction has three-star or more confidence level, a "synergy or trade-off" interaction is considered.
- If all interactions for a given mitigation measure and SDG combination are the same, the resulting interaction is represented with a bold symbol.
- If all three-star and four-star interactions are of the same nature, but a lower-confidence interaction is opposite, the interaction is represented with a regular symbol.
- Confidence is defined by the rounded average of all available confidence levels of the predominant direction (rounded down; four-star confidence in Table 5.2 is also reported as three-star in the Chapter 2 synthesis)
- If a measure in Table 5.2 is assessed to result in either a neutral effect or a synergy or trade-off, the synergy or trade-off is reported in the Chapter 2 synthesis, but the confidence level is reduced by one notch.

To derive relative synergy–risk profiles for the four scenario archetypes used in Chapter 2 (S1, S2, S5, LED, see Sections 2.1 and

Table 2.SM.12 | Geophysical characteristics of mitigation pathways derived at median peak temperature and at the end of the century (2100). Overshoot severity is the sum of median degree warming years exceeding 1.5°C over the 21st century. NA indicates that no mitigation pathways exhibit the given geophysical characteristic. Radiative forcing metrics are: total anthropogenic radiative forcing (RF all), CO_2 radiative forcing (RF CO_2), and non-CO_2 radiative forcing (RF non CO_2). Cumulative CO_2 emissions until peak median warming or 2100 are given for submitted and harmonized IAM outputs and are rounded at the nearest 10 $GtCO_2$. Values show: median (25th to 75th percentile) across scenarios. 'NoR' indicates that median warming exceeds 1.5°C but never returns below it before 2100. Scenarios with year-2010 Kyoto-GHG emissions outside the range assessed by IPCC AR5 Working Group III are excluded, as are scenario duplicates that would bias ranges towards a single study.
[*]: this statistic is computed from the three scenarios where median warming exceeds 2°C and returns below 2°C before 2100.

			Geophysical Characteristics at Peak Warming											Geophysical Characteristics in 2100									Geophysical Characteristics of the Temperature Overshoot				
Category	# scenarios with climate assessment	Peak|Median warming	Peak|Year	Peak|CO_2 [ppm]	Peak|RF all [W m^{-2}]	Peak|RF CO_2 [W m^{-2}]	Peak|RF non CO_2 [W m^{-2}]	Net zero CO_2 |Year	Cumulative CO_2 emissions (2016 to peak warming) as submitted [$GtCO_2$]	Cumulative CO_2 emissions (2016 to peak warming) harmonized [$GtCO_2$]	Peak|Exeedance Probability 1.5°C [%]	Peak|Exeedance Probability 2.0°C [%]	Peak|Exeedance Probability 2.5°C [%]	2100| CO_2 [ppm]	2100|RF all [W m^{-2}]	2100|RF CO_2 [W m^{-2}]	2100|RF non-CO_2 [W m^{-2}]	Cumulative CO_2 emissions (2016-2100) as submitted [$GtCO_2$]	Cumulative CO_2 emissions (2016-2100) harmonized [$GtCO_2$]	2100|Exeedance Probability 1.5°C [%]	2100|Exeedance Probability 2.0°C [%]	2100|Exeedance Probability 2.5°C [%]	Exceedance year|1.5°C [year]	Overshoot duration|1.5°C [number of years]	Overshoot severity|1.5°C [temperature-years]	Exceedance year|2.0°C [year]	Overshoot duration|2.0°C [number of years]
Below-1.5°C	5	1.5 (1.5, 1.5)	2041 (2040, 2046)	423 (422, 424)	2.9 (2.8, 2.9)	2.3 (2.3, 2.3)	0.6 (0.6, 0.6)	2044 (2038, 2050)	480 (480, 490)	460 (460, 470)	45 (42, 46)	5 (5, 5)	1 (1, 1)	376 (374, 378)	1.8 (1.8, 2.0)	1.6 (1.6, 1.7)	0.3 (0.2, 0.3)	180 (180, 180)	150 (150, 220)	16 (14, 19)	3 (3, 4)	1 (1, 1)	NA	NA	NA	NA	NA
1.5°C-low-OS	37	1.6 (1.5, 1.6)	2048 (2045, 2050)	431 (429, 435)	3.0 (2.9, 3.0)	2.4 (2.3, 2.4)	0.6 (0.5, 0.6)	2050 (2047, 2055)	620 (600, 670)	620 (590, 670)	60 (56, 62)	10 (9, 12)	1 (1, 2)	380 (376, 387)	2.1 (2.0, 2.2)	1.7 (1.6, 1.8)	0.3 (0.3, 0.4)	260 (180, 360)	270 (140, 340)	28 (25, 32)	7 (6, 8)	1 (1, 2)	2035 (2033, 2036)	27 (21, 37)	1 (1, 2)	NA	NA
1.5°C-high-OS	36	1.7 (1.6, 1.7)	2051 (2048, 2053)	447 (440, 454)	3.2 (3.1, 3.3)	2.6 (2.5, 2.7)	0.6 (0.6, 0.7)	2052 (2049, 2059)	840 (760, 930)	870 (760, 930)	75 (72, 78)	18 (14, 20)	3 (2, 4)	385 (374, 405)	2.2 (2.0, 2.4)	1.8 (1.6, 2.0)	0.4 (0.3, 0.5)	330 (190, 630)	360 (180, 620)	33 (30, 45)	8 (8, 12)	2 (1, 3)	2033 (2032, 2033)	52 (43, 60)	6 (4, 8)	NA	NA
Lower-2°C	54	1.7 (1.7, 1.8)	2061 (2059, 2074)	454 (446, 458)	3.2 (3.1, 3.3)	2.6 (2.5, 2.7)	0.6 (0.5, 0.7)	2070 (2063, 2079)	990 (890, 1080)	1000 (900, 1070)	79 (75, 82)	26 (22, 28)	6 (6, 7)	425 (419, 436)	2.8 (2.6, 2.9)	2.3 (2.2, 2.4)	0.4 (0.4, 0.5)	840 (780, 970)	860 (770, 970)	66 (59, 72)	21 (17, 26)	7 (6, 9)	2033 (2032, 2034)	NoR	NoR	NA	NA
Higher-2°C	54	1.9 (1.9, 2.0)	2078 (2069, 2100)	473 (464, 478)	3.4 (3.3, 3.5)	2.8 (2.8, 2.9)	0.5 (0.5, 0.7)	2084 (2070, post-2100)	1320 (1170, 1450)	1320 (1150, 1490)	87 (85, 89)	40 (38, 46)	13 (11, 15)	451 (435, 471)	3.1 (2.9, 3.3)	2.6 (2.4, 2.8)	0.5 (0.4, 0.5)	1260 (1000, 1450)	1260 (1000, 1470)	83 (76, 86)	38 (31, 43)	13 (10, 15)	2033 (2032, 2034)	NoR	NoR	NA	NA
Above-2°C	182	3.1 (2.2, 3.8)	Post-2100	651 (520, 777)	5.4 (3.9, 6.6)	4.6 (3.4, 5.5)	0.8 (0.6, 1.2)	post-2100	3550 (2000, 4790)	3530 (1980, 4780)	100 (95, 100)	96 (69, 100)	84 (31, 97)	651 (510, 777)	5.4 (3.8, 6.6)	4.6 (3.2, 5.5)	0.8 (0.5, 1.2)	3550 (1980, 4790)	3530 (1970, 4780)	100 (95, 100)	96 (68, 100)	84 (30, 97)	2032 (2031, 2033)	NoR	NoR	2051 (2047, 2058)	35 (26, 37) [*]

2SM

2.3), the relative deployment of the selected mitigation measures is used. For each mitigation measure, a proxy indicator is used (see Table 2.SM.14). The proxy indicator values are displayed on a relative scale from zero to one, where the value of the lowest pathway is set to the origin and the values of the other pathways scaled so that the maximum is one. The pathways with proxy indicator values that are neither 0 nor 1 receive a 0.5 weighting. These 0, 0.5, or 1 values are used to determine the relative achievement of specific synergies or trade-offs per SDG in each scenario, by summing each respective interaction type (synergy, trade-off, or synergy or trade-off) over all proxy indicators. Ultimately these sums are synthesized in one interaction based on the majority of sub-interactions (synergy, trade-off, or synergy or trade-off). In cases where both synergies and trade-offs are identified, the 'synergy or trade-off' interaction is attributed.

Table 2.SM.13 | Mapping of mitigation measures assessed in Table 5.2 of Chapter 5 to the condensed set of mitigation measured used for the mitigation-SDG synthesis of Chapter 2.

Table 5.2 Mitigation Measures Set			Chapter 2 Condensed Set
Demand	Industry	Accelerating energy efficiency improvement	DEMAND: Accelerating energy efficiency improvements in end use sectors
		Low-carbon fuel switch	DEMAND: Fuel switch and access to modern low-carbon energy
		Decarbonization/CCS/CCU	Not included
	Buildings	Behavioural response	DEMAND: Behavioural response reducing Building and Transport demand
		Accelerating energy efficiency improvement	DEMAND: Accelerating energy efficiency improvements in end use sectors
		Improved access & fuel switch to modern low-carbon energy	DEMAND: Fuel switch and access to modern low-carbon energy
	Transport	Behavioural response	DEMAND: Behavioural response reducing Building and Transport demand
		Accelerating energy efficiency improvement	DEMAND: Accelerating energy efficiency improvements in end use sectors
		Improved access & fuel switch to modern low-carbon energy	DEMAND: Fuel switch and access to modern low-carbon energy
Supply	Replacing coal	Non-biomass renewables: solar, wind, hydro	SUPPLY: Non-biomass renewables: solar, wind, hydro
		Increased use of biomass	SUPPLY: Increased use of biomass
		Nuclear/advanced nuclear	SUPPLY: Nuclear/advanced nuclear
		CCS: Bio energy	SUPPLY: Bioenergy with carbon capture and storage (BECCS)
	Advanced coal	CCS: Fossil	SUPPLY: Fossil fuels with carbon capture and storage (fossil-CCS)
Land & Ocean	Agriculture & Livestock	Behavioural response: Sustainable healthy diets and reduced food waste	DEMAND: Behavioural response: Sustainable healthy diets and reduced food waste
		Land based greenhouse gas reduction and soil carbon sequestration	LAND: Land-based greenhouse gas reduction and soil carbon sequestration
		Greenhouse gas reduction from improved livestock production and manure management systems	LAND: Greenhouse gas reduction from improved livestock production and manure management systems
	Forest	Reduced deforestation, REDD+	LAND: Reduced deforestation, REDD+, afforestation and reforestation
		Afforestation and reforestation	LAND: Reduced deforestation, REDD+, afforestation and reforestation
		Behavioural response (responsible sourcing)	Not included
	Oceans	Ocean iron fertilization	Not included
		Blue carbon	Not included
		Enhanced Weathering	Not included

Table 2.SM.14 | Mitigation measure and proxy indicators reflecting relative deployment of given measure across pathway archetypes. Values of Indicators 2, 3, and 4 are inversely related with the deployment of the respective measures.

Mitigation Measure		Pathway Proxy	
Group	**Description**	**Code**	**Description**
Demand	Accelerating energy efficiency improvements in end-use sectors	1	Compound annual growth rate of primary energy (PE) to final energy (FE) conversion from 2020 to 2050
	Behavioural response reducing Building and Transport demand	2	Percent change in FE between 2010 and 2050
	Fuel switch and access to modern low-carbon energy	3	Year-2050 carbon intensity of FE
	Behavioural response: Sustainable healthy diets and reduced food waste	4	Year-2050 share of non-livestock in food energy supply
Supply	Non-biomass renewables: solar, wind, hydro	5	Year-2050 PE from non-biomass renewables
	Increased use of biomass	6	Year-2050 PE from biomass
	Nuclear/advanced nuclear	7	Year-2050 PE from nuclear
	Bioenergy with carbon capture and storage (BECCS)	8	Year-2050 BECCS deployment in $GtCO_2$
	Fossil fuels with carbon capture and storage (fossil-CCS)	9	Year-2050 fossil-CCS deployment in $GtCO_2$
Land	Land based greenhouse gas reduction and soil carbon sequestration	10	Cumulative AFOLU CO_2 emissions over the 2020–2100 period
	Greenhouse gas reduction from improved livestock production and manure management systems	11	CH_4 and N_2O AFOLU emissions per unit of total food energy supply
	Reduced deforestation, REDD+, afforestation and reforestation	12	Change in global forest area between 2020 and 2050

References

Ackerman, F., S.J. DeCanio, R.B. Howarth, and K. Sheeran, 2009: Limitations of integrated assessment models of climate change. *Climatic Change*, **95(3–4)**, 297–315, doi:10.1007/s10584-009-9570-x.

Adler, M.D. et al., 2017: Priority for the worse-off and the social cost of carbon. *Nature Climate Change*, **7(6)**, 443–449, doi:10.1038/nclimate3298.

Allen, M.R. et al., 2018: A solution to the misrepresentations of CO_2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. *npj Climate and Atmospheric Science*, **1(1)**, 16, doi:10.1038/s41612-018-0026-8.

Amann, M., Z. Klimont, and F. Wagner, 2013: Regional and Global Emissions of Air Pollutants: Recent Trends and Future Scenarios. *Annual Review of Environment and Resources*, **38(1)**, 31–55, doi:10.1146/annurev-environ-052912-173303.

Bauer, N. et al., 2017: Shared Socio-Economic Pathways of the Energy Sector – Quantifying the Narratives. *Global Environmental Change*, **42**, 316–330, doi:10.1016/j.gloenvcha.2016.07.006.

Bauer, N. et al., 2018: Global energy sector emission reductions and bioenergy use: overview of the bioenergy demand phase of the EMF-33 model comparison. *Climatic Change*, 1–16, doi:10.1007/s10584-018-2226-y.

Beck, S. and M. Mahony, 2017: The IPCC and the politics of anticipation. *Nature Climate Change*, **7(5)**, 311–313, doi:10.1038/nclimate3264.

Bertram, C. et al., 2015: Complementing carbon prices with technology policies to keep climate targets within reach. *Nature Climate Change*, **5(3)**, 235–239, doi:10.1038/nclimate2514.

Bertram, C. et al., 2018: Targeted policies can compensate most of the increased sustainability risks in 1.5°C mitigation scenarios. *Environmental Research Letters*, **13(6)**, 064038, doi:10.1088/1748-9326/aac3ec.

Blanford, G.J., E. Kriegler, and M. Tavoni, 2014: Harmonization vs. fragmentation: Overview of climate policy scenarios in EMF27. *Climatic Change*, **123(3–4)**, 383–396, doi:10.1007/s10584-013-0951-9.

Bonsch, M. et al., 2014: Trade-offs between land and water requirements for large-scale bioenergy production. *GCB Bioenergy*, **8(1)**, 11–24, doi:10.1111/gcbb.12226.

Brunner, S. and K. Enting, 2014: Climate finance: A transaction cost perspective on the structure of state-to-state transfers. *Global Environmental Change*, **27**, 138–143, doi:10.1016/j.gloenvcha.2014.05.005.

Burke, M., S.M. Hsiang, and E. Miguel, 2015: Global non-linear effect of temperature on economic production. *Nature*, **527**, 235–239, doi:10.1038/nature15725.

Burke, M., W.M. Davis, and N.S. Diffenbaugh, 2018: Large potential reduction in economic damages under UN mitigation targets. *Nature*, **557(7706)**, 549–553, doi:10.1038/s41586-018-0071-9.

Burke, M. et al., 2016: Opportunities for advances in climate change economics. *Science*, **352(6283)**, 292–293, doi:10.1126/science.aad9634.

Cai, Y., K.L. Judd, T.M. Lenton, T.S. Lontzek, and D. Narita, 2015: Environmental tipping points significantly affect the cost-benefit assessment of climate policies. *Proceedings of the National Academy of Sciences*, **112(15)**, 4606–4611, doi:10.1073/pnas.1503890112.

Cameron, C. et al., 2016: Policy trade-offs between climate mitigation and clean cook-stove access in South Asia. *Nature Energy*, **1(1)**, 15010, doi:10.1038/nenergy.2015.10.

Chen, C. and M. Tavoni, 2013: Direct air capture of CO_2 and climate stabilization: A model based assessment. *Climatic Change*, **118(1)**, 59–72, doi:10.1007/s10584-013-0714-7.

Chilvers, J. et al., 2017: Realising transition pathways for a more electric, low-carbon energy system in the United Kingdom: Challenges, insights and opportunities. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, **231(6)**, 440–477, doi:10.1177/0957650917695448.

Clarke, L. et al., 2009: International climate policy architectures: Overview of the EMF 22 International Scenarios. *Energy Economics*, **31**, S64–S81, doi:10.1016/j.eneco.2009.10.013.

Clarke, L. et al., 2014: Assessing transformation pathways. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 413–510.

Collins, M. et al., 2013: Long-term Climate Change: Projections, Commitments and Irreversibility. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1029–1136.

Craxton, M., J. Merrick, C. Makridis, and J. Taggart, 2017: On the climate policy implications of substitutability and flexibility in the economy: An in-depth integrated assessment model diagnostic. *Technological Forecasting and Social Change*, **125**, 289–298, doi:10.1016/j.techfore.2017.07.003.

Creutzig, F. et al., 2017: The underestimated potential of solar energy to mitigate climate change. *Nature Energy*, **2(9)**, 17140, doi:10.1038/nenergy.2017.140.

Dell, M., B.F. Jones, and B.A. Olken, 2014: What Do We Learn from the Weather? The New Climate–Economy Literature. *Journal of Economic Literature*, **52(3)**, 740–798, www.jstor.org/stable/24434109.

Dennig, F., M.B. Budolfson, M. Fleurbaey, A. Siebert, and R.H. Socolow, 2015: Inequality, climate impacts on the future poor, and carbon prices. *Proceedings of the National Academy of Sciences*, **112(52)**, 15827–15832, doi:10.1073/pnas.1513967112.

Dietz, S. and N. Stern, 2008: Why Economic Analysis Supports Strong Action on Climate Change: A Response to the Stern Review's Critics. *Review of Environmental Economics and Policy*, **2(1)**, 94–113, doi:10.1093/reep/ren001.

Edelenbosch, O.Y. et al., 2017a: Comparing projections of industrial energy demand and greenhouse gas emissions in long-term energy models. *Energy*, **122**, 701–710, doi:10.1016/j.energy.2017.01.017.

Edelenbosch, O.Y. et al., 2017b: Decomposing passenger transport futures: Comparing results of global integrated assessment models. *Transportation Research Part D: Transport and Environment*, **55**, 281–293, doi:10.1016/j.trd.2016.07.003.

Edelenbosch, O.Y. et al., 2017c: Transport fuel demand responses to fuel price and income projections: Comparison of integrated assessment models. *Transportation Research Part D: Transport and Environment*, **55**, 310–321, doi:10.1016/j.trd.2017.03.005.

Edenhofer, O. and M. Kowarsch, 2015: Cartography of pathways: A new model for environmental policy assessments. *Environmental Science & Policy*, **51**, 56–64, doi:10.1016/j.envsci.2015.03.017.

Edenhofer, O. et al., 2010: The Economics of Low Stabilization: Model Comparison of Mitigation Strategies and Costs. *The Energy Journal*, **31(Special Issue 1)**, 11–48, doi:10.2307/41323490.

Etminan, M., G. Myhre, E.J. Highwood, and K.P. Shine, 2016: Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. *Geophysical Research Letters*, **43(24)**, 12,614–12,623, doi:10.1002/2016gl071930.

Figueres, C. et al., 2017: Three years to safeguard our climate. *Nature*, **546(7660)**, 593–595, doi:10.1038/546593a.

Forster, P. et al., 2007: Changes in Atmospheric Constituents and in Radiative Forcing. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 129–234.

Frank, S. et al., 2017: Reducing greenhouse gas emissions in agriculture without compromising food security? *Environmental Research Letters*, **12(10)**, 105004, doi:10.1088/1748-9326/aa8c83.

Frank, S. et al., 2018: Structural change as a key component for agricultural non-CO_2 mitigation efforts. *Nature Communications*, **9(1)**, 1060, doi:10.1038/s41467-018-03489-1.

Fricko, O. et al., 2016: Energy sector water use implications of a 2°C climate policy. *Environmental Research Letters*, **11(3)**, 034011, doi:10.1088/1748-9326/11/3/034011.

Geels, F.W., B.K. Sovacool, T. Schwanen, and S. Sorrell, 2017: Sociotechnical transitions for deep decarbonization. *Science*, **357(6357)**, 1242–1244, doi:10.1126/science.aao3760.

Grubb, M., J.C. Hourcade, and K. Neuhoff, 2014: *Planetary economics: Energy, climate change and the three domains of sustainable development*. Routledge Earthscan, Abingdon, UK and New York, NY, USA, 520 pp.

2SM

Grubler, A., 2010: The costs of the French nuclear scale-up: A case of negative learning by doing. *Energy Policy*, **38(9)**, 5174–5188, doi:10.1016/j.enpol.2010.05.003.

Grubler, A. et al., 2018: A low energy demand scenario for meeting the 1.5°C target and sustainable development goals without negative emission technologies. *Nature Energy*, **3(6)**, 515–527, doi:10.1038/s41560-018-0172-6.

Gschrey, B., W. Schwarz, C. Elsner, and R. Engelhardt, 2011: High increase of global F-gas emissions until 2050. *Greenhouse Gas Measurement and Management*, **1(2)**, 85–92, doi:10.1080/20430779.2011.579352.

Guivarch, C., R. Crassous, O. Sassi, and S. Hallegatte, 2011: The costs of climate policies in a second-best world with labour market imperfections. *Climate Policy*, **11(1)**, 768–788, doi:10.3763/cpol.2009.0012.

Haegel, N.M. et al., 2017: Terawatt-scale photovoltaics: Trajectories and challenges. *Science*, **356(6334)**, 141–143, doi:10.1126/science.aal1288.

Hallegatte, S. and J. Rozenberg, 2017: Climate change through a poverty lens. *Nature Climate Change*, **7(4)**, 250–256, doi:10.1038/nclimate3253.

Havlík, P. et al., 2014: Climate change mitigation through livestock system transitions. *Proceedings of the National Academy of Sciences*, **111(10)**, 3709–3714, doi:10.1073/pnas.1308044111.

Hejazi, M. et al., 2014: Long-term global water projections using six socioeconomic scenarios in an integrated assessment modeling framework. *Technological Forecasting and Social Change*, **81**, 205–226, doi:10.1016/j.techfore.2013.05.006.

Hoesly, R.M. et al., 2018: Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS). *Geoscientific Model Development*, **11(1)**, 369–408, doi:10.5194/gmd-11-369-2018.

Holz, C., L.S. Siegel, E. Johnston, A.P. Jones, and J. Sterman, 2018: Ratcheting ambition to limit warming to 1.5°C – trade-offs between emission reductions and carbon dioxide removal. *Environmental Research Letters*, **13(6)**, 064028, doi:10.1088/1748-9326/aac0c1.

Houghton, R. et al., 2012: Carbon emissions from land use and land-cover change. *Biogeosciences*, **9(12)**, 5125–5142, doi:10.5194/bg-9-5125-2012.

Hsiang, S. et al., 2017: Estimating economic damage from climate change in the United States. *Science*, **356(6345)**, 1362–1369, doi:10.1126/science.aal4369.

Humpenöder, F. et al., 2018: Large-scale bioenergy production: how to resolve sustainability trade-offs? *Environmental Research Letters*, **13(2)**, 024011, doi:10.1088/1748-9326/aa9e3b.

IEA, 2017: *Energy Technology Perspectives 2017: Catalyzing Energy Technology Transformations*. International Energy Agency (IEA), Paris, France, 443 pp.

Iyer, G.C. et al., 2015: Improved representation of investment decisions in assessments of CO_2 mitigation. *Nature Climate Change*, **5(5)**, 436–440, doi:10.1038/nclimate2553.

Johnson, N. et al., 2017: A reduced-form approach for representing the impacts of wind and solar PV deployment on the structure and operation of the electricity system. *Energy Economics*, **64**, 651–664, doi:10.1016/j.eneco.2016.07.010.

Knutti, R. and J. Rogelj, 2015: The legacy of our CO_2 emissions: a clash of scientific facts, politics and ethics. *Climatic Change*, **133(3)**, 361–373, doi:10.1007/s10584-015-1340-3.

Kolstad, C. et al., 2014: Social, Economic and Ethical Concepts and Methods. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadne, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 207–282.

Krey, V., G. Luderer, L. Clarke, and E. Kriegler, 2014a: Getting from here to there – energy technology transformation pathways in the EMF27 scenarios. *Climatic Change*, **123**, 369–382, doi:10.1007/s10584-013-0947-5.

Krey, V. et al., 2014b: Annex II: Metrics & Methodology. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1281–1328.

Kriegler, E. et al., 2014: The role of technology for achieving climate policy objectives: Overview of the EMF 27 study on global technology and climate policy strategies. *Climatic Change*, **123(3–4)**, 353–367, doi:10.1007/s10584-013-0953-7.

Kriegler, E. et al., 2015a: Diagnostic indicators for integrated assessment models of climate policy. *Technological Forecasting and Social Change*, **90(Part A)**, 45–61, doi:10.1016/j.techfore.2013.09.020.

Kriegler, E. et al., 2015b: Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. *Technological Forecasting and Social Change*, **90(Part A)**, 24–44, doi:10.1016/j.techfore.2013.09.021.

Kriegler, E. et al., 2016: Will economic growth and fossil fuel scarcity help or hinder climate stabilization?: Overview of the RoSE multi-model study. *Climatic Change*, **136(1)**, 7–22, doi:10.1007/s10584-016-1668-3.

Kriegler, E. et al., 2018: Short term policies to keep the door open for Paris climate goals. *Environmental Research Letters*, **13(7)**, 074022, doi:10.1088/1748-9326/aac4f1.

Kunreuther, H. et al., 2014: Integrated Risk and Uncertainty Assessment of Climate Change Response Policies. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 151–205.

Laitner, J., S. De Canio, and I. Peters, 2000: Incorporating Behavioural, Social, and Organizational Phenomena in the Assessment of Climate Change Mitigation Options. In: *Society, Behaviour, and Climate Change Mitigation* [Jochem, E., J. Sathaye, and D. Bouille (eds.)]. Springer Netherlands, Dordrecht, The Netherlands, pp. 1–64, doi:10.1007/0-306-48160-x_1.

Le Quéré, C. et al., 2018: Global Carbon Budget 2017. *Earth System Science Data*, **10(1)**, 405–448, doi:10.5194/essd-10-405-2018.

Leach, N.J. et al., 2018: Current level and rate of warming determine emissions budgets under ambitious mitigation. *Nature Geoscience*, **11(8)**, 574–579, doi:10.1038/s41561-018-0156-y.

Li, F.G.N. and N. Strachan, 2017: Modelling energy transitions for climate targets under landscape and actor inertia. *Environmental Innovation and Societal Transitions*, **24**, 106–129, doi:10.1016/j.eist.2016.08.002.

Li, F.G.N., E. Trutnevyte, and N. Strachan, 2015: A review of socio-technical energy transition (STET) models. *Technological Forecasting and Social Change*, **100**, 290–305, doi:10.1016/j.techfore.2015.07.017.

Liu, J.-Y. et al., 2018: Socioeconomic factors and future challenges of the goal of limiting the increase in global average temperature to 1.5°C. *Carbon Management*, 1–11, doi:10.1080/17583004.2018.1477374.

Löffler, K. et al., 2017: Designing a Model for the Global Energy System – GENeSYS-MOD: An Application of the Open-Source Energy Modeling System (OSeMOSYS). *Energies*, **10(10)**, 1468, doi:10.3390/en10101468.

Lontzek, T.S., Y. Cai, K.L. Judd, and T.M. Lenton, 2015: Stochastic integrated assessment of climate tipping points indicates the need for strict climate policy. *Nature Climate Change*, **5(5)**, 441–444, doi:10.1038/nclimate2570.

Lucon, O. et al., 2014: Buildings. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 671–738.

Luderer, G., C. Bertram, K. Calvin, E. De Cian, and E. Kriegler, 2016: Implications of weak near-term climate policies on long-term mitigation pathways. *Climatic Change*, **136(1)**, 127–140, doi:10.1007/s10584-013-0899-9.

Luderer, G. et al., 2012: The economics of decarbonizing the energy system – results and insights from the RECIPE model intercomparison. *Climatic Change*, **114(1)**, 9–37, doi:10.1007/s10584-011-0105-x.

Luderer, G. et al., 2013: Economic mitigation challenges: how further delay closes the door for achieving climate targets. *Environmental Research Letters*, **8(3)**, 034033, doi:10.1088/1748-9326/8/3/034033.

Luderer, G. et al., 2017: Assessment of wind and solar power in global low-carbon energy scenarios: An introduction. *Energy Economics*, **64**, 542–551, doi:10.1016/j.eneco.2017.03.027.

Luderer, G. et al., 2018: Residual fossil CO_2 emissions in 1.5–2°C pathways. *Nature Climate Change*, **8(7)**, 626–633, doi:10.1038/s41558-018-0198-6.

Marcucci, A., S. Kypreos, and E. Panos, 2017: The road to achieving the long-term Paris targets: Energy transition and the role of direct air capture. *Climatic Change*, **144(2)**, 181–193, doi:10.1007/s10584-017-2051-8.

McCollum, D.L. et al., 2017: Improving the behavioral realism of global integrated assessment models: An application to consumers' vehicle choices. *Transportation Research Part D: Transport and Environment*, **55**, 322–342, doi:10.1016/j.trd.2016.04.003.

McCollum, D.L. et al., 2018: Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. *Nature Energy*, **3(7)**, 589–599, doi:10.1038/s41560-018-0179-z.

Meinshausen, M., T.M.L. Wigley, and S.C.B. Raper, 2011a: Emulating atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 2: Applications. *Atmospheric Chemistry and Physics*, **11(4)**, 1457–1471, doi:10.5194/acp-11-1457-2011.

Meinshausen, M. et al., 2009: Greenhouse-gas emission targets for limiting global warming to 2°C. *Nature*, **458(7242)**, 1158–1162, doi:10.1038/nature08017.

Meinshausen, M. et al., 2011b: The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic Change*, **109(1–2)**, 213–241, doi:10.1007/s10584-011-0156-z.

Mercure, J.-F. et al., 2018: Environmental impact assessment for climate change policy with the simulation-based integrated assessment model E3ME-FTT-GENIE. *Energy Strategy Reviews*, **20**, 195–208, doi:10.1016/j.esr.2018.03.003.

Mouratiadou, I. et al., 2016: The impact of climate change mitigation on water demand for energy and food: An integrated analysis based on the Shared Socioeconomic Pathways. *Environmental Science & Policy*, **64**, 48–58, doi:10.1016/j.envsci.2016.06.007.

Mouratiadou, I. et al., 2018: Water demand for electricity in deep decarbonisation scenarios: a multi-model assessment. *Climatic Change*, **147(1)**, 91–106, doi:10.1007/s10584-017-2117-7.

Mundaca, L., L. Neij, E. Worrell, and M. McNeil, 2010: Evaluating Energy Efficiency Policies with Energy-Economy Models. *Annual Review of Environment and Resources*, **35(1)**, 305–344, doi:10.1146/annurev-environ-052810-164840.

Mundaca, L., M. Mansoz, L. Neij, and G. Timilsina, 2013: Transaction costs analysis of low-carbon technologies. *Climate Policy*, **13(4)**, 490–513, doi:10.1080/14693062.2013.781452.

Myhre, G. et al., 2013: Anthropogenic and Natural Radiative Forcing. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 659–740.

Myhre, G. et al., 2017: Multi-model simulations of aerosol and ozone radiative forcing due to anthropogenic emission changes during the period 1990–2015. *Atmospheric Chemistry and Physics*, **17(4)**, 2709–2720, doi:10.5194/acp-17-2709-2017.

Nordhaus, W.D., 2007: A Review of The Stern Review on the Economics of Climate Change. *Journal of Economic Literature*, **45(3)**, 686–702, www.jstor.org/stable/27646843.

OECD/IEA and IRENA, 2017: *Perspectives for the Energy Transition: Investment Needs for a Low-Carbon Energy System*. OECD/IEA and IRENA, 204 pp.

Parkinson, S. et al., 2019: Balancing clean water-climate change mitigation trade-offs. *Environmental Research Letters,* **14(1),** 014009, doi:10.1088/1748-9326/aaf2a3

Patt, A.G., 2015: *Transforming energy: Solving climate change with technology policy*. Cambridge University Press, New york, 349 pp.

Patt, A.G. et al., 2010: Adaptation in integrated assessment modeling: where do we stand? *Climatic Change*, **99**, 383–402, doi:10.1007/s10584-009-9687-y.

Pauliuk, S., A. Arvesen, K. Stadler, and E.G. Hertwich, 2017: Industrial ecology in integrated assessment models. *Nature Climate Change*, **7(1)**, 13–20, doi:10.1038/nclimate3148.

Pietzcker, R.C. et al., 2017: System integration of wind and solar power in integrated assessment models: A cross-model evaluation of new approaches. *Energy Economics*, **64**, 583–599, doi:10.1016/j.eneco.2016.11.018.

Pizer, W. et al., 2014: Using and improving the social cost of carbon. *Science*, **346(6214)**, 1189–1190, doi:10.1126/science.1259774.

Popp, A. et al., 2014: Land-use transition for bioenergy and climate stabilization: Model comparison of drivers, impacts and interactions with other land use based mitigation options. *Climatic Change*, **123(3–4)**, 495–509, doi:10.1007/s10584-013-0926-x.

Popp, A. et al., 2017: Land-use futures in the shared socio-economic pathways. *Global Environmental Change*, **42**, 331–345, doi:10.1016/j.gloenvcha.2016.10.002.

Rao, S. et al., 2017: Future air pollution in the Shared Socio-economic Pathways. *Global Environmental Change*, **42**, 346–358, doi:10.1016/j.gloenvcha.2016.05.012.

Revesz, R. et al., 2014: Global warming: Improve economic models of climate change. *Nature*, **508(7495)**, 173–175, doi:10.1038/508173a.

Riahi, K. et al., 2015: Locked into Copenhagen pledges – Implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technological Forecasting and Social Change*, **90(Part A)**, 8–23, doi:10.1016/j.techfore.2013.09.016.

Riahi, K. et al., 2017: The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, **42**, 153–168, doi:10.1016/j.gloenvcha.2016.05.009.

Rockström, J. et al., 2017: A roadmap for rapid decarbonization. *Science*, **355(6331)**, 1269–1271, doi:10.1126/science.aah3443.

Rogelj, J., D.L. McCollum, B.C. O'Neill, and K. Riahi, 2013a: 2020 emissions levels required to limit warming to below 2 C. *Nature Climate Change*, **3(4)**, 405–412, doi:10.1038/nclimate1758.

Rogelj, J., D.L. McCollum, A. Reisinger, M. Meinshausen, and K. Riahi, 2013b: Probabilistic cost estimates for climate change mitigation. *Nature*, **493(7430)**, 79–83, doi:10.1038/nature11787.

Rogelj, J. et al., 2014: Disentangling the effects of CO_2 and short-lived climate forcer mitigation. *Proceedings of the National Academy of Sciences*, **111(46)**, 16325–16330, doi:10.1073/pnas.1415631111.

Rogelj, J. et al., 2015: Energy system transformations for limiting end-of-century warming to below 1.5°C. *Nature Climate Change*, **5(6)**, 519–527, doi:10.1038/nclimate2572.

Rogelj, J. et al., 2018: Scenarios towards limiting global mean temperature increase below 1.5°C. *Nature Climate Change*, **8(4)**, 325–332, doi:10.1038/s41558-018-0091-3.

Rubin, E.S., J.E. Davison, and H.J. Herzog, 2015: The cost of CO_2 capture and storage. *International Journal of Greenhouse Gas Control*, **40**, 378–400, doi:10.1016/j.ijggc.2015.05.018.

Schneider von Deimling, T. et al., 2012: Estimating the near-surface permafrost-carbon feedback on global warming. *Biogeosciences*, **9(2)**, 649–665, doi:10.5194/bg-9-649-2012.

Schneider von Deimling, T. et al., 2015: Observation-based modelling of permafrost carbon fluxes with accounting for deep carbon deposits and thermokarst activity. *Biogeosciences*, **12(11)**, 3469–3488, doi:10.5194/bg-12-3469-2015.

Schwanitz, V.J., 2013: Evaluating integrated assessment models of global climate change. *Environmental Modelling & Software*, **50**, 120–131, doi:10.1016/j.envsoft.2013.09.005.

Shah, N., M. Wei, V. Letschert, and A. Phadke, 2015: *Benefits of Leapfrogging to Superefficiency and Low Global Warming Potential Refrigerants in Room Air Conditioning*. LBNL-1003671, Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA, USA, 58 pp.

Shell International B.V., 2018: *Shell Scenarios: Sky – Meeting the Goals of the Paris Agreement*. Shell International B.V. 36 pp.

Shindell, D.T. et al., 2012: Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security. *Science*, **335(6065)**, 183–189, doi:10.1126/science.1210026.

Smith, C.J. et al., 2018: FAIR v1.3: a simple emissions-based impulse response and carbon cycle model. *Geoscientific Model Development*, **11(6)**, 2273–2297, doi:10.5194/gmd-11-2273-2018.

Stanton, E.A., F. Ackerman, and S. Kartha, 2009: Inside the integrated assessment models: Four issues in climate economics. *Climate and Development*, **1(2)**, 166–184, doi:10.3763/cdev.2009.0015.

Stern, N., 2016: Current climate models are grossly misleading. *Nature*, **530**, 407–409, doi:10.1038/530407a.

Stevanović, M. et al., 2016: The impact of high-end climate change on agricultural welfare. *Science Advances*, **2(8)**, e1501452, doi:10.1126/sciadv.1501452.

Stiglitz, J.E. et al., 2017: *Report of the High-Level Commission on Carbon Prices*. Carbon Pricing Leadership Coalition (CPLC), 68 pp.

Stocker, T.F. et al., 2013: Technical Summary. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*

[Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 33–115.

Strefler, J., T. Amann, N. Bauer, E. Kriegler, and J. Hartmann, 2018a: Potential and costs of carbon dioxide removal by enhanced weathering of rocks. *Environmental Research Letters*, **13(3)**, 034010, doi:10.1088/1748-9326/aaa9c4.

Strefler, J. et al., 2018b: Between Scylla and Charybdis: Delayed mitigation narrows the passage between large-scale CDR and high costs. *Environmental Research Letters*, **13(4)**, 044015, doi:10.1088/1748-9326/aab2ba.

Sussams, L. and J. Leaton, 2017: *Expect the Unexpected – The Disruptive Power of Low-carbon Technology*. Carbon Tracker Initiative, London, UK, 52 pp.

Tavoni, M., E. De Cian, G. Luderer, J.C. Steckel, and H. Waisman, 2012: The value of technology and of its evolution towards a low carbon economy. *Climatic Change*, **114(1)**, 39–57, doi:10.1007/s10584-011-0294-3.

Tavoni, M. et al., 2015: Post-2020 climate agreements in the major economies assessed in the light of global models. *Nature Climate Change*, **5(2)**, 119–126, doi:10.1038/nclimate2475.

Trutnevyte, E., N. Strachan, P.E. Dodds, D. Pudjianto, and G. Strbac, 2015: Synergies and trade-offs between governance and costs in electricity system transition. *Energy Policy*, **85**, 170–181, doi:10.1016/j.enpol.2015.06.003.

Turnheim, B. et al., 2015: Evaluating sustainability transitions pathways: Bridging analytical approaches to address governance challenges. *Global Environmental Change*, **35**, 239–253, doi:10.1016/j.gloenvcha.2015.08.010.

Ürge-Vorsatz, D., A. Novikova, S. Köppel, and B. Boza-Kiss, 2009: Bottom–up assessment of potentials and costs of CO_2 emission mitigation in the buildings sector: insights into the missing elements. *Energy Efficiency*, **2(4)**, 293–316, doi:10.1007/s12053-009-9051-0.

van Marle, M.J.E. et al., 2017: Historic global biomass burning emissions for CMIP6 (BB4CMIP) based on merging satellite observations with proxies and fire models (1750–2015). *Geoscientific Model Development*, **10(9)**, 3329–3357, doi:10.5194/gmd-10-3329-2017.

van Sluisveld, M.A.E., S.H. Martínez, V. Daioglou, and D.P. van Vuuren, 2016: Exploring the implications of lifestyle change in 2°C mitigation scenarios using the IMAGE integrated assessment model. *Technological Forecasting and Social Change*, **102**, 309–319, doi:10.1016/j.techfore.2015.08.013.

van Sluisveld, M.A.E. et al., 2015: Comparing future patterns of energy system change in 2°C scenarios with historically observed rates of change. *Global Environmental Change*, **35**, 436–449, doi:10.1016/j.gloenvcha.2015.09.019.

van Vuuren, D.P. et al., 2011: The representative concentration pathways: An overview. *Climatic Change*, **109(1)**, 5–31, doi:10.1007/s10584-011-0148-z.

van Vuuren, D.P. et al., 2015: Pathways to achieve a set of ambitious global sustainability objectives by 2050: Explorations using the IMAGE integrated assessment model. *Technological Forecasting and Social Change*, **98**, 303–323, doi:10.1016/j.techfore.2015.03.005.

van Vuuren, D.P. et al., 2018: Alternative pathways to the 1.5°C target reduce the need for negative emission technologies. *Nature Climate Change*, **8(5)**, 391–397, doi:10.1038/s41558-018-0119-8.

Velders, G.J.M., D.W. Fahey, J.S. Daniel, S.O. Andersen, and M. McFarland, 2015: Future atmospheric abundances and climate forcings from scenarios of global and regional hydrofluorocarbon (HFC) emissions. *Atmospheric Environment*, **123**, 200–209, doi:10.1016/j.atmosenv.2015.10.071.

Vrontisi, Z. et al., 2018: Enhancing global climate policy ambition towards a 1.5°C stabilization: a short-term multi-model assessment. *Environmental Research Letters*, **13(4)**, 044039, doi:10.1088/1748-9326/aab53e.

Warszawski, L. et al., 2014: The Inter-Sectoral Impact Model Intercomparison Project (ISIMIP): Project framework. *Proceedings of the National Academy of Sciences*, **111(9)**, 3228–3232, doi:10.1073/pnas.1312330110.

Weindl, I. et al., 2017: Livestock and human use of land: Productivity trends and dietary choices as drivers of future land and carbon dynamics. *Global and Planetary Change*, **159**, 1–10, doi:10.1016/j.gloplacha.2017.10.002.

Weyant, J., 2017: Some Contributions of Integrated Assessment Models of Global Climate Change. *Review of Environmental Economics and Policy*, **11(1)**, 115–137, doi:10.1093/reep/rew018.

Wilkerson, J.T., B.D. Leibowicz, D.D. Turner, and J.P. Weyant, 2015: Comparison of integrated assessment models: Carbon price impacts on U.S. energy. *Energy Policy*, **76**, 18–31, doi:10.1016/j.enpol.2014.10.011.

Wilson, C. and H. Dowlatabadi, 2007: Models of Decision Making and Residential Energy Use. *Annual Review of Environment and Resources*, **32(1)**, 169–203, doi:10.1146/annurev.energy.32.053006.141137.

Wilson, C., A. Grubler, K.S. Gallagher, and G.F. Nemet, 2012: Marginalization of end-use technologies in energy innovation for climate protection. *Nature Climate Change*, **2(11)**, 780–788, doi:10.1038/nclimate1576.

Wilson, C., A. Grubler, N. Bauer, V. Krey, and K. Riahi, 2013: Future capacity growth of energy technologies: are scenarios consistent with historical evidence? *Climatic Change*, **118(2)**, 381–395, doi:10.1007/s10584-012-0618-y.

Wilson, C. et al., 2017: *Evaluating Process-Based Integrated Assessment Models of Climate Change Mitigation*. IIASA Working Paper WP-17-007, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, 37 pp.

Wong-Parodi, G., T. Krishnamurti, A. Davis, D. Schwartz, and B. Fischhoff, 2016: A decision science approach for integrating social science in climate and energy solutions. *Nature Climate Change*, **6(6)**, 563–569, doi:10.1038/nclimate2917.

Zhang, R., S. Fujimori, and T. Hanaoka, 2018: The contribution of transport policies to the mitigation potential and cost of 2°C and 1.5°C goals. *Environmental Research Letters*, **13(5)**, 054008, doi:10.1088/1748-9326/aabb0d.

2.SM.2 Part 2

Contributing Modelling Framework Reference Cards
For each of the contributing modelling frameworks, a reference card has been created highlighting the key features of the model. These reference cards are either based on information received from contributing modelling teams upon submission of scenarios to the SR1.5 database, or alternatively are drawn from the ADVANCE IAM wiki documentation, available at www.iamcdocumentation.eu (last accessed on 15 May 2018) and updated. These reference cards are provided in part 2 of this Supplementary Material.

2.SM.2.1 Reference Card – AIM/CGE

About

Name and version
AIM/CGE

Institution and users
National Institute for Environmental Studies (NIES), Japan

Model scope and methods

Objective
AIM/CGE is developed to analyse climate mitigation and impacts. The energy system is disaggregated to meet this objective on both the energy supply and demand sides. Agricultural sectors have also been disaggregated for the appropriate land-use treatment. The model is designed to be flexible in its use for global analysis.

Concept
General equilibrium with technology-explicit modules in power sectors

Solution method
Solving a mixed complementarity problem

Anticipation
Myopic

Temporal dimension
Base year: 2005
Time steps: Annual
Horizon: 2100

Spatial dimension
Number of regions: 17
Japan, China, India, Southeast Asia, Rest of Asia, Oceania, EU25, Rest of Europe, Former Soviet Union, Turkey, Canada, United States, Brazil, Rest of South America, Middle East, North Africa, Rest of Africa

Policy implementation
Climate policies such as emissions targets, emission permit trading and so on. Energy taxes and subsidies

Socio-economic drivers

Exogenous drivers
Total factor productivity
Note: GDP is endogenous, while TFP is exogenous; but TFP can be calibrated so as to reproduce a given GDP pathway

Endogenous drivers
GDP (Non-baseline scenarios that take into account either climate change mitigation or impacts.)

Development
GDP per capita

Macro economy

Economic sectors
Agriculture, industry, energy, transport, services

Cost measures
GDP loss, welfare loss, consumption loss

Trade
Coal, oil, gas, electricity, food crops, emissions permits, non-energy goods

Energy

Behaviour
None

Resource use
Coal, oil, gas, biomass

Electricity technologies
Coal, gas, oil, nuclear, biomass, wind, solar PV, CCS

Conversion technologies
Oil to liquids, biomass to liquids

Grid and infrastructure
None

Energy technology substitution
Discrete technology choices

Energy service sectors
Transportation, industry, residential and commercial

Land use

Land cover
Abandoned land, cropland, forest, grassland, extensive pastures
note: 6 AEZs (agro-ecological zones) by crop, pasture, forestry, other forest, natural grassland and others. There is a land competition under multinomial logit selection.

Other resources

None

Emissions and climate

Greenhouse gases
CO_2, CH_4, N_2O, HFCs, CFCs, SF_6

Pollutants
NO_x, SO_x, BC, OC, VOC, CO

Climate indicators
CO_2e concentration (ppm), radiative forcing (W m^{-2}), temperature change (°C)

2.SM.2.2 Reference Card – BET

About

Name and version
BET EMF33

Institution and users
CRIEPI, University of Tokyo, *Role of end-use technologies in long-term GHG reduction scenarios developed with the BET model* doi: 10.1007/s10584-013-0938-6

Model scope and methods

Objective
The model is used for climate change studies on long-term mitigation scenarios. Typical application is to examine the role of electrification and advanced end-use technologies in climate change mitigation in a more systematic fashion, ranging from changes in usage of end-use technologies to power generation mix.

Concept
General equilibrium (closed economy)

Solution method
Optimization

Anticipation
Inter-temporal (foresight)

Temporal dimension
Base year: 2010
Time steps: 10
Horizon: 2010–2230

Spatial dimension
Number of regions: 13
BRA (Brazil), CAZ (Canada, Australia, and New Zealand), CHA (China incl. Hong Kong), EUR (EU27 + Switzerland, Norway, and Iceland), IND (India), JPN (Japan), MNA (Middle East and North Africa), OAS (Other Asia), OLA (Other Latin America), ORF (Other Reforming Economies), RUS (Russia), SSA (Sub-Saharan Africa), USA (United States)

Policy implementation
Emission tax/pricing, cap and trade

Socio-economic drivers

Exogenous drivers
Population, total factor productivity, autonomous energy efficiency improvements

Endogenous drivers
GDP, end-use service demand

Macro economy

Economic sectors
Aggregated representation (single-sector economy)

Cost measures
GDP loss, consumption loss, energy system costs

Trade
Coal, oil, gas, hydrogen, food crops (exogenous), emissions permits, non-energy goods

Energy

Behaviour
None

Resource use
Coal, conventional oil, unconventional oil, conventional gas, unconventional gas, uranium, bioenergy

Electricity technologies
Coal w/o CCS, coal w/ CCS, gas w/o CCS, gas w/ CCS, oil w/o CCS, bioenergy w/o CCS, bioenergy w/ CCS, geothermal power, nuclear power, solar power (central PV), wind power (onshore), wind power (offshore), hydroelectric power, hydrogen fuel

Conversion technologies
Coal to hydrogen w/ CCS, electrolysis, coal to liquids w/o CCS, bioliquids w/o CCS, oil refining, biomass to gas w/o CCS

Grid and infrastructure
Electricity
Note: Generalized transmission and distribution costs are included, but not modelled in a spatially explicit manner.
Gas
Note: Generalized gas network costs are included, but not modelled in a spatially explicit manner.

Energy technology substitution
Linear choice (lowest cost, only for the supply side), expansion and decline constraints, system integration constraints

Energy service sectors
Transportation, industry, residential and commercial

Land use

Land cover
Cropland food crops, cropland feed crops, cropland energy crops, managed forest, natural forest, pasture

Other resources

None

Emissions and climate

Greenhouse gases
CO_2

Pollutants
None

Climate indicators
CO_2 concentration (ppm), radiative forcing (W m^{-2})

2SM

2.SM.2.3 Reference Card – C-ROADS

About

Name and version

C-ROADS v5.005

Institution and users

Climate Interactive, US, https://www.climateinteractive.org/.

Model scope and methods

Objective

The purpose of C-ROADS is to improve public and decision-maker understanding of the long-term implications of international emissions and sequestration futures with a rapid-iteration, interactive tool as a path to effective action that stabilizes the climate.

Concept

C-ROADS takes future population, economic growth and GHG emissions as scenario inputs specified by the user and currently omits the costs of policy options and climate change damage.

Solution method

Recursive dynamic solution method (myopic)

Anticipation

Simulation modelling framework, without foresight.

Temporal dimension

Base year: 1850
Time steps: 0.25 year time step
Horizon: 2100

Spatial dimension

Number of regions: 20
USA ,European Union (EU) 27 (EU27) (plus Iceland, Norway and Switzerland), Russia (includes fraction of former USSR), other Eastern Europe, Canada, Japan, Australia, New Zealand, South Korea, Mexico, China, India, Indonesia, Philippines, Thailand, Taiwan, Hong Kong, Malaysia, Pakistan, Singapore, Brazil, Latin America excluding Mexico and Brazil, Middle East, South Africa, Africa excluding South Africa, Asia excluding China, India, Indonesia, and those included in Other Large Asia

Policy implementation

The model includes implicit representation of policies. For each well-mixed GHG, regionally specified socio-economic drivers, emissions per GDP, and emissions changes relative to a reference year or reference scenario determine emissions pathways.

Socioeconomic drivers

Exogenous drivers

Exogenous population, exogenous GDP per capita rates and convergence times are used to model GDP over time.

Endogenous drivers

None

Development

None

Macro economy

Economic sectors

Not represented by the model

Cost measures

Not represented by the model

Trade

Not represented by the model

Energy

Behaviour

Not represented by the model

Resource use

Not represented by the model

Electricity technologies

Not represented by the model

Conversion technologies

Not represented by the model

Grid and infrastructure

Not represented by the model

Energy technology substitution

Not represented by the model

Energy service sectors

Not represented by the model

Land use

Land cover

Not represented by the model

Other resources

None

Emissions and climate

Greenhouse gases

CO_2, CH_4, N_2O, HFCs, CFCs, SF_6, PFCs

Pollutants

Not modelled. Covered by the model in terms of radiative forcing; uses projections of a specified SSP scenario

Climate indicators

The cycle of each well-mixed greenhouse gas is explicitly modelled. CO_2 concentration (ppm), CH_4 concentration (ppb), N_2O concentration (ppb), HFCs concentration (ppt), SF_6 concentration (ppt), PFCs concentration (ppt), CO_2e concentration (ppm), radiative forcing ($W\ m^{-2}$)

The model uses the radiative efficiencies and explicitly-modelled concentration over time of each well-mixed greenhouse to determine its radiative forcing (RF). The model also uses a specified SSP scenario for exogenous values of other forcings, which includes those from aerosols, albedo, solar irradiance and volcanic activity. The total RF is the sum of these components.
Temperature change (°C), sea level rise, ocean acidification.

2.SM.2.4 Reference Card – DNE21+

About

Name and version
DNE21+ V.14C

Institution and users
Research Institute of Innovative Technology for the Earth (RITE), 9-2 Kizugawadai, Kizugawa-shi, Kyoto 619-0292
http://www.rite.or.jp/Japanese/labo/sysken/about-global-warming/download-data/RITE_GHGMitigationAssessmentModel_20150130.pdf
https://www.rite.or.jp/system/en/research/new-earth/dne21-model-analyses/climate/

Model scope and methods

Objective
None

Concept
Minimizing energy systems cost

Solution method
Optimization

Anticipation
Inter-temporal (foresight)

Temporal dimension
Base year: 2000
Time steps: 5 year steps (2000 - 2030); 10 year-steps (2030 - 2050)
Horizon: 2000-2050

Spatial dimension
Number of regions: 54
ARG+ (Argentina, Paraguay, Uruguay), AUS (Australia), BRA (Brazil), CAN (Canada), CHN (China), EU15 (EU-15), EEU (Eastern Europe – Other EU-28), IND (India), IDN (Indonesia), JPN (Japan), MEX (Mexico), RUS (Russia), SAU (Saudi Arabia), SAF (South Africa), ROK (South Korea), TUR (Turkey), USA (United States of America), OAFR (Other Africa), MEA (Middle East & North Africa), NZL (New Zealand), OAS (Other Asia), OFUE (Other FUSSR – Eastern Europe), OFUA (Other FUSSR – Asia), OLA (Other Latin America), OWE (Other Western Europe)

Policy implementation
Emission tax/pricing, cap and trade, fuel taxes, fuel subsidies, feed-in-tariff, portfolio standard, capacity targets, emission standards, energy efficiency standards, land protection, pricing carbon stocks

Socio-economic drivers

Exogenous drivers
Population, population age structure, education level, urbanization rate, GDP, income distribution, labour participation rate, labour productivity

Macro economy
Economic sectors
Agriculture, industry, energy, services

Cost measures
Energy system costs

Trade
Coal, oil, gas, electricity, emissions permits

Energy
Behaviour
Transportation, industry, residential & commercial, technology adoption

Resource use
Coal, conventional oil, unconventional oil, conventional gas, unconventional gas

Electricity technologies
Coal w/o CCS, coal w/ CCS, gas w/o CCS, gas w/ CCS, oil w/o CCS, oil w/ CCS, bioenergy w/o CCS, bioenergy w/ CCS, geothermal power, nuclear power, solar power, wind power, hydroelectric power

Conversion technologies
Coal to hydrogen w/o CCS, coal to hydrogen w/ CCS, natural gas to hydrogen w/o CCS, natural gas to hydrogen w/ CCS, biomass to hydrogen w/o CCS, biomass to hydrogen w/ CCS, electrolysis, coal to liquids w/o CCS, bioliquids w/o CCS, oil refining, coal to gas w/o CCS

Grid and infrastructure
Electricity, gas, CO_2, H_2

Energy technology substitution
Linear choice (lowest cost), system integration constraints

Energy service sectors
Transportation, industry, residential and commercial

Land use
Land cover
Cropland food crops, cropland feed crops, cropland energy crops, managed forest, natural forest, pasture

Other resources
Other resources
Water

Emissions and climate
Greenhouse gases
CO_2, CH_4, N_2O, HFCs, CFCs, SF_6

Pollutants
NO_x, SO_x, BC, OC

Climate indicators
CO_2e concentration (ppm), radiative forcing (W m^{-2}), temperature change (°C)

2.SM.2.5 Reference Card – FARM 3.2

About
Name and version
Future Agricultural Resources Model 3.2

Institution and users
United States Department of Agriculture, Economic Research Service; Öko-Institut, Germany https://www.ers.usda.gov/webdocs/publications/81903/err-223.pdf?v=42738

Model scope and methods
Objective
The Future Agricultural Resources Model (FARM) was originally designed as a static computable general equilibrium (CGE) model to simulate land use and climate impacts at a global scale. It has since been extended to simulate energy and agricultural systems through 2100 to enable participation in the energy modelling forum (EMF) and the agricultural modelling intercomparison project (AgMIP) model comparison studies.

Concept
FARM models land-use shifts among crops, pasture, and forests in response to population growth; changes in agricultural productivity; and policies such as a renewable portfolio standard or greenhouse gas cap-and-trade.

Solution method
General equilibrium recursive-dynamic simulation

Anticipation
Myopic

Temporal dimension
Base year: 2011
Time steps: 5 years
Horizon: 2101

Spatial dimension
Number of regions: 15
United States, Japan, European Union west (EU-15), European Union east, Other OECD90, Russian Federation, Other Reforming Economies China region, India, Indonesia, Other Asia, Middle East and North Africa, Sub-Saharan Africa, Brazil, Other Latin America

Policy implementation
Emissions tax/pricing, cap and trade, fuel taxes and subsidies, portfolio standards, agricultural producer, subsidies, agricultural consumer subsidies, land protection

Socio economic drivers
Exogenous drivers
Population, labour productivity, land productivity, autonomous energy efficiency improvements, other input-specific productivity

Endogenous drivers
None

Development
None

Macro economy

Economic sectors
Agriculture, industry, energy, services

Cost measures
GDP loss, welfare loss, equivalent variation, consumption loss

Trade
Coal, oil, gas, electricity, food crops, non-energy goods

Energy

Behaviour
Substitution between energy and non-energy inputs in response to changes in relative prices

Resource use
Coal (supply curve), conventional oil (supply curve), conventional gas (supply curve), biomass (supply curve)

Electricity technologies
Coal (w/o and w/ CCS), gas (w/o and w/ CCS), oil (w/o and w/ CCS), nuclear, biomass (w/o and w/ CCS), wind, solar PV

Conversion technologies
Fuel to liquid, oil refining

Grid and infrastructure
Electricity (aggregate), gas (aggregate), CO_2 (aggregate)

Energy technology substitution
Discrete technology choices with mostly high substitutability through production functions

Energy service sectors
Transportation (land, water, air), buildings

Land use

Land cover
Crop land, food crops, feed crops, energy crops, managed forest, pastures

Other resources

Other resources
None

Emissions and climate

Greenhouse gases
CO_2, fossil fuels, cement, land use

Pollutants
None

Climate indicators
None

2.SM.2.6 Reference Card – GCAM 4.2

About

Name and version
Global Change Assessment Model 4.2

Institution and users
Joint Global Change Research Institute – http://jgcri.github.io/gcam-doc/v4.2/toc.html

Model scope and methods

Objective
GCAM is a global integrated assessment model that represents the behaviour of, and complex interactions between five systems: the energy system, water, agriculture and land use, the economy, and the climate.

Concept
The core operating principle for GCAM is that of market equilibrium. Representative agents in GCAM use information on prices, as well as other information that might be relevant, and make decisions about the allocation of resources. These representative agents exist throughout the model, representing, for example, regional electricity sectors, regional refining sectors, regional energy demand sectors, and land users who have to allocate land among competing crops within any given land region. Markets are the means by which these representative agents interact with one another. Agents pass goods and services along with prices into the markets. Markets exist for physical flows such as electricity or agricultural commodities, but they also can exist for other types of goods and services, for example tradable carbon permits.

Solution method
Partial equilibrium (price elastic demand) recursive-dynamic

Anticipation
Myopic

Temporal dimension
Base year: 2010
Time steps: 5 years
Horizon: 2100

Spatial dimension
Number of regions: 32 (For CD-Links scenarios, GCAM included 82 regions)
USA (For CD-Links scenarios, the USA was subdivided into 50 states plus the District of Columbia), Eastern Africa, Northern Africa, Southern Africa, Western Africa, Australia and New Zealand, Brazil, Canada, Central America and Caribbean, Central Asia, China, EU-12, EU-15, Eastern Europe, Non-EU Europe, European Free Trade Association, India, Indonesia, Japan, Mexico, Middle East, Pakistan, Russia, South Africa, Northern South America, Southern South America, South Asia, South Korea, Southeast Asia, Taiwan, Argentina, Colombia

Policy implementation
Climate policies, Emission tax/pricing, cap and trade, energy policies,

fuel taxes, fuel subsidies, portfolio standard, energy technology policies, capacity targets, energy efficiency standards, land-use policies, land protection, afforestation

Socio-economic drivers

Exogenous drivers

Population, GDP, labour participation rate, labour productivity

Endogenous drivers

None

Development

None

Macro economy

Economic sectors

Agriculture, industry, energy, transport, services, residential and commercial

Cost measures

Area under marginal abatement cost (MAC) curve

Trade

Coal, oil, gas, uranium, bioenergy crops, food crops, emissions permits

Energy

Behaviour

None

Resource use

Coal (supply curve), conventional oil (supply curve), unconventional oil (supply curve), conventional gas (supply curve), unconventional gas (supply curve), uranium (supply curve), biomass (process model), land

Electricity technologies

Coal (w/ o and w/ CCS), gas (w/o and w/ CCS), oil (w/o and w/ CCS), nuclear, biomass (w/o and w/ CCS), wind (onshore), solar PV (central PV, distributed PV, and concentrating solar power), CCS

Conversion technologies

CHP, hydrogen from coal, oil, gas, and biomass, w/o and w/ CCS, nuclear and solar thermochemical, fuel to gas, coal to gas w/o CCS, biomass (w/o and w/ CCS), fuel to liquid, coal to liquids (w/o and w/ CCS), gas to liquids (w/o and w/ CCS), biomass to liquids (w/o and w/ CCS)

Grid and infrastructure

None

Energy technology substitution

Discrete technology choices with usually high substitutability through logit-choice model

Energy service sectors

Transportation, residential and commercial, industry

Land use

Land cover

Cropland, food crops, feed crops, energy crops, forest, managed forest, natural forest, pasture, shrubland, tundra, urban, rock, ice, desert

Other resources

Other resources

Water, cement

Emissions and climate

Greenhouse gases

CO_2 (fossil fuels, cement, land use), CH_4 (energy, land use, other), N_2O (energy, land use, other), HFCs, CFCs, SF_6

Pollutants

NO_x (energy, land use), SO_x (energy, land use), BC (energy, land use), OC (energy, land use), NH_3 (energy, land use)

Climate indicators

Kyoto-gases concentration, radiative forcing (W m^{-2}), temperature change (°C)

2.SM.2.7 Reference Card – GEM-E3

About

Name and version

GEM-E3

Institution and users

Institute of Communication and Computer Systems (ICCS), Greece
https://ec.europa.eu/jrc/en/gem-e3

Model scope and methods

Objective

The model puts emphasis on: (i) the analysis of market instruments for energy-related environmental policy, such as taxes, subsidies, regulations, emission permits etc., at a degree of detail that is sufficient for national, sectoral and world-wide policy evaluation; and (ii) the assessment of distributional consequences of programmes and policies, including social equity, employment and cohesion for less-developed regions.

Concept

General equilibrium

Solution method

The model is formulated as a simultaneous system of equations with an equal number of variables. The system is solved for each year following a time-forward path. The model uses the GAMS software and is written as a mixed non-linear complementarity problem solved by using the PATH algorithm with the standard solver options.

Anticipation

Myopic

Temporal dimension

Base year: 2011
Time steps: Five year time steps
Horizon: 2050

Spatial dimension

Different spatial dimension depending on application. Main applications feature one of the two regional disaggregation below.

Number of regions: 38
Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Germany, Denmark, Spain, Estonia, Finland, France, United Kingdom, Greece, Hungary, Ireland, Italy, Lithuania, Luxembourg, Latvia, Malta, Netherlands, Poland, Portugal, Slovakia, Slovenia, Sweden, Romania, USA, Japan, Canada, Brazil, China, India, Oceania, Russian federation, Rest of Annex I, Rest of the World

Or

Number of regions: 19
EU28, USA, Japan, Canada, Brazil, China, India, South Korea, Indonesia, Mexico, Argentina, Turkey, Saudi Arabia, Oceania, Russian federation, rest of energy producing countries, South Africa, rest of Europe, rest of the World

Policy implementation

Taxes, permits trading, subsidies, energy efficiency standards, CO_2 standards, emission-reduction targets, trade agreements, R&D, adaptation.

Socio-economic drivers

Exogenous drivers

Total factor productivity, labour productivity, capital technical progress, energy technical progress, materials technical progress, active population growth

Endogenous drivers

Learning-by-doing

Development

GDP per capita, labour participation rate

Macro economy

Economic sectors

Agriculture, industry, energy, transport, services, other

Note: GEM-E3 represents the following sectors: Agriculture, coal, crude oil, oil, gas, electricity supply, ferrous metals, non-ferrous metals, chemical products, paper & pulp, non-metallic minerals, electric goods, conventional transport equipment, other equipment goods, consumer goods industries, construction, air transport, land transport – passenger, land transport – freight, water transport – passenger, water transport – freight, biofuel feedstock, biomass, ethanol, biodiesel, advanced electric appliances, electric vehicles, equipment for wind, equipment for PV, equipment for CCS, market services, non-market services, coal fired, oil fired, gas fired, nuclear, biomass, hydroelectric, wind, PV, CCS coal, CCS gas

Cost measures

GDP loss, welfare loss, consumption loss

Trade

Coal, oil, gas, electricity, emissions permits, non-energy goods, agriculture, ferrous and non-ferrous metals, chemical products, other energy intensive, electric goods, transport equipment, other equipment goods, consumer goods industries

Energy

Behaviour

The GEM-E3 model endogenously computes energy consumption, depending on energy prices, realized energy efficiency expenditures and autonomous energy efficiency improvements. Each agent decides how much energy it will consume in order to optimize its behaviour (i.e., to maximize profits for firms and utility for households) subject to technological constraints (i.e., a production function). At a sectoral level, energy consumption is derived from profit maximization under a nested CES (constant elasticity of substitution) specification. Energy enters the production function together with other production factors (capital, labour, materials). Substitution of energy and the rest of the production factors is imperfect (energy is considered an essential input to the production process) and it is induced by changes in the relative prices of each input. Residential energy consumption is derived from the utility maximization problem of households. Households allocate their income between different consumption categories and savings to maximize their utility subject to their budget constraint. Consumption is split between durable (e.g., vehicles, electric appliances) and non-durable goods. For durable goods, stock accumulation depends on new purchases and scrapping.

Durable goods consume (non-durable) goods and services, including energy products. The latter are endogenously determined depending on the stock of durable goods and on relative energy prices.

Resource use
Coal, oil, gas, biomass

Electricity technologies
Coal, gas, oil, nuclear, biomass, wind, solar PV, ,CCS

Conversion technologies
None

Grid and infrastructure
Electricity

Energy technology substitution
Discrete technology choices

Energy service sectors
Transportation, industry, residential and commercial

Land use
Land cover
No land use is simulated in the current version of GEM-E3.

Other resources
Other resources

Emissions and climate
Greenhouse gases
CO_2, CH_4, N_2O, HFCs, CFCs, SF_6

Pollutants
NO_x, SO_x

Climate indicators
None

2.SM.2.8 Reference Card – GENeSYS-MOD 1.0

About
Name and version
GENeSYS-MOD 1.0

Institution and users
Technische Universität (TU) Berlin, Germany / German Institute for Economic Research (DIW Berlin), Germany

Model scope and methods
Objective
The Global Energy System Model (GENeSYS-MOD) is an open-source energy system model, based on the Open-Source Energy Modelling System (OSeMOSYS). The aim is to analyse potential pathways and scenarios for the future energy system, for example, for an assessment of climate targets. It incorporates the power, heat, and transportation sectors and specifically considers sector-coupling aspects between these traditionally segregated sectors.

Concept
The model minimizes the total discounted system costs by choosing the cost-optimal mix of generation and sector-coupling technologies for the power, heat, and transportation sectors.

Solution method
Linear program optimization (minimizing total discounted system costs)

Anticipation
Perfect foresight

Temporal dimension
Base year: 2015
Time steps: 2015, 2020, 2030, 2035, 2040, 2045, 2050
Horizon: 2015–2050

Spatial dimension
Number of regions: 10
Europe, Africa, North America, South America, Oceania, China and Mongolia, India, Middle East, Former Soviet Union, Remaining Asian countries (mostly Southeast-Asia)

Policy implementation
Emission tax/pricing, emissions budget, fuel taxes, fuel subsidies, capacity targets, emission standards, energy efficiency standards

Socio-economic drivers
Exogenous drivers
Technical progress (such as efficiency measures), GDP per capita, population

Endogenous drivers
None

Development
None

Macro economy

Economic sectors
None

Cost measures
None

Trade

Energy

Behaviour
None

Resource use
Coal, oil, gas, uranium, biomass

Electricity technologies
Coal, gas, oil, nuclear, biomass, wind (onshore & offshore), solar PV (utility PV & rooftop PV), CSP, geothermal, hydropower, wave & tidal power

Conversion technologies
CHP, hydrogen (electrolysis & fuel cells), electricity & gas storages

Grid and infrastructure
Electricity

Energy technology substitution
Discrete technology choices, expansion and decline constraints, system integration constraints

Energy service sectors
Transportation (split up in passenger & freight), total power demand, heat (divided up in warm water / space heating & process heat)

Land use

Land cover
None

Other resources

Other resources
None

Emissions and climate

Greenhouse gases
CO_2

Pollutants
None

Climate indicators
None

2.SM.2.9 Reference Card – GRAPE-15 1.0

About

Name and version
GRAPE-15 1.0

Institution and users
The Institute of Applied Energy, Japan – https://doi.org/10.5547/ISSN0195-6574-EJ-VolSI2006-NoSI3-13

Model scope and methods

Objective
GRAPE is an integrated assessment model with an inter-temporal optimization model, which consists of modules for energy, macro economy, climate, land use and environmental impacts.

Concept
None

Solution method
Partial equilibrium (fixed demand) inter-temporal optimization

Anticipation
Perfect foresight

Temporal dimension
Base year: 2005
Time steps: 5 years
Horizon: 2110

Spatial dimension
Number of regions: 15
Canada, USA, Western Europe, Japan, Oceania, China, Southeast Asia, India, Middle East, Sub-Sahara Africa, Brazil, other Latin America, Central Europe, Eastern Europe, Russia

Policy implementation
Emissions taxes/pricing, cap and trade, land protection

Socio-economic drivers

Exogenous drivers
Population, population age structure, education level, urbanization rate, GDP, income distribution, total factor productivity, autonomous energy efficiency improvements

Endogenous drivers
None

Development
Income distribution in a region (exogenous), urbanization rate (exogenous), education level (exogenous)

Macro economy

Economic sectors
Agriculture, industry, energy, transport, services

Cost measures
GDP loss, welfare loss, consumption loss, energy system costs

Trade
Coal, oil, gas, electricity, bioenergy crops, food crops, non-energy goods, hydrogen

Energy
Behaviour
None

Resource use
Coal (supply curve), conventional oil (supply curve), unconventional oil (supply curve), conventional gas (supply curve), unconventional gas (supply curve), uranium (supply curve), biomass (supply curve), water (process model), land

Electricity technologies
Coal (w/o and w/ CCS), gas (w/o and w/ CCS), oil (w/o and w/ CCS), nuclear, biomass (w/o and w/ CCS), wind (onshore and offshore), solar PV (central and distributed), geothermal, hydroelectric, hydrogen

Conversion technologies
CHP, coal/oil/gas/biomass-to-heat, hydrogen, coal to H_2 (w/o and w/ CCS), oil to H_2 (w/o and w/ CCS), gas to H_2 (w/o and w/ CCS), biomass to H_2 (w/o CCS), nuclear and solar thermochemical, electrolysis, fuel to gas, coal to gas (w/o and w/ CCS), fuel to liquid, coal to liquids (w/o and w/ CCS), gas to liquids (w/o and w/ CCS), biomass to liquids (w/o and w/ CCS), oil refining

Grid and infrastructure
Electricity, Gas, Heat, CO_2,H_2

Energy technology substitution
Discrete technology choices with mostly high substitutability through linear choice (lowest cost), expansion and decline constraints

Energy service sectors
Transportation, industry, residential and commercial

Land use
Land cover
Energy cropland, forest, pastures, built-up area

Other resources
Other resources
Water

Emissions and climate
Greenhouse gases
CO_2, fossil fuels, land use, CH_4, energy, land use, N_2O, energy, HFCs, CFCs, SF_6, CO, energy use

Pollutants
Only for energy, NO_x, SO_x, BC, OC, Ozone

Climate indicators
CO_2e concentration (ppm), radiative Forcing (W m^{-2}), temperature change (°C)

2.SM.2.10 Reference Card – ETP Model

About
Name and version
ETP Model, version 3

Institution and users
International Energy Agency – http://www.iea.org/etp/etpmodel/

Model scope and methods
Objective
The analysis and modelling aim to identify an economical way for society to reach the desired outcomes of reliable, affordable and clean energy. For a variety of reasons, the scenario results do not necessarily reflect the least-cost ideal. The ETP analysis takes into account those policies that have already been implemented or decided. In the short term, this means that deployment pathways may differ from what would be most cost-effective. In the longer term, the analysis emphasizes a normative approach, and fewer constraints governed by current political objectives apply in the modelling. The objective of this methodology is to provide a model for a cost-effective transition to a sustainable energy system.

Concept
Partial equilibrium (fixed energy service and material demands), with the exception for the transport sector, where 'avoid and shift' policies are being considered.

Solution method
Optimization for power, other transformation and industry sectors; simulation for agriculture, residential, services and transport sectors

Anticipation
Inter-temporal (foresight)

Temporal dimension
Base year: 2014
Time steps: 5 years
Horizon: 2060

Spatial dimension
Number of regions: differs between energy sectors (28-39 model regions)
Asian countries except Japan, countries of the Middle East and Africa, Latin American countries, OECD90 and EU (and EU candidate) countries, countries from the Reforming Economies of the Former Soviet Union World, OECD countries, non-OECD countries, Brazil, China, South Africa, Russia, India, ASEAN region countries, USA, European Union (28 member countries), Mexico

Policy implementation
Emission tax/pricing, cap and trade, fuel taxes, fuel subsidies, feed-in-tariff, portfolio standards, capacity targets, emission standards, energy efficiency standards

Socio economic drivers
Exogenous drivers
Population, urbanization rate, GDP, autonomous energy efficiency

improvements

Endogenous drivers
None

Development
None

Macro economy
Economic sectors
Agriculture, industry, residential, services, transport, power, other transformation

Cost measures
None

Trade
Coal, oil, gas, electricity

Energy
Behaviour
None

Resource use
Coal (supply curve), conventional oil (process model), unconventional oil (supply curve), conventional gas (process model), unconventional gas (supply curve), bioenergy (supply curve)

Electricity technologies
Coal (w/o and w/ CCS), gas (w/o and w/ CCS), oil (w/o and w/ CCS) nuclear, biomass (w/o and w/ CCS), solar power (central PV, distributed PV, and CSP), wind power (onshore and offshore), hydroelectric power, ocean power

Conversion technologies
Coal to hydrogen (w/o CCS and w/ CCS), natural gas to hydrogen (w/o CCS and w/ CCS), oil to hydrogen (w/o CCS), biomass to hydrogen (w/o CCS and w/ CCS), coal to liquids (w/o CCS and w/ CCS), gas to liquids (w/o CCS and w/ CCS), bioliquids (w/o CCS and w/ CCS), oil refining, coal to gas (w/o CCS and w/ CCS), oil to gas (w/o CCS and w/ CCS), biomass to gas (w/o CCS and w/ CCS), coal heat, natural gas heat, oil heat , biomass heat, geothermal heat, solarthermal heat, CHP (coupled heat and power)

Grid and infrastructure
Electricity (spatially explicit), gas (aggregate), heat (aggregate), hydrogen (aggregate), CO_2 (spatially explicit), gas spatially explicit for gas pipelines and LNG infrastructure between model regions

Energy technology substitution
Lowest cost with adjustment penalties. Discrete technology choices with mostly high substitutability in some sectors and mostly low substitutability in other sectors.
Expansion and decline constraints.
System integration constraints.

Energy service sectors
Transportation, industry, residential and commercial

Land use
Land cover
Not represented by the model

Other resources
Other resources
None

Emissions and climate
Greenhouse gases
CO_2 fossil fuels (endogenous & controlled)
CO_2 cement (endogenous & controlled)

Pollutants
None

Climate indicators
None

2.SM.2.11 Reference Card – IEA World Energy Model

About

Name and version
IEA World Energy Model (version 2016)

Institution and users
International Energy Agency - https://www.iea.org/weo/
http://www.iea.org/media/weowebsite/2016/WEM_Documentation_WEO2016.pdf

Model scope and methods

Objective
The model is a large-scale simulation model designed to replicate how energy markets function and is the principal tool used to generate detailed sector-by-sector and region-by-region projections for the World Energy Outlook (WEO) scenarios.

Concept
Partial equilibrium (price elastic demand)

Solution method
Simulation

Anticipation
Mix of `Inter-temporal (foresight)´ and `Recursive-dynamic (myopic)´

Temporal dimension
Base year: 2014
Time steps: 1 year steps
Horizon: 2050

Spatial dimension
Number of regions: 25
United States, Canada, Mexico, Chile, Japan, Korea, OECD Oceania, Other OECD Europe, France, Germany, Italy, United Kingdom, Europe 21 excluding EUG4, Europe 7, Eurasia, Russia, Caspian, China, India, Indonesia, South East Asia (excluding Indonesia), rest of Other Developing Asia, Brazil, other Latin America, North Africa, other Africa South Africa, Middle East

Policy implementation
Emission tax/pricing, cap and trade (global and regional), fuel taxes, fuel subsidies, feed-in-tariff, portfolio standard, capacity targets, emission standards, energy efficiency standards

Socio economic drivers

Exogenous drivers
Population (exogenous), urbanization rate (exogenous), GDP (exogenous)

Endogenous drivers
Autonomous energy efficiency improvements (endogenous)

Development
None

Macro economy

Economic sectors
Agriculture (economic), industry (physical & economic), services (economic), energy (physical & economic)

Cost measures
Energy system cost mark-up

Trade
Coal, oil, gas, bioenergy crops, emissions permits

Energy

Behaviour
Price elasticity

Resource use
Coal (process model), conventional oil (process model), unconventional oil (process model), conventional gas (process model), unconventional gas (process model), bioenergy (process model)

Electricity technologies
Coal, gas, oil, nuclear, geothermal, bioenergy, wind (onshore and offshore), solar PV (central and distributed), CCS*, CSP, Hydropower, ocean power
*Note: CCS can be combined with coal, gas and biomass power generation technologies

Conversion technologies
Natural gas to hydrogen w/o CCS, coal to liquids w/o CCS, coal to gas w/o CCS, coal heat, natural gas heat, oil heat, bioenergy heat, geothermal heat, solarthermal heat, CHP (coupled heat and power)

Grid and infrastructure
Electricity (aggregate), gas (aggregate)

Energy technology substitution
Logit choice model, weibull function, discrete technology choices with mostly high substitutability in some sectors and mostly low substitutability in other sectors, expansion and decline constraints, system integration constraints

Energy service sectors
Transportation, industry, residential, commercial

Land use

Land cover
Not covered by the model

Other resources

Other resources

Emissions and climate

*Greenhouse gases**
CO_2, CH_4, N_2O, HFCs (exogenous), CFCs (exogenous), SF_6 (exogenous)

*Pollutants**
NO_x, SO_x, BC, OC, CO, NH_3, VOC

*NOTE: Non-energy CO_2, non-energy CH_4, non-energy N_2O, CFC, HFC, SF_6, CO, NOx, VOC, SO_2, are assumptions-based and not disaggregated (only total emissions are available).

Climate indicators
CO_2e concentration (ppm), radiative forcing (W m^{-2}), temperature change (°C)

2.SM.2.12 Reference Card – IMACLIM

About
Name and version
IMACLIM 1.1 (Advance), IMACLIM-NLU 1.0 (EMF33)

Institution and users
Centre International de Recherche sur l'Environnement et le Développement (CIRED), France, http://www.centre-cired.fr.
Société de Mathématiques Appliquées et de Sciences Humaines (SMASH), France, http://www.smash.fr.

Model scope and methods
Objective
Imaclim-R is intended to study the interactions between energy systems and the economy to assess the feasibility of low-carbon development strategies and the transition pathway towards a low-carbon future.

Concept
Hybrid: general equilibrium with technology explicit modules. Recursive dynamics: each year the equilibrium is solved (system of non-linear equations), in between years the parameters for the equilibrium evolve according to specified functions.

Solution method
Imaclim-R is implemented in Scilab and uses the function fsolve from a shared C++ library to solve the static equilibrium system of non-linear equations.

Anticipation
Recursive dynamics: each year the equilibrium is solved (system of non-linear equations), in between years, the parameters for the equilibrium evolve according to specified functions.

Temporal dimension
Base year: 2001
Time steps: annual
Horizon: 2050 or 2100

Spatial dimension
Number of regions: 12
USA, Canada, Europe, China, India, Brazil, Middle East, Africa, Commonwealth of Independent States, OECD Pacific, rest of Asia, rest of Latin America

Policy implementation
Baseline does not include explicit climate policies. Climate/energy policies can be implemented in a number of ways, depending on the policy. A number of general or specific policy choices can be modelled, including: emissions or energy taxes, permit trading, specific technology subsidies, regulations, technology and/or resource constraints

Socio economic drivers
Exogenous drivers
Labour productivity, energy technical progress, population, active population

Note: Our model growth engine is composed of exogenous trends of active population growth and exogenous trends of labour productivity growth. The two sets of assumptions on demography and labour productivity, although exogenous, only prescribe natural growth. Effective growth results endogenously from the interaction of these driving forces with short-term constraints: (i) available capital flows for investments and (ii) rigidities, such as fixed technologies, immobility of the installed capital across sectors or rigidities in real wages, which may lead to partial utilization of production factors (labour and capital).

Endogenous drivers
None

Development
GDP per capita

Macro economy

Economic sectors
Agriculture, industry, energy, transport, services, construction
Note: The energy sector is divided into five sub-sectors: oil extraction, gas extraction, coal extraction, refinery, power generation. The transport sector is divided into three sub-sectors: terrestrial transport, air transport, water transport. The industry sector has one sub-sector: Energy intensive industry.

Cost measures
GDP loss, welfare loss, consumption loss, energy system costs

Cost measures
GDP loss, welfare loss, consumption loss, energy system costs

Trade
Coal, oil, gas, electricity, bioenergy crops, capital, emissions permits, non-energy goods, refined liquid fuels

Energy

Behaviour
Price response (via elasticities), and non-price drivers (infrastructure and urban forms conditioning location choices, different asymptotes on industrial goods consumption saturation levels with income rise, speed of personal vehicle ownership rate increase, speed of residential area increase).

Resource use
Coal, oil, gas, biomass

Electricity technologies
Coal, gas, oil, nuclear, biomass, wind, solar PV, CCS

Conversion technologies
Fuel to liquid

Grid and infrastructure
Electricity

Energy technology substitution
Discrete technology choices, expansion and decline constraints, system integration constraints

Energy service sectors
Transportation, industry, residential and commercial, agriculture

Land use

Land cover
Cropland, forest, extensive pastures, intensive pastures, inaccessible pastures, urban areas, unproductive land

Note: MACLIM 1.1 (Advance): Bioenergy production is determined by the fuel and electricity modules of Imaclim-R using supply curves from Hoogwijk et al. (2009) (bioelectricity) and IEA (biofuel).

IMACLIM-NLU 1.0 (EMF33): In this version the Imaclim-R model is linked to the land-use mode Nexus Land use. Bioenergy demand level is determined by the fuel and electricity modules of Imaclim-R. The Nexus Land use gives the corresponding price of biomass feedstock, taking into account the land constraints and food production The production of biomass for electricity and ligno-cellulosic fuels is located on marginal lands (i.e., less fertile or accessible lands). By increasing the demand for land, and spurring agricultural intensification, Bioenergy propels land and food prices.

Other resources

Other resources
None

Emissions and climate

Greenhouse gases
CO_2

Pollutants
None

Climate indicators
None

2.SM.2.13 Reference Card – IMAGE

About

Name and version

IMAGE framework 3.0

Institution and users

Utrecht University (UU), Netherlands, http://www.uu.nl.

PBL Netherlands Environmental Assessment Agency (PBL), Netherlands, http://www.pbl.nl.

Model scope and methods

Objective

IMAGE is an ecological–environmental model framework that simulates the environmental consequences of human activities worldwide. The objective of the IMAGE model is to explore the long-term dynamics and impacts of global changes that result. More specifically, the model aims to analyse interactions between human development and the natural environment to gain better insight into the processes of global environmental change, to identify response strategies to global environmental change based on assessment of options, and to indicate key inter-linkages and associated levels of uncertainty in processes of global environmental change.

Concept

The IMAGE framework can best be described as a geographically explicit integrated assessment simulation model, focusing on a detailed representation of relevant processes with respect to human use of energy, land and water in relation to relevant environmental processes.

Solution method

Recursive dynamic solution method

Anticipation

Simulation modelling framework, without foresight. However, a simplified version of the energy/climate part of the model (called FAIR) can be run prior to running the framework to obtain data for climate policy simulations.

Temporal dimension

Base year: 1970

Time steps: 1-5 year time step

Horizon: 2100

Spatial dimension

Number of regions: 26

Canada, USA, Mexico, rest of Central America, Brazil, rest of South America, Northern Africa, Western Africa, Eastern Africa, South Africa, Western Europe, Central Europe, Turkey, Ukraine +, Asian-Stan, Russia +, Middle East, India +, Korea, China +, Southeastern Asia, Indonesia +, Japan, Oceania, rest of South Asia, rest of Southern Africa

Policy implementation

Key areas where policy responses can be introduced in the model are: Climate policy, energy policies (air pollution, access and energy security), land use policies (food), specific policies to project biodiversity, measures to reduce the imbalance of the nitrogen cycle

Socio-economic drivers

Exogenous drivers

Exogenous GDP, GDP per capita, population

Endogenous drivers

Energy demand, renewable price, fossil fuel prices, carbon prices, technology progress, energy intensity, preferences, learning by doing, agricultural demand, value added

Development

GDP per capita, income distribution in a region, urbanization rate

Note: GDP per capita and income distribution are exogenous

Macro economy

Economic sectors

Note: No explicit economy representation in monetary units. Explicit economy representation in terms of energy is modelled (for the agriculture, industry, energy, transport and built environment sectors)

Cost measures

Area under MAC, energy system costs

Trade

Coal, oil, gas, uranium, bioenergy crops, food crops, emissions permits, non-energy goods, bioenergy products, livestock products

Energy

Behaviour

In the energy model, substitution among technologies is described in the model using the multinomial logit formulation. The multinomial logit model implies that the market share of a certain technology or fuel type depends on costs relative to competing technologies. The option with the lowest costs gets the largest market share, but in most cases not the full market. We interpret the latter as a representation of heterogeneity in the form of specific market niches for every technology or fuel.

Resource use

Coal, oil, gas, uranium, biomass

Note: Distinction between traditional and modern biomass

Electricity technologies

Coal w/ CCS, coal w/o CCS, gas w/ CCS, gas w/o CCS, oil w/ CCS, oil w/o CCS, nuclear, biomass w/ CCS, biomass w/o CCS, wind, solar PV, CSP, hydropower, geothermal

Note: wind: onshore and offshore; coal: conventional, IGCC, IGCC + CCS, IGCC + CHP, IGCC + CHP + CCS; oil: conventional, OGCC, OGCC + CCS, OGCC + CHP, OGCC + CHP + CCS); natural gas: conventional, CC, CC + CCS, CC + CHP, CC + CHP + CCS; biomass: conventional, CC, CC + CCS, CC + CHP, CC + CHP + CCS; hydropower and geothermal: exogenous

Conversion technologies
CHP, hydrogen

Grid and infrastructure
Electricity

Energy technology substitution
Discrete technology choices, expansion and decline constraints, system integration constraints

Energy service sectors
Transportation, industry, residential and commercial

Land use
Land cover
Forest, cropland, grassland, abandoned land, protected land

Other resources
Other resources
Water, metals, cement

Emissions and climate
Greenhouse gases
CO_2, CH_4, N_2O, HFCs, CFCs, SF_6, PFCs

Pollutants
NO_x, SO_x, BC, OC, ozone, VOC, NH_3, CO

Climate indicators
CO_2e concentration (ppm), radiative forcing (W m^{-2}), temperature change (°C)

2.SM.2.14 Reference Card – MERGE-ETL 6.0

About
Name and version
MERGE-ETL 6.0

Institution and users
Paul Scherrer Institut
https://www.psi.ch/eem/ModelsEN/2012MergeDescription.pdf
https://www.psi.ch/eem/ModelsEN/2014MergeCalibration.pdf

Model scope and methods
Objective
MERGE (Model for Evaluating Regional and Global Effects of GHG reductions policies) is an integrated assessment model originally developed by Manne et al. (1995). It divides the world in geopolitical regions, each one represented by two coupled submodels describing the energy and economic sectors, respectively. MERGE acts as a global social planner with perfect foresight and determines the economic equilibrium in each region that maximizes global welfare, defined as a linear combination of the current and future regional welfares. Besides these regional energy–economic submodels, and linked to them, MERGE includes global submodels of greenhouse gas emissions and the climate to allow the analysis of the effectiveness and impacts of climate policies and the role of technologies to realize climate targets. The model is sufficiently flexible to explore views on a wide range of contentious issues: costs of abatement, damages of climate change, valuation and discounting.

Concept
The MERGE-ETL model is a hard-linked hybrid model as the energy sectors are fully integrated with the rest of the economy. The model combines a bottom-up description of the energy system disaggregated into electric and non-electric sectors, a top-down economic model based on macroeconomic production functions, and a simplified climate cycle model. The energy sectors endogenously account for technological change with explicit representation of two-factor learning curves.

Solution method
General equilibrium (closed economy). Two different solutions can be produced: a cooperative globally optimal solution and a non-cooperative solution equivalent to Nash equilibrium. It is programmed in GAMS and uses the CONOPT solver.

Anticipation
Inter-temporal (foresight) or myopic.

Temporal dimension
Base year: 2015
Time steps: 10 years
Horizon: 2015-2100

Spatial dimension
Number of regions: 10
EUP (European Union), RUS (Russia), MEA (Middle East), IND (India), CHI (China), JPN (Japan), CANZ (Canada, Australia and New

Zealand), USA (United States of America), ROW (Rest of the World), SWI (Switzerland)

Policy implementation
Emission tax/pricing, cap and trade, fuel taxes, fuel subsidies, feed-in-tariff, portfolio standard, capacity targets

Socio economic drivers

Exogenous drivers
Population, population age structure, autonomous energy efficiency improvements

Development
GDP

Macro economy

Economic sectors
One final good, electric and non-electric demand sectors

Cost measures
GDP loss, welfare loss, consumption loss, area under mac, energy system costs

Trade
Non-energy goods, coal, oil, gas, uranium, bioenergy crops, emissions permits

Energy

Behaviour
Considered in side-constraints controlling technology deployment rates

Resource use
Coal, conventional oil, unconventional oil, conventional gas, unconventional gas, uranium, bioenergy
Note: Cost-supply curves for the different resources are considered

Electricity technologies
Coal, gas, oil, nuclear, biomass, wind, solar PV, hydrogen
Note: CCS can be combined with coal, gas and biomass power generation technologies

Conversion technologies
Hydrogen,fuel to liquids
Note: CCS can be combined with coal, gas and biomass technologies

Grid and infrastructure
Electricity, gas, CO_2, H_2

Energy technology substitution
Expansion and decline constraints, system integration constraints, early technology retirement

Energy service sectors
Electric and non-electric demand that is further disaggregated to seven energy sectors/fuels, namely coal, oil, gas, biofuels, hydrogen, solar and heat

Land use

Land cover

Other resources

Other resources

Emissions and climate

Greenhouse gases, CO_2, CH_4, N_2O, HFCs, SF_6

Pollutants
None

Climate indicators
CO_2e concentration (ppm), radiative forcing (W m^{-2}), temperature change (°C), climate damages $ or equivalent

2.SM.2.15 Reference Card – MESSAGE(ix)-GLOBIOM

About

Name and version

MESSAGE-GLOBIOM 1.0 and MESSAGEix-GLOBIOM 1.0

Institution and users

International Institute for Applied Systems Analysis (IIASA), Austria, global model description: http://data.ene.iiasa.ac.at/message-globiom/. Model documentation and code (MESSAGEix) http://messageix.iiasa.ac.at

Main users: IIASA, the MESSAGE model is distributed via the International Atomic Energy Agency (IAEA) to member countries, the new MESSAGEix model is available as an open source tool via GitHub (https://github.com/iiasa/message_ix)

Model scope and methods

Objective

MESSAGE-GLOBIOM is an integrated assessment framework designed to assess the transformation of the energy and land systems vis-a-vis the challenges of climate change and other sustainability issues. It consists of the energy model MESSAGE, the land use model GLOBIOM, the air pollution and GHG model GAINS, the aggregated macroeconomic model MACRO and the simple climate model MAGICC.

Concept

Hybrid model (energy engineering and land use partial equilibrium models soft-linked to macroeconomic general equilibrium model)

Solution method

Hybrid model (linear program optimization for the energy systems and land use modules, non-linear program optimization for the macroeconomic module)

Anticipation

Myopic/Perfect Foresight (MESSAGE can be run both with perfect foresight and myopically, while GLOBIOM runs myopically)

Temporal dimension

Base year: 2010

Time steps: 1990, 1995, 2000, 2005, 2010, 2020, 2030, 2040, 2050, 2060, 2070, 2080, 2090, 2100, 2110

Horizon: 1990-2110

Spatial dimension

Number of regions: 11+1

AFR (Sub-Saharan Africa), CPA (Centrally Planned Asia & China), EEU (Eastern Europe), FSU (Former Soviet Union), LAM (Latin America and the Caribbean), MEA (Middle East and North Africa), NAM (North America), PAO (Pacific OECD), PAS (Other Pacific Asia), SAS (South Asia), WEU (Western Europe), GLB (international shipping)

Policy implementation

GHG and energy taxes; GHG emission cap and permits trading; energy taxes and subsidies; micro-financing (for energy access analysis); regulation: generation capacity, production and share targets

Socio economic drivers

Exogenous drivers

Labour productivity, energy technical progress, GDP per capita, population

Endogenous drivers

None

Development

GDP per capita, income distribution in a region, number of people relying on solid cooking fuels

Macro economy

Economic sectors

Note: MACRO represents the economy in a single sector with the production function including capital, labour and energy nests

Cost measures

GDP loss, consumption loss, area under marginal abatement cost (MAC) curve, energy system costs

Trade

Coal, oil, gas, uranium, electricity, food crops, emissions permits

Note: bioenergy is only traded after processing to a secondary fuel (e.g., liquid biofuel)

Energy

Behaviour

Non-monetary factors of decision making (e.g., behavioural impacts) are represented in MESSAGE via so-called inconvenience costs. These are generally included in the consumer-dominated energy end-use sectors (transportation sector, residential and commercial sector) and are particularly relevant in the modelling of energy access in developing countries.

Resource use

Coal, oil, gas, uranium, biomass

Note: modern and traditional applications of biomass are distinguished

Electricity technologies

Coal w /o CCS, coal w/ CCS, gas w/o CCS, gas w/ CCS, oil w/o CCS, biomass w/o CCS, biomass w/ CCS, nuclear, wind onshore, wind offshore, solar PV, CSP, geothermal, hydropower

Note: CCS can be combined with coal, gas and biomass power generation technologies

Conversion technologies

CHP, hydrogen, fuel to gas, fuel to liquid

Note: CHP can be combined with all thermal power plant types; hydrogen can be produced from coal, gas and biomass feedstocks and electricity; fuel to liquids is represented for coal, gas and biomass feedstocks; and fuel to gas is represented for coal and biomass feedstocks

Grid and infrastructure

Electricity, Gas, Heat, CO_2, Hydrogen

Energy technology substitution

Discrete technology choices, expansion and decline constraints, system integration constraints

Energy service sectors

Transportation, Industry, Residential and commercial

Note: non-energy use (feedstock) of energy carriers is separately represented, but generally reported under industry

Land use

Land cover

Forest (natural/managed), short-rotation plantations, cropland, grassland, other natural land

Other resources

Other resources

Water, cement

Note: cement is not modelled as a separate commodity, but process emissions from cement production are represented

Emissions and climate

Greenhouse gases

CO_2, CH_4, N_2O, HFCs, CFCs, SF_6

Pollutants

NO_x, SO_x, BC, OC, CO, NH_3, VOC

Climate indicators

CO_2e concentration (ppm), radiative forcing (W m^{-2}), temperature change (°C)

2.SM.2.16 Reference Card – POLES

About

Name and version

POLES ADVANCE (other versions are in use in other applications)

Institution and users

JRC - Joint Research Centre - European Commission (EC-JRC), Belgium, http://ec.europa.eu/jrc/en/poles.

Main users: - European Commission JRC; Université de Grenoble UPMF, France - Enerdata

Model scope and methods

Objective

POLES was originally developed to assess energy markets, combining a detailed description of energy demand, transformation and primary supply for all energy vectors. It provides full energy balances on a yearly basis using frequent data updates so as to deliver robust forecasts for both short- and long-term horizons. It has quickly been used, since the late 90s, to assess energy-related CO_2 mitigation policies. Over time, other GHG emissions have been included (energy and industry non-CO_2 from the early 2000s), and linkages with agricultural and land use models have been progressively implemented.

Concept

Partial equilibrium

Solution method

Recursive simulation

Anticipation

Myopic

Temporal dimension

Base year: 1990-2015 (data up to current time –1/–2)

Time steps: yearly

Horizon: 2050–2100

Spatial dimension

Number of regions: 66

Policy implementation

Energy taxes per sector and fuel, carbon pricing, feed-in-tariffs, green certificates, low interest rates, investment subsidies, fuel efficiency standards in vehicles and buildings, white certificates

Socio economic drivers

Exogenous drivers

Exogenous GDP, population

Endogenous drivers

Value added, mobility needs, fossil fuel prices, buildings surfaces

Development

GDP per capita, urbanization rate

Macro economy

Economic sectors
Agriculture, industry, services

Cost measures
Area under MAC, energy system costs
Note: Investments: supply-side only

Trade
Coal, oil, gas, bioenergy crops, liquid biofuels

Energy

Behaviour
Activity drivers depend on income per capita and energy prices via elasticities. Energy demand depends on activity drivers, energy prices and technology costs. Primary energy supply depends on remaining resources, production cost and price effects.

Resource use
Coal, oil, gas, uranium, biomass

Electricity technologies
Coal, gas, oil, nuclear, biomass, wind, solar PV, CCS, hydropower, geothermal, solar CSP, ocean

Conversion technologies
CHP, hydrogen, fuel to liquid

Grid and infrastructure
Gas, H_2

Energy technology substitution
None

Energy service sectors
Transportation, industry, residential and commercial

Land use

Land cover
Cropland, forest, grassland, urban areas, desert

Other resources

Other resources
Metals
Note: Steel tons

Emissions and climate

Greenhouse gases
CO_2, CH_4, N_2O, HFCs, SF_6, PFCs

Pollutants
None

Climate indicators
None

2.SM.2.17 Reference Card – REMIND - MAgPIE

About

Name and version
REMIND 1.7 – MAgPIE 3.0

Institution and users
Potsdam Institut für Klimafolgenforschung (PIK), Germany,
https://www.pik-potsdam.de/remind
https://www.pik-potsdam.de/magpie

Model scope and methods

Objective
REMIND-MAgPIE is an integrated assessment modeling framework to assess energy and land use transformations and their implications for limiting global warming and achieving sustainable development goals.

REMIND (Regionalized Model of Investment and Development) is a global multiregional model incorporating the economy, the climate system and a detailed representation of the energy sector. It allows analysing technology options and policy proposals for climate mitigation, and models regional energy investments and interregional trade in goods, energy carriers and emissions allowances.

MAgPIE (Model of Agricultural Production and its Impacts on the Environment) is a global multiregional economic land-use optimization model designed for scenario analysis up to the year 2100. MAgPIE provides a holistic framework to explore future transformation pathways of the land system, including multiple trade-offs with ecosystem services and sustainable development.

Concept
REMIND: Hybrid model that couples an economic growth model with a detailed energy system model and a simple climate model.

MAgPIE: Gridded land-use optimization model with 10 socio-economic world regions. MAgPIE takes regional economic conditions, such as demand for agricultural commodities, technological development, and production costs, as well as spatially explicit data on potential crop yields, carbon stocks and water constraints (from the dynamic global vegetation model LPJmL), under current and future climatic conditions into account.

Solution method
REMIND: Inter-temporal optimization that, based on a Ramsey-type growth model, maximizes regional welfare in a Nash equilibrium or, alternatively, Pareto optimum using the Negishi algorithm.

MAgPIE: Partial equilibrium model of the agricultural sector with recursive-dynamic optimization. The objective function of MAgPIE is the fulfilment of agricultural demand for 10 world regions at minimum global costs under consideration of biophysical and socio-economic constraints. Major cost types in MAgPIE are factor requirement costs (capital, labor, fertilizer), land conversion costs, transportation costs to the closest market, investment costs for yield-increasing technological change (TC) and costs for GHG emissions in mitigation scenarios.

REMIND and MAgPIE are coupled by exchanging greenhouse gas prices and bioenergy demand from REMIND to MAgPIE, and bioenergy prices and AFOLU greenhouse gas emissions from MAgPIE to REMIND, and iterating until an equilibrium of prices and quantities is established.

Anticipation
REMIND: Perfect Foresight
MAgPIE: Myopic

Temporal dimension
REMIND:
Base year: 2005
Time steps: flexible time steps, default is 5-year time steps until 2060 and 10-year time steps until 2100; period from 2100–2150 is calculated to avoid distortions due to end effects, but typically only the time span 2005–2100 is used for model applications.

MAgPIE:
Base year: 1995
Time steps: 5 and/or 10 years
Horizon: 1995–2100

Spatial dimension
Number of regions: 11
AFR - Sub-Saharan Africa (excluding South Africa)
CHN - China
EUR - European Union
JPN - Japan
IND - India
LAM - Latin America
MEA - Middle East, North Africa, and Central Asia
OAS - other Asian countries (mainly Southeast Asia)
RUS - Russia
ROW - rest of the World (Australia, Canada, New Zealand, Non-EU Europe, South Africa)
USA - United States of America
Note: MAgPIE operates on 10 socio-economic world regions which are mapped to REMIND-defined regions.

Policy implementation
REMIND: Pareto-optimal achievement of policy targets on temperature, radiative forcing, GHG concentration, or cumulative carbon budgets. Alternatively, calculation of Nash equilibrium without internalized technology spillovers. Possibility to analyse changes in expectations about climate policy goals as well as pre-specified policy packages until 2030/2050, including, for example, energy capacity and efficiency targets, renewable energy quotas, carbon and other taxes, and energy subsidies

MAgPIE: 1st- and 2nd-generation bioenergy, pricing of GHG emissions from land-use change (CO_2) and agricultural land use (CH_4, N_2O), land-use regulation, REDD+ policies, afforestation, agricultural trade policies

Socio economic drivers
Exogenous drivers
REMIND: Labour productivity, energy efficiency parameters of the production function, population.

MAgPIE: Demand for bioenergy, food, feed, and material demand from the agricultural sector.

Endogenous drivers
REMIND: Investments in industrial capital stock and specific energy technology capital stocks. Endogenous learning-by-doing for wind and solar power as well as electric and fuel cell vehicle technologies (global learning curve, internalized spillovers).

MAgPIE: Investments in agricultural productivity, land conversion and (re)allocation of agricultural production.

Development
REMIND: GDP per capita
MAgPIE: GDP per capita

Macro economy (REMIND)
Economic sectors
Note: The macroeconomic part contains a single sector representation of the entire economy. A generic final good is produced from capital, labour, and different final energy types

Cost measures
GDP loss, welfare loss, consumption loss

Trade
Coal, oil, gas, uranium, bioenergy crops, capital, emissions permits, non-energy goods

Energy (REMIND)
Behaviour
Energy demands react to energy prices and technology costs. Price response of final energy demand through CES production function. No explicit modelling of behavioural change. Baseline energy demands are calibrated in such a way that the energy demand patterns in different regions slowly converge when displayed as per capita energy demand over per capita GDP.

Resource use
Coal, oil, gas, uranium, biomass

Electricity technologies
Coal (with and w/o CCS), gas (with and w/o CCS), oil (w/o CCS), nuclear, biomass (with and w/o CCS), wind, solar PV, solar CSP, hydropower, geothermal, hydrogen

Conversion technologies
CHP, Heat pumps, hydrogen (from fossil fuels and biomass with and w/o CCS; electrolytic hydrogen), fuel to gas, fuel to liquid (from fossil fuels and biomass with and w/o CCS), heat plants

Grid and infrastructure

Electricity, Gas, Heat, CO_2, H_2

Note: Generalized transmission and distribution costs are included, but not modelled on an explicit spatial level. Regionalized additional grid and storage costs for renewable integration are included.

Energy technology substitution

Discrete technology choices with high to full substitutability, expansion and decline constraints, system integration constraints

Note: Expansion and decline, and system integration are influenced though cost mark-ups rather than constraints.

Energy service sectors

Transportation, industry, residential and commercial

Note: In older versions of REMIND (REMIND 1.6 and earlier), the industry and residential and commercial sectors are not treated separately but represented jointly by one stationary sector (referred to as 'Other Sector').

Land use (MAgPIE)

MAgPIE allocates land use to fulfil competing demands for commodities, feed, carbon storage, land conservation and environmental protection. Land use is broadly categorized in cropland, forest land, pasture land, and other natural land. Regional food energy demand is defined for an exogenously given population in 16 food energy categories, based on regional diets. Future trends in food demand are derived from a cross-country regression analysis, based on future scenarios on GDP and population growth. MAgPIE takes technological development and production costs as well as spatially explicit data on potential crop yields, land and water constraints (from LPJmL) into account. It includes agricultural trade with different levels of regional self-sufficiency constraints. MAgPIE calculates the following AFOLU GHG emissions: CO_2 from land use change (including changes to soil and plant carbon content), N_2O from fertilizing agricultural soils and manure management, and CH_4 from enteric fermentation, manure management and rice cultivation.

Other resources

Other resources

Cement

Note: Cement production is not explicitly modelled, but emissions from cement production are accounted for.

Emissions and climate

Greenhouse gases

CO_2, CH_4, N_2O, HFCs, PFCs, SF_6

Pollutants

NO_x, SO_x, BC, OC, ozone, CO, VOC, NH_3

Note: Ozone is not modelled as emission but is an endogenous result of atmospheric chemistry.

Climate indicators

CO_2 concentration (ppm), other GHG concentrations, radiative forcing (W m^{-2}), temperature change (°C)

Note: Different emissions are accounted for with different levels of detail depending on the types and sources of emissions (directly by source, via marginal abatement cost (MAC) curves, by econometric estimates, exogenous).

2.SM.2.18 Reference Card – Shell - World Energy Model

About

Name and version

Shell World Energy Model 2018

2018 Edition (Version 2.10 series)

Institution and users

Shell Corporation B.V., www.shell.com/scenariosenergymodels

Model scope and methods

Objective

Exploratory simulations of plausible scenarios, covering both short-term drivers and momentum, together with the capability for long-term transformation of the energy system.

Concept

Partial equilibrium (price elastic demand)

Solution method

Simulation

Anticipation

Recursive-dynamic (myopic)

Temporal dimension

Base year: 2017

Time steps: 1 year steps

Horizon: 2100

Spatial dimension

Number of regions: 100 (= 82 top countries + 18 rest of the world regions)

Policy implementation

Emission tax/pricing, cap and trade, fuel taxes, fuel subsidies, energy efficiency standards

Socio economic drivers

Exogenous drivers

Population

Autonomous Energy Efficiency Improvements

Endogenous drivers

None

Development

None

Macro economy

Economic sectors

Number of sectors: 14

Industry, services, energy, energy service (sector-specific) and energy demand (in EJ) for each sector

Cost measures

None

Trade
Coal, oil, gas, bioenergy crops

Energy
Behaviour
None

Resource use
Coal, conventional oil (process model), unconventional oil (process model), conventional gas (process model), unconventional gas (process model), bioenergy (fixed)

Electricity technologies
Coal (w/o CCS and w/ CCS), gas (w/o CCS and w/ CCS), oil (w/o CCS and w/ CCS), bioenergy (w/o CCS and w/ CCS), geothermal power, nuclear power, solar power (central PV, distributed PV, CSP), wind power, hydroelectric power, ocean power

Conversion technologies
Coal to hydrogen (w/o CCS and w/ CCS), natural gas to hydrogen (w/o CCS and w/ CCS), oil to hydrogen (w/o CCS and w/ CCS), biomass to hydrogen (w/o CCS and w/ CCS), nuclear thermochemical hydrogen electrolysis, coal to liquids (w/o CCS and w/ CCS), gas to liquids (w/o CCS and w/ CCS), bioliquids (w/o CCS and w/ CCS), oil refining, coal to gas (w/o CCS and w/ CCS), oil to gas (w/o CCS and w/ CCS), biomass to gas (w/o CCS and w/ CCS), coal heat, natural gas heat, oil heat, biomass heat, geothermal heat, solarthermal heat

Grid and infrastructure
None

Energy technology substitution
Logit choice model, discrete technology choices with mostly high substitutability, mostly a constrained logit model; some derivative choices (e.g., refinery outputs) have pathway dependent choices, constraints are imposed both endogenously and after off-model analysis

Energy service sectors
Transportation, industry, residential and commercial

Land use
Land cover
None

Other resources
Other resources
None

Emissions and climate
Greenhouse gases, CO_2 fossil fuels (endogenous & uncontrolled)

Pollutants
None

Climate indicators
None

2.SM.2.19 Reference Card – WITCH

About
Name and version
WITCH

Institution and users
Fondazione Eni Enrico Mattei (FEEM), Italy, http://www.feem.it.
Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC), Italy, http://www.cmcc.it.
http://www.witchmodel.org/

Model scope and methods
Objective
WITCH evaluates the impacts of climate policies on global and regional economic systems and provides information on the optimal responses of these economies to climate change. The model considers the positive externalities from leaning-by-doing and learning-by-researching in the technological change.

Concept
Hybrid: Economic optimal growth model, including a bottom-up energy sector and a simple climate model, embedded in a 'game theory' framework.

Solution method
Regional growth models solved by non-linear optimization and game theoretic setup solved by tatonnement algorithm (cooperative solution: Negishi welfare aggregation, non-cooperative solution: Nash equilibrium)

Anticipation
Perfect foresight

Temporal dimension
Base year: 2005
Time steps: 5
Horizon: 2150

Spatial dimension
Number of regions: 14
cajaz: Canada, Japan, New Zealand
china: China, including Taiwan
easia: South East Asia
india: India
kosau: South Korea, South Africa, Australia
laca: Latin America, Mexico and Caribbean
indo: Indonesia
mena: Middle East and North Africa
neweuro: EU new countries + Switzerland + Norway
oldeuro: EU old countries (EU-15)
sasia: South Asia
ssa: Sub Saharan Africa
te: Non-EU Eastern European countries, including Russia
usa: United States of America

2SM

Policy implementation
Quantitative climate targets (temperature, radiative forcing, concentration), carbon budgets, emissions profiles as optimization constraints, carbon taxes, allocation and trading of emission permits, banking and borrowing, subsidies, taxes and penalty on energies sources.

Socio economic drivers
Exogenous drivers
Total factor productivity, labour productivity, capital technical progress

Development
None

Macro economy
Economic sectors
Energy, other
Note: A single economy sector is represented. Production inputs are capital, labour and energy services, accounting for the energy sector split into 8 energy technologies sectors (coal, oil, gas, wind and solar, nuclear, electricity and biofuels).

Cost measures
GDP loss, welfare loss, consumption loss, energy system costs

Trade
Coal, oil, gas, emissions permits

Energy
Resource use
Coal, oil, gas, uranium, biomass

Electricity technologies
Coal, gas, oil, nuclear, biomass, wind, solar PV, CCS

Conversion technologies
None

Grid and infrastructure
Electricity, CO_2

Energy technology substitution
Expansion and decline constraints, system integration constraints

Energy service sectors
Transportation

Land use
Land cover
Cropland, forest
Note: Bioenergy related cost and emissions are obtained by soft linking with the GLOBIOM model.

Other resources
Other resources
Water

Emissions and climate
Greenhouse gases, CO_2, CH_4, N_2O, HFCs, CFCs, SF_6

Pollutants
NO_x, SO_x, BC, OC

Climate indicators
CO_2e concentration (ppm), radiative forcing (W m^{-2}), temperature change (°C), limate damages $ or equivalent

5

Sustainable Development, Poverty Eradication and Reducing Inequalities

Coordinating Lead Authors:
Joyashree Roy (India), Petra Tschakert (Australia/Austria), Henri Waisman (France)

Lead Authors:
Sharina Abdul Halim (Malaysia), Philip Antwi-Agyei (Ghana), Purnamita Dasgupta (India), Bronwyn Hayward (New Zealand), Markku Kanninen (Finland), Diana Liverman (USA), Chukwumerije Okereke (UK/Nigeria), Patricia Fernanda Pinho (Brazil), Keywan Riahi (Austria), Avelino G. Suarez Rodriguez (Cuba)

Contributing Authors:
Fernando Aragón-Durand (Mexico), Mustapha Babiker (Sudan), Mook Bangalore (USA), Paolo Bertoldi (Italy), Bishwa Bhaskar Choudhary (India), Edward Byres (Austria/Brazil), Anton Cartwright (South Africa), Riyanti Djalante (Japan/Indonesia), Kristie L. Ebi (USA), Neville Ellis (Australia), Francois Engelbrecht (South Africa), Maria Figueroa (Denmark/Venezuela), Mukesh Gupta (India), Diana Hinge Salili (Vanuatu), Daniel Huppmann (Austria), Saleemul Huq (Bangladesh/UK), Daniela Jacob (Germany), Rachel James (UK), Debora Ley (Guatemala/Mexico), Peter Marcotullio (USA), Omar Massera (Mexico), Reinhard Mechler (Germany), Haileselassie Amaha Medhin (Ethiopia), Shagun Mehrotra (USA/India), Peter Newman (Australia), Karen Paiva Henrique (Brazil), Simon Parkinson (Canada), Aromar Revi (India), Wilfried Rickels (Germany), Lisa Schipper (UK/Sweden), Jörn Schmidt (Germany), Seth Schultz (USA), Pete Smith (UK), William Solecki (USA), Shreya Some (India), Nenenteiti Teariki-Ruatu (Kiribati), Adelle Thomas (Bahamas), Penny Urquhart (South Africa), Margaretha Wewerinke-Singh (Netherlands)

Review Editors:
Svitlana Krakovska (Ukraine), Ramon Pichs Madruga (Cuba), Roberto Sanchez (Mexico)

Chapter Scientist:
Neville Ellis (Australia)

This chapter should be cited as:
Roy, J., P. Tschakert, H. Waisman, S. Abdul Halim, P. Antwi-Agyei, P. Dasgupta, B. Hayward, M. Kanninen, D. Liverman, C. Okereke, P.F. Pinho, K. Riahi, and A.G. Suarez Rodriguez, 2018: Sustainable Development, Poverty Eradication and Reducing Inequalities. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. In Press.

Table of Contents

Executive Summary

This chapter takes sustainable development as the starting point and focus for analysis. It considers the broad and multifaceted bi-directional interplay between sustainable development, including its focus on eradicating poverty and reducing inequality in their multidimensional aspects, and climate actions in a 1.5°C warmer world. These fundamental connections are embedded in the Sustainable Development Goals (SDGs). The chapter also examines synergies and trade-offs of adaptation and mitigation options with sustainable development and the SDGs and offers insights into possible pathways, especially climate-resilient development pathways towards a 1.5°C warmer world.

Sustainable Development, Poverty and Inequality in a 1.5°C Warmer World

Limiting global warming to 1.5°C rather than 2°C above pre-industrial levels would make it markedly easier to achieve many aspects of sustainable development, with greater potential to eradicate poverty and reduce inequalities (*medium evidence, high agreement*). Impacts avoided with the lower temperature limit could reduce the number of people exposed to climate risks and vulnerable to poverty by 62 to 457 million, and lessen the risks of poor people to experience food and water insecurity, adverse health impacts, and economic losses, particularly in regions that already face development challenges (*medium evidence, medium agreement*). {5.2.2, 5.2.3} Avoided impacts expected to occur between 1.5°C and 2°C warming would also make it easier to achieve certain SDGs, such as those that relate to poverty, hunger, health, water and sanitation, cities and ecosystems (SDGs 1, 2, 3, 6, 11, 14 and 15) (*medium evidence, high agreement*). {5.2.3, Table 5.2 available at the end of the chapter}

Compared to current conditions, 1.5°C of global warming would nonetheless pose heightened risks to eradicating poverty, reducing inequalities and ensuring human and ecosystem well-being (*medium evidence, high agreement*). Warming of 1.5°C is not considered 'safe' for most nations, communities, ecosystems and sectors and poses significant risks to natural and human systems as compared to the current warming of 1°C (*high confidence*). {Cross-Chapter Box 12 in Chapter 5} The impacts of 1.5°C of warming would disproportionately affect disadvantaged and vulnerable populations through food insecurity, higher food prices, income losses, lost livelihood opportunities, adverse health impacts and population displacements (*medium evidence, high agreement*). {5.2.1} Some of the worst impacts on sustainable development are expected to be felt among agricultural and coastal dependent livelihoods, indigenous people, children and the elderly, poor labourers, poor urban dwellers in African cities, and people and ecosystems in the Arctic and Small Island Developing States (SIDS) (*medium evidence, high agreement*). {5.2.1, Box 5.3, Chapter 3, Box 3.5, Cross-Chapter Box 9 in Chapter 4}

Climate Adaptation and Sustainable Development

Prioritization of sustainable development and meeting the SDGs is consistent with efforts to adapt to climate change (*high confidence*). Many strategies for sustainable development enable transformational adaptation for a 1.5°C warmer world, provided attention is paid to reducing poverty in all its forms and to promoting equity and participation in decision-making (*medium evidence, high agreement*). As such, sustainable development has the potential to significantly reduce systemic vulnerability, enhance adaptive capacity, and promote livelihood security for poor and disadvantaged populations (*high confidence*). {5.3.1}

Synergies between adaptation strategies and the SDGs are expected to hold true in a 1.5°C warmer world, across sectors and contexts (*medium evidence, medium agreement*). Synergies between adaptation and sustainable development are significant for agriculture and health, advancing SDGs 1 (extreme poverty), 2 (hunger), 3 (healthy lives and well-being) and 6 (clean water) (*robust evidence, medium agreement*). {5.3.2} Ecosystem- and community-based adaptation, along with the incorporation of indigenous and local knowledge, advances synergies with SDGs 5 (gender equality), 10 (reducing inequalities) and 16 (inclusive societies), as exemplified in drylands and the Arctic (*high evidence, medium agreement*). {5.3.2, Box 5.1, Cross-Chapter Box 10 in Chapter 4}

Adaptation strategies can result in trade-offs with and among the SDGs (*medium evidence, high agreement*). Strategies that advance one SDG may create negative consequences for other SDGs, for instance SDGs 3 (health) versus 7 (energy consumption) and agricultural adaptation and SDG 2 (food security) versus SDGs 3 (health), 5 (gender equality), 6 (clean water), 10 (reducing inequalities), 14 (life below water) and 15 (life on the land) (*medium evidence, medium agreement*). {5.3.2}

Pursuing place-specific adaptation pathways towards a 1.5°C warmer world has the potential for significant positive outcomes for well-being in countries at all levels of development (*medium evidence, high agreement*). Positive outcomes emerge when adaptation pathways (i) ensure a diversity of adaptation options based on people's values and the trade-offs they consider acceptable, (ii) maximize synergies with sustainable development through inclusive, participatory and deliberative processes, and (iii) facilitate equitable transformation. Yet such pathways would be difficult to achieve without redistributive measures to overcome path dependencies, uneven power structures, and entrenched social inequalities (*medium evidence, high agreement*). {5.3.3}

Mitigation and Sustainable Development

The deployment of mitigation options consistent with 1.5°C pathways leads to multiple synergies across a range of sustainable development dimensions. At the same time, the rapid pace and magnitude of change that would be required to limit warming to 1.5°C, if not carefully managed, would lead to trade-offs with some sustainable development dimensions (*high confidence*). The number of synergies between mitigation response options and sustainable development exceeds the number of trade-offs in energy demand and supply sectors; agriculture, forestry and other land use (AFOLU); and for oceans (*very high confidence*). {Figure 5.2, Table 5.2 available at the end of the chapter} The 1.5°C pathways indicate robust synergies, particularly for the SDGs 3 (health), 7 (energy), 12 (responsible consumption and production) and 14 (oceans) (*very high confidence*). {5.4.2, Figure 5.3} For SDGs 1 (poverty), 2 (hunger), 6 (water) and 7 (energy), there is a risk of trade-offs or negative side effects from stringent mitigation actions compatible with 1.5°C of warming (*medium evidence, high agreement*). {5.4.2}

Appropriately designed mitigation actions to reduce energy demand can advance multiple SDGs simultaneously. Pathways compatible with 1.5°C that feature low energy demand show the most pronounced synergies and the lowest number of trade-offs with respect to sustainable development and the SDGs (*very high confidence*). Accelerating energy efficiency in all sectors has synergies with SDGs 7 (energy), 9 (industry, innovation and infrastructure), 11 (sustainable cities and communities), 12 (responsible consumption and production), 16 (peace, justice and strong institutions), and 17 (partnerships for the goals) (*robust evidence, high agreement*). {5.4.1, Figure 5.2, Table 5.2} Low-demand pathways, which would reduce or completely avoid the reliance on bioenergy with carbon capture and storage (BECCS) in 1.5°C pathways, would result in significantly reduced pressure on food security, lower food prices and fewer people at risk of hunger (*medium evidence, high agreement*). {5.4.2, Figure 5.3}

The impacts of carbon dioxide removal options on SDGs depend on the type of options and the scale of deployment (*high confidence*). If poorly implemented, carbon dioxide removal (CDR) options such as bioenergy, BECCS and AFOLU would lead to trade-offs. Appropriate design and implementation requires considering local people's needs, biodiversity and other sustainable development dimensions (*very high confidence*). {5.4.1.3, Cross-Chapter Box 7 in Chapter 3}

The design of the mitigation portfolios and policy instruments to limit warming to 1.5°C will largely determine the overall synergies and trade-offs between mitigation and sustainable development (*very high confidence*). Redistributive policies that shield the poor and vulnerable can resolve trade-offs for a range of SDGs (*medium evidence, high agreement*). Individual mitigation options are associated with both positive and negative interactions with the SDGs (*very high confidence*). {5.4.1} However, appropriate choices across the mitigation portfolio can help to maximize positive side effects while minimizing negative side effects (*high confidence*). {5.4.2, 5.5.2} Investment needs for complementary policies resolving trade-offs with a range of SDGs are only a small fraction of the overall mitigation investments in 1.5°C pathways (*medium evidence, high agreement*). {5.4.2, Figure 5.4} Integration of mitigation with adaptation and sustainable development compatible with 1.5°C warming requires a systems perspective (*high confidence*). {5.4.2, 5.5.2}

Mitigation consistent with 1.5°C of warming create high risks for sustainable development in countries with high dependency on fossil fuels for revenue and employment generation (*high confidence*). These risks are caused by the reduction of global demand affecting mining activity and export revenues and challenges to rapidly decrease high carbon intensity of the domestic economy (*robust evidence, high agreement*). {5.4.1.2, Box 5.2} Targeted policies that promote diversification of the economy and the energy sector could ease this transition (*medium evidence, high agreement*). {5.4.1.2, Box 5.2}

Sustainable Development Pathways to 1.5°C

Sustainable development broadly supports and often enables the fundamental societal and systems transformations that would be required for limiting warming to 1.5°C above pre-industrial levels (*high confidence*). Simulated pathways that feature the most sustainable worlds (e.g., Shared Socio-Economic Pathways (SSP) 1) are associated with relatively lower mitigation and adaptation challenges and limit warming to 1.5°C at comparatively lower mitigation costs. In contrast, development pathways with high fragmentation, inequality and poverty (e.g., SSP3) are associated with comparatively higher mitigation and adaptation challenges. In such pathways, it is not possible to limit warming to 1.5°C for the vast majority of the integrated assessment models (*medium evidence, high agreement*). {5.5.2} In all SSPs, mitigation costs substantially increase in 1.5°C pathways compared to 2°C pathways. No pathway in the literature integrates or achieves all 17 SDGs (*high confidence*). {5.5.2} Real-world experiences at the project level show that the actual integration between adaptation, mitigation and sustainable development is challenging as it requires reconciling trade-offs across sectors and spatial scales (*very high confidence*). {5.5.1}

Without societal transformation and rapid implementation of ambitious greenhouse gas reduction measures, pathways to limiting warming to 1.5°C and achieving sustainable development will be exceedingly difficult, if not impossible, to achieve (*high confidence*). The potential for pursuing such pathways differs between and within nations and regions, due to different development trajectories, opportunities and challenges (*very high confidence*). {5.5.3.2, Figure 5.1} Limiting warming to 1.5°C would require all countries and non-state actors to strengthen their contributions without delay. This could be achieved through sharing efforts based on bolder and more committed cooperation, with support for those with the least capacity to adapt, mitigate and transform (*medium evidence, high agreement*). {5.5.3.1, 5.5.3.2} Current efforts towards reconciling low-carbon trajectories and reducing inequalities, including those that avoid difficult trade-offs associated with transformation, are partially successful yet demonstrate notable obstacles (*medium evidence, medium agreement*). {5.5.3.3, Box 5.3, Cross-Chapter Box 13 in this chapter}

Social justice and equity are core aspects of climate-resilient development pathways for transformational social change. Addressing challenges and widening opportunities between and within countries and communities would be necessary to achieve sustainable development and limit warming to 1.5°C, without making the poor and disadvantaged worse off (*high confidence*). Identifying and navigating inclusive and socially acceptable pathways towards low-carbon, climate-resilient futures is a challenging yet important endeavour, fraught with moral, practical and political difficulties and inevitable trade-offs (*very high confidence*). {5.5.2, 5.5.3.3, Box 5.3} It entails deliberation and problem-solving processes to negotiate societal values, well-being, risks and resilience and to determine what is desirable and fair, and to whom (*medium evidence, high agreement*). Pathways that encompass joint, iterative planning and transformative visions, for instance in Pacific SIDS like Vanuatu and in urban contexts, show potential for liveable and sustainable futures (*high confidence*). {5.5.3.1, 5.5.3.3, Figure 5.5, Box 5.3, Cross-Chapter Box 13 in this chapter}

The fundamental societal and systemic changes to achieve sustainable development, eradicate poverty and reduce inequalities while limiting warming to 1.5°C would require meeting a set of institutional, social, cultural, economic and technological conditions (*high confidence*). The coordination and monitoring of policy actions across sectors and spatial scales is essential to support sustainable development in 1.5°C warmer conditions (*very high confidence*). {5.6.2, Box 5.3} External funding and technology transfer better support these efforts when they consider recipients' context-specific needs (*medium evidence, high agreement*). {5.6.1} Inclusive processes can facilitate transformations by ensuring participation, transparency, capacity building and iterative social learning (*high confidence*). {5.5.3.3, Cross-Chapter Box 13, 5.6.3} Attention to power asymmetries and unequal opportunities for development, among and within countries, is key to adopting 1.5°C-compatible development pathways that benefit all populations (*high confidence*). {5.5.3, 5.6.4, Box 5.3} Re-examining individual and collective values could help spur urgent, ambitious and cooperative change (*medium evidence, high agreement*). {5.5.3, 5.6.5}

5.1 Scope and Delineations

This chapter takes sustainable development as the starting point and focus for analysis, considering the broader bi-directional interplay and multifaceted interactions between development patterns and climate actions in a 1.5°C warmer world and in the context of eradicating poverty and reducing inequality. It assesses the impacts of keeping temperatures at or below 1.5°C of global warming above pre-industrial levels on sustainable development and compares the impacts avoided at 1.5°C compared to 2°C (Section 5.2). It then examines the interactions, synergies and trade-offs of adaptation (Section 5.3) and mitigation (Section 5.4) measures with sustainable development and the Sustainable Development Goals (SDGs). The chapter offers insights into possible pathways towards a 1.5°C warmer world, especially through climate-resilient development pathways providing a comprehensive vision across different contexts (Section 5.5). The chapter also identifies the conditions that would be needed to simultaneously achieve sustainable development, poverty eradication, the reduction of inequalities, and the 1.5°C climate objective (Section 5.6).

5.1.1 Sustainable Development, SDGs, Poverty Eradication and Reducing Inequalities

Chapter 1 (see Cross-Chapter Box 4 in Chapter 1) defines sustainable development as 'development that meets the needs of the present and future generations' through balancing economic, social and environmental considerations, and then introduces the United Nations (UN) 2030 Agenda for Sustainable Development, which sets out 17 ambitious goals for sustainable development for all countries by 2030. These SDGs are: no poverty (SDG 1), zero hunger (SDG 2), good health and well-being (SDG 3), quality education (SDG 4), gender equality (SDG 5), clean water and sanitation (SDG 6), affordable and clean energy (SDG 7), decent work and economic growth (SDG 8), industry, innovation and infrastructure (SDG 9), reduced inequalities (SDG 10), sustainable cities and communities (SDG 11), responsible consumption and production (SDG 12), climate action (SDG 13), life below water (SDG 14), life on land (SDG 15), peace, justice and strong institutions (SDG 16) and partnerships for the goals (SDG 17).

The IPCC Fifth Assessment Report (AR5) included extensive discussion of links between climate and sustainable development, especially in Chapter 13 (Olsson et al., 2014) and Chapter 20 (Denton et al., 2014) in Working Group II and Chapter 4 (Fleurbaey et al., 2014) in Working Group III. However, the AR5 preceded the 2015 adoption of the SDGs and the literature that argues for their fundamental links to climate (Wright et al., 2015; Salleh, 2016; von Stechow et al., 2016; Hammill and Price-Kelly, 2017; ICSU, 2017; Maupin, 2017; Gomez-Echeverri, 2018).

The SDGs build on efforts under the UN Millennium Development Goals to reduce poverty, hunger, and other deprivations. According to the UN, the Millennium Development Goals were successful in reducing poverty and hunger and improving water security (UN, 2015a). However, critics argued that they failed to address within-country disparities, human rights and key environmental concerns, focused only on developing countries, and had numerous measurement and attribution problems (Langford et al., 2013; Fukuda-Parr et al., 2014). While improvements in water security, slums and health may have reduced some aspects of climate vulnerability, increases in incomes were linked to rising greenhouse gas (GHG) emissions and thus to a trade-off between development and climate change (Janetos et al., 2012; UN, 2015a; Hubacek et al., 2017).

While the SDGs capture many important aspects of sustainable development, including the explicit goals of poverty eradication and reducing inequality, there are direct connections from climate to other measures of sustainable development including multidimensional poverty, equity, ethics, human security, well-being and climate-resilient development (Bebbington and Larrinaga, 2014; Robertson, 2014; Redclift and Springett, 2015; Barrington-Leigh, 2016; Helliwell et al., 2018; Kirby and O'Mahony, 2018) (see Glossary). The UN proposes sustainable development as 'eradicating poverty in all its forms and dimensions, combating inequality within and among countries, preserving the planet, creating sustained, inclusive and sustainable economic growth and fostering social inclusion' (UN, 2015b). There is *robust evidence* of the links between climate change and poverty (see Chapter 1, Cross-Chapter Box 4). The AR5 concluded with *high confidence* that disruptive levels of climate change would preclude reducing poverty (Denton et al., 2014; Fleurbaey et al., 2014). International organizations have since stated that climate changes 'undermine the ability of all countries to achieve sustainable development' (UN, 2015b) and can reverse or erase improvements in living conditions and decades of development (Hallegatte et al., 2016).

Climate warming has unequal impacts on different people and places as a result of differences in regional climate changes, vulnerabilities and impacts, and these differences then result in unequal impacts on sustainable development and poverty (Section 5.2). Responses to climate change also interact in complex ways with goals of poverty reduction. The benefits of adaptation and mitigation projects and funding may accrue to some and not others, responses may be costly and unaffordable to some people and countries, and projects may disadvantage some individuals, groups and development initiatives (Sections 5.3 and 5.4, Cross-Chapter Box 11 in Chapter 4).

5.1.2 Pathways to 1.5°C

Pathways to 1.5°C (see Chapter 1, Cross-Chapter Box 1 in Chapter 1, Glossary) include ambitious reductions in emissions and strategies for adaptation that are transformational, as well as complex interactions with sustainable development, poverty eradication and reducing inequalities. The AR5 WGII introduced the concept of climate-resilient development pathways (CRDPs) (see Glossary) which combine adaptation and mitigation to reduce climate change and its impacts, and emphasize the importance of addressing structural and intersecting inequalities, marginalization and multidimensional poverty to 'transform […] the development pathways themselves towards greater social and environmental sustainability, equity, resilience, and justice' (Olsson et al., 2014). This chapter assesses literature on CRDPs relevant to 1.5°C global warming (Section 5.5.3), to understand better the possible societal and systems transformations (see Glossary) that reduce inequality and increase well-being

(Figure 5.1). It also summarizes the knowledge on conditions to achieve such transformations, including changes in technologies, culture, values, financing and institutions that support low-carbon and resilient pathways and sustainable development (Section 5.6).

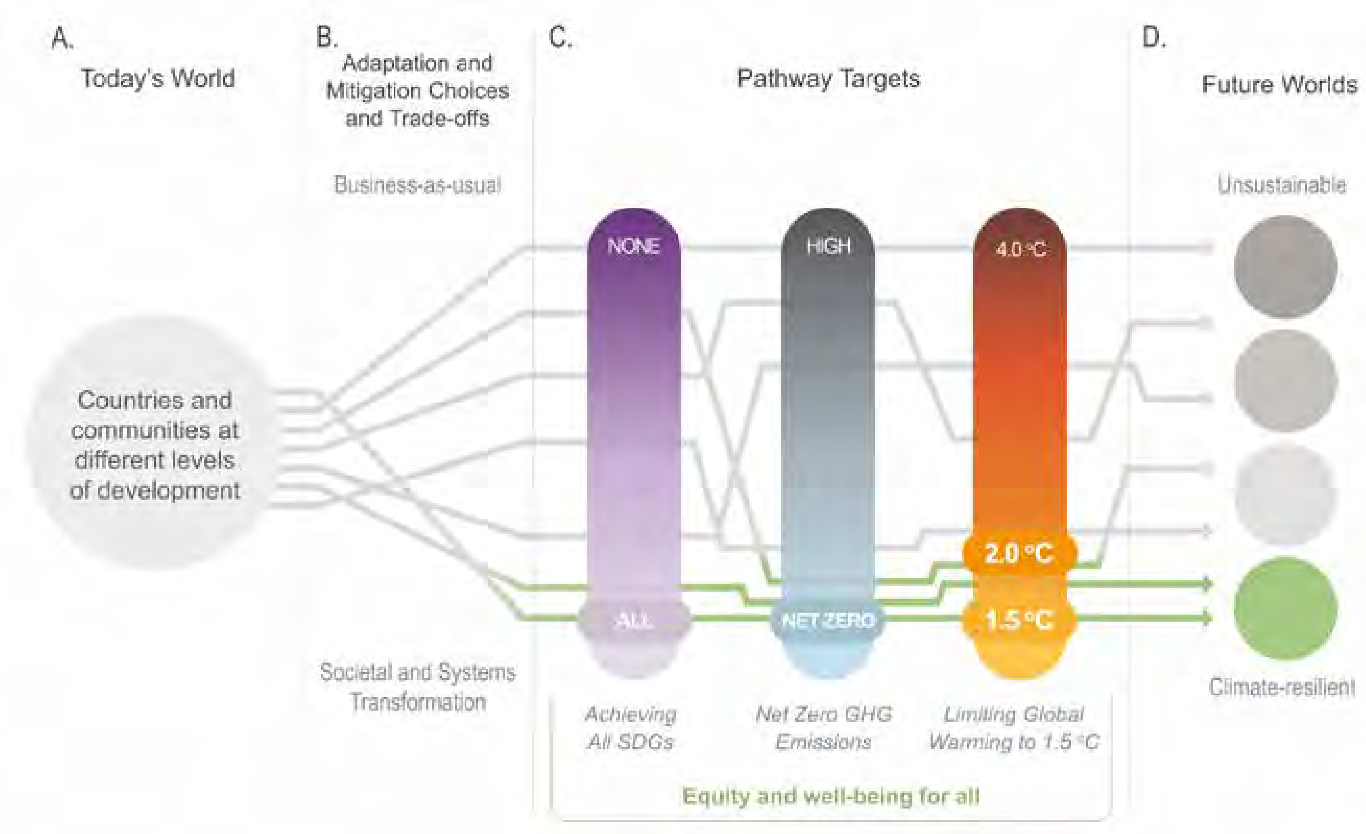


Figure 5.1 | Climate-resilient development pathways (CRDPs) (green arrows) between a current world in which countries and communities exist at different levels of development (A) and future worlds that range from climate-resilient (bottom) to unsustainable (top) (D). CRDPs involve societal transformation rather than business-as-usual approaches, and all pathways involve adaptation and mitigation choices and trade-offs (B). Pathways that achieve the Sustainable Development Goals by 2030 and beyond, strive for net zero emissions around mid-21st century, and stay within the global 1.5°C warming target by the end of the 21st century, while ensuring equity and well-being for all, are best positioned to achieve climate-resilient futures (C). Overshooting on the path to 1.5°C will make achieving CRDPs and other sustainable trajectories more difficult; yet, the limited literature does not allow meaningful estimates.

5.1.3 Types of Evidence

A variety of sources of evidence are used to assess the interactions of sustainable development and the SDGs with the causes, impacts and responses to climate change of 1.5°C warming. This chapter builds on Chapter 3 to assess the sustainable development implications of impacts at 1.5°C and 2°C, and on Chapter 4 to examine the implications of response measures. Scientific and grey literature, with a post-AR5 focus, and data that evaluate, measure and model sustainable development–climate links from various perspectives, quantitatively and qualitatively, across scales, and through well-documented case studies are assessed.

Literature that explicitly links 1.5°C global warming to sustainable development across scales remains scarce; yet we find relevant insights in many recent publications on climate and development that assess impacts across warming levels, the effects of adaptation and mitigation response measures, and interactions with the SDGs. Relevant evidence also stems from emerging literature on possible pathways, overshoot and enabling conditions (see Glossary) for integrating sustainable development, poverty eradication and reducing inequalities in the context of 1.5°C.

5.2 Poverty, Equality and Equity Implications of a 1.5°C Warmer World

Climate change could lead to significant impacts on extreme poverty by 2030 (Hallegatte et al., 2016; Hallegatte and Rozenberg, 2017). The AR5 concluded, with *very high confidence*, that climate change and climate variability worsen existing poverty and exacerbate inequalities, especially for those disadvantaged by gender, age, race, class, caste, indigeneity and (dis)ability (Olsson et al., 2014). New literature on these links is substantial, showing that the poor will continue to experience climate change severely, and climate change will exacerbate poverty (*very high confidence*) (Fankhauser and Stern, 2016; Hallegatte et al., 2016; O'Neill et al., 2017a; Winsemius et al., 2018). The understanding of regional impacts and risks of 1.5°C global warming and interactions with patterns of societal vulnerability and poverty remains limited. Yet identifying and addressing poverty and inequality is at the core of staying within a safe and just space for humanity (Raworth, 2017; Bathiany et al., 2018). Building on relevant findings from Chapter 3 (see Section 3.4), this section examines anticipated impacts and risks of 1.5°C and higher warming on sustainable development, poverty, inequality and equity (see Glossary).

5.2.1 Impacts and Risks of a 1.5°C Warmer World: Implications for Poverty and Livelihoods

Global warming of 1.5°C will have consequences for sustainable development, poverty and inequalities. This includes residual risks, limits to adaptation, and losses and damages (Cross-Chapter Box 12 in this chapter; see Glossary). Some regions have already experienced a 1.5°C warming, with impacts on food and water security, health and other components of sustainable development (*medium evidence, medium agreement*) (see Chapter 3, Section 3.4). Climate change is also already affecting poorer subsistence communities through decreases in crop production and quality, increases in crop pests and diseases, and disruption to culture (Savo et al., 2016). It disproportionally affects children and the elderly and can increase gender inequality (Kaijser and Kronsell, 2014; Vinyeta et al., 2015; Carter et al., 2016; Hanna and Oliva, 2016; Li et al., 2016).

At 1.5°C warming, compared to current conditions, further negative consequences are expected for poor people, and inequality and vulnerability (*medium evidence, high agreement*). Hallegatte and Rozenberg (2017) report that by 2030 (roughly approximating a 1.5°C warming), 122 million additional people could experience extreme poverty, based on a 'poverty scenario' of limited socio-economic progress, comparable to the Shared Socio-Economic Pathway (SSP) 4 (inequality), mainly due to higher food prices and declining health, with substantial income losses for the poorest 20% across 92 countries. Pretis et al. (2018) estimate negative impacts on economic growth in lower-income countries at 1.5°C warming, despite uncertainties. Impacts are likely to occur simultaneously across livelihood, food, human, water and ecosystem security (*limited evidence, high agreement*) (Byers et al., 2018), but the literature on interacting and cascading effects remains scarce (Hallegatte et al., 2014; O'Neill et al., 2017b; Reyer et al., 2017a, b).

Chapter 3 outlines future impacts and risks for ecosystems and human systems, many of which could also undermine sustainable development and efforts to eradicate poverty and hunger, and to protect health and ecosystems. Chapter 3 findings (see Section 3.5.2.1) suggest increasing Reasons for Concern from moderate to high at a warming of 1.1° to 1.6°C, including for indigenous people and their livelihoods, and ecosystems in the Arctic (O'Neill et al., 2017b). In 2050, based on the Hadley Centre Climate Prediction Model 3 (HadCM3) and the Special Report on Emission Scenarios A1b scenario (roughly comparable to 1.5°C warming), 450 million more flood-prone people would be exposed to doubling in flood frequency, and global flood risk would increase substantially (Arnell and Gosling, 2016). For droughts, poor people are expected to be more exposed (85% in population terms) in a warming scenario greater than 1.5°C for several countries in Asia and southern and western Africa (Winsemius et al., 2018). In urban Africa, a 1.5°C warming could expose many households to water poverty and increased flooding (Pelling et al., 2018). At 1.5ºC warming, fisheries-dependent and coastal livelihoods, of often disadvantaged populations, would suffer from the loss of coral reefs (see Chapter 3, Box 3.4).

Global heat stress is projected to increase in a 1.5°C warmer world, and by 2030, compared to 1961–1990, climate change could be responsible for additional annual deaths of 38,000 people from heat stress, particularly among the elderly, and 48,000 from diarrhoea, 60,000 from malaria, and 95,000 from childhood undernutrition (WHO, 2014). Each 1°C increase could reduce work productivity by 1 to 3% for people working outdoors or without air conditioning, typically the poorer segments of the workforce (Park et al., 2015).

The regional variation in the 'warming experience at 1.5°C' (see Chapter 1, Section 1.3.1) is large (see Chapter 3, Section 3.3.2). Declines in crop yields are widely reported for Africa (60% of observations), with serious consequences for subsistence and rain-fed agriculture and food security (Savo et al., 2016). In Bangladesh, by 2050, damages and losses are expected for poor households dependent on freshwater fish stocks due to lack of mobility, limited access to land and strong reliance on local ecosystems (Dasgupta et al., 2017). Small Island Developing States (SIDS) are expected to experience challenging conditions at 1.5°C warming due to increased risk of internal migration and displacement and limits to adaptation (see Chapter 3, Box 3.5, Cross-Chapter Box 12 in this chapter). An anticipated decline of marine fisheries of 3 million metric tonnes per degree warming would have serious regional impacts for the Indo-Pacific region and the Arctic (Cheung et al., 2016).

5.2.2 Avoided Impacts of 1.5°C versus 2°C Warming for Poverty and Inequality

Avoided impacts between 1.5°C and 2°C warming are expected to have significant positive implications for sustainable development, and reducing poverty and inequality. Using the SSPs (see Chapter 1, Cross-Chapter Box 1 in Chapter 1, Section 5.5.2), Byers et al. (2018) model the number of people exposed to multi-sector climate risks and vulnerable to poverty (income < $10/day), comparing 2°C and 1.5°C; the respective declines are from 86 million to 24 million for SSP1 (sustainability), from 498 million to 286 million for SSP2 (middle of the road), and from 1220 million to 763 million for SSP3 (regional rivalry), which suggests overall 62–457 million fewer people exposed and vulnerable at 1.5°C warming. Across the SSPs, the largest populations exposed and vulnerable are in South Asia (Byers et al., 2018). The avoided impacts on poverty at 1.5°C relative to 2°C are projected to depend at least as much or more on development scenarios than on warming (Wiebe et al., 2015; Hallegatte and Rozenberg, 2017).

Limiting warming to 1.5°C is expected to reduce the number of people exposed to hunger, water stress and disease in Africa (Clements, 2009). It is also expected to limit the number of poor people exposed to floods and droughts at higher degrees of warming, especially in African and Asian countries (Winsemius et al., 2018). Challenges for poor populations – relating to food and water security, clean energy access and environmental well-being – are projected to be less at 1.5°C, particularly for vulnerable people in Africa and Asia (Byers et al., 2018). The overall projected socio-economic losses compared to the present day are less at 1.5°C (8% loss of gross domestic product per capita) compared to 2°C (13%), with lower-income countries projected to experience greater losses, which may increase economic inequality between countries (Pretis et al., 2018).

5.2.3 Risks from 1.5°C versus 2°C Global Warming and the Sustainable Development Goals

The risks that can be avoided by limiting global warming to 1.5ºC rather than 2°C have many complex implications for sustainable development (ICSU, 2017; Gomez-Echeverri, 2018). There is *high confidence* that constraining warming to 1.5°C rather than 2°C would reduce risks for unique and threatened ecosystems, safeguarding the services they provide for livelihoods and sustainable development and making adaptation much easier (O'Neill et al., 2017b), particularly in Central America, the Amazon, South Africa and Australia (Schleussner et al., 2016; O'Neill et al., 2017b; Reyer et al., 2017b; Bathiany et al., 2018).

In places that already bear disproportionate economic and social challenges to their sustainable development, people will face lower risks at 1.5°C compared to 2°C. These include North Africa and the Levant (less water scarcity), West Africa (less crop loss), South America and Southeast Asia (less intense heat), and many other coastal nations and island states (lower sea level rise, less coral reef loss) (Schleussner et al., 2016; Betts et al., 2018). The risks for food, water and ecosystems, particularly in subtropical regions such as Central America and countries such as South Africa and Australia, are expected to be lower at 1.5°C than at 2°C warming (Schleussner et al., 2016). Fewer people would be exposed to droughts and heat waves and the associated health impacts in countries such as Australia and India (King et al., 2017; Mishra et al., 2017).

Limiting warming to 1.5°C would make it markedly easier to achieve the SDGs for poverty eradication, water access, safe cities, food security, healthy lives and inclusive economic growth, and would help to protect terrestrial ecosystems and biodiversity (*medium evidence, high agreement*) (Table 5.2 available at the end of the chapter). For example, limiting species loss and expanding climate refugia will make it easier to achieve SDG 15 (see Chapter 3, Section 3.4.3). One indication of how lower temperatures benefit the SDGs is to compare the impacts of Representative Concentration Pathway (RCP) 4.5 (lower emissions) and RCP8.5 (higher emissions) on the SDGs (Ansuategi et al., 2015). A low emissions pathway allows for greater success in achieving SDGs for reducing poverty and hunger, providing access to clean energy, reducing inequality, ensuring education for all and making cities more sustainable. Even at lower emissions, a medium risk of failure exists to meet goals for water and sanitation, and marine and terrestrial ecosystems.

Action on climate change (SDG 13), including slowing the rate of warming, would help reach the goals for water, energy, food and land (SDGs 6, 7, 2 and 15) (Obersteiner et al., 2016; ICSU, 2017) and contribute to poverty eradication (SDG 1) (Byers et al., 2018). Although the literature that connects 1.5°C to the SDGs is limited, a pathway that stabilizes warming at 1.5°C by the end of the century is expected to increase the chances of achieving the SDGs by 2030, with greater potential to eradicate poverty, reduce inequality and foster equity (*limited evidence, medium agreement*). There are no studies on overshoot and dimensions of sustainable development, although literature on 4°C of warming suggests the impacts would be severe (Reyer et al., 2017b).

Table 5.1 | Sustainable development implications of avoided impacts between 1.5°C and 2°C global warming.

Impacts	Chapter 3 Section	1.5°C	2°C	Sustainable Development Goals (SDGs) More Easily Achieved when Limiting Warming to 1.5°C
Water scarcity	3.4.2.1	4% more people exposed to water stress	8% more people exposed to water stress, with 184–270 million people more exposed	SDG 6 water availability for all
	Table 3.4	496 (range 103–1159) million people exposed and vulnerable to water stress	586 (range 115–1347) million people exposed and vulnerable to water stress	
Ecosystems	3.4.3, Table 3.4	Around 7% of land area experiences biome shifts	Around 13% (range 8–20%) of land area experiences biome shifts	SDG 15 to protect terrestrial ecosystems and halt biodiversity loss
	Box 3.5	70–90% of coral reefs at risk from bleaching	99% of coral reefs at risk from bleaching	
Coastal cities	3.4.5.1	31–69 million people exposed to coastal flooding	32–79 million exposed to coastal flooding	SDG 11 to make cities and human settlements safe and resilient
	3.4.5.2	Fewer cities and coasts exposed to sea level rise and extreme events	More people and cities exposed to flooding	
Food systems	3.4.6, Box 3.1	Significant declines in crop yields avoided, some yields may increase	Average crop yields decline	SDG 2 to end hunger and achieve food security
	Table 3.4	32–36 million people exposed to lower yields	330–396 million people exposed to lower yields	
Health	3.4.5.1	Lower risk of temperature-related morbidity and smaller mosquito range	Higher risks of temperature-related morbidity and mortality and larger geographic range of mosquitoes	SDG 3 to ensure healthy lives for all
	3.4.5.2	3546–4508 million people exposed to heat waves	5417–6710 million people exposed to heat waves	

Cross-Chapter Box 12 | Residual Risks, Limits to Adaptation and Loss and Damage

Lead Authors:
Riyanti Djalante (Japan/Indonesia), Kristie L. Ebi (USA), Debora Ley (Guatemala/Mexico), Reinhard Mechler (Germany), Patricia Fernanda Pinho (Brazil), Aromar Revi (India), Petra Tschakert (Australia/Austria)

Contributing Authors:
Karen Paiva Henrique (Brazil), Saleemul Huq (Bangladesh/UK), Rachel James (UK), Adelle Thomas (Bahamas), Margaretha Wewerinke-Singh (Netherlands)

Introduction
Residual climate-related risks, limits to adaptation, and loss and damage (see Glossary) are increasingly assessed in the scientific literature (van der Geest and Warner, 2015; Boyd et al., 2017; Mechler et al., 2019). The AR5 (IPCC, 2013; Oppenheimer et al., 2014) documented impacts that have been detected and attributed to climate change, projected increasing climate-related risks with continued global warming, and recognized barriers and limits to adaptation. It recognized that adaptation is constrained by biophysical, institutional, financial, social and cultural factors, and that the interaction of these factors with climate change can lead to soft adaptation limits (adaptive actions currently not available) and hard adaptation limits (adaptive actions appear infeasible leading to unavoidable impacts) (Klein et al., 2014).

Loss and damage: concepts and perspectives
'Loss and Damage' (L&D) has been discussed in international climate negotiations for three decades (INC, 1991; Calliari, 2016; Vanhala and Hestbaek, 2016). A work programme on L&D was established as part of the Cancun Adaptation Framework in 2010 supporting developing countries particularly vulnerable to climate change impacts (UNFCCC, 2011a). In 2013, the Conference of the Parties (COP) 19 established the Warsaw International Mechanism for Loss and Damage (WIM) as a formal part of the United Nations Framework Convention on Climate Change (UNFCCC) architecture (UNFCCC, 2014). It acknowledges that L&D 'includes, and in some cases involves more than, that which can be reduced by adaptation' (UNFCCC, 2014). The Paris Agreement recognized 'the importance of averting, minimizing and addressing loss and damage associated with the adverse effects of climate change' through Article 8 (UNFCCC, 2015).

There is no one definition of L&D in climate policy, and analysis of policy documents and stakeholder views has demonstrated ambiguity (Vanhala and Hestbaek, 2016; Boyd et al., 2017). UNFCCC documents suggest that L&D is associated with adverse impacts of climate change on human and natural systems, including impacts from extreme events and slow-onset processes (UNFCCC, 2011b, 2014, 2015). Some documents focus on impacts in developing or particularly vulnerable countries (UNFCCC, 2011b, 2014). They refer to economic (loss of assets and crops) and non-economic (biodiversity, culture, health) impacts, the latter also being an action area under the WIM workplan, and irreversible and permanent loss and damage. Lack of clarity of what the term addresses (avoidance through adaptation and mitigation, unavoidable losses, climate risk management, existential risk) was expressed among stakeholders, with further disagreement ensuing about what constitutes anthropogenic climate change versus natural climate variability (Boyd et al., 2017).

Limits to adaptation and residual risks
The AR5 described adaptation limits as points beyond which actors' objectives are compromised by intolerable risks threatening key objectives such as good health or broad levels of well-being, thus requiring transformative adaptation for overcoming soft limits (see Chapter 4, Sections 4.2.2.3, 4.5.3 and Cross-Chapter Box 9, Section 5.3.1) (Dow et al., 2013; Klein et al., 2014). The AR5 WGII risk tables, based on expert judgment, depicted the potential for, and the limits of, additional adaptation to reduce risk. Near-term (2030–2040) risks can be used as a proxy for 1.5°C warming by the end of the century and compared to longer-term (2080–2100) risks associated with an approximate 2°C warming. Building on the AR5 risk approach, Cross-Chapter Box 12, Figure 1 provides a stylised application example to poverty and inequality.

Cross-Chapter Box 12 (continued)

Cross-Chapter Box 12, Figure 1 | Stylized reduced risk levels due to avoided impacts between 2°C and 1.5°C warming (in solid red-orange), additional avoided impacts with adaptation under 2°C (striped orange) and under 1.5°C (striped yellow), and unavoidable impacts (losses) with no or very limited potential for adaptation (grey), extracted from the AR5 WGII risk tables (Field et al., 2014), and underlying chapters by Adger et al. (2014) and Olsson et al. (2014). For some systems and sectors (A), achieving 1.5°C could reduce risks to low (with adaptation) from very high (without adaptation) and high (with adaptation) under 2°C. For other areas (C), no or very limited adaptation potential is anticipated, suggesting limits, with the same risks for 1.5°C and 2°C. Other risks are projected to be medium under 2°C with further potential for reduction, especially with adaptation, to very low levels (B).

Limits to adaptation, residual risks, and losses in a 1.5°C warmer world

The literature on risks at 1.5°C (versus 2°C and more) and potentials for adaptation remains limited, particularly for specific regions, sectors, and vulnerable and disadvantaged populations. Adaptation potential at 1.5°C and 2°C is rarely assessed explicitly, making an assessment of residual risk challenging. Substantial progress has been made since the AR5 to assess which climate change impacts on natural and human systems can be attributed to anthropogenic emissions (Hansen and Stone, 2016) and to examine the influence of anthropogenic emissions on extreme weather events (NASEM, 2016), and on consequent impacts on human life (Mitchell et al., 2016), but less so on monetary losses and risks (Schaller et al., 2016). There has also been some limited research to examine local-level limits to adaptation (Warner and Geest, 2013; Filho and Nalau, 2018). What constitutes losses and damages is context-dependent and often requires place-based research into what people value and consider worth protecting (Barnett et al., 2016; Tschakert et al., 2017). Yet assessments of non-material and intangible losses are particularly challenging, such as loss of sense of place, belonging, identity, and damage to emotional and mental well-being (Serdeczny et al., 2017; Wewerinke-Singh, 2018a). Warming of 1.5°C is not considered 'safe' for most nations, communities, ecosystems and sectors, and poses significant risks to natural and human systems as compared to the current warming of 1°C (high confidence) (see Chapter 3, Section 3.4, Box 3.4, Box 3.5, Table 3.5, Cross-Chapter Box 6 in Chapter 3). Table 5.2, drawing on findings from Chapters 3, 4 and 5, presents examples of soft and hard limits in natural and human systems in the context of 1.5°C and 2°C of warming.

Cross-Chapter Box 12, Table 1 | Soft and hard adaptation limits in the context of 1.5°C and 2°C of global warming.

System/Region	Example	Soft Limit	Hard Limit
Coral reefs	Loss of 70–90% of tropical coral reefs by mid-century under 1.5°C scenario (total loss under 2°C scenario) (see Chapter 3, Sections 3.4.4 and 3.5.2.1, Box 3.4)		✓
Biodiversity	6% of insects, 8% of plants and 4% of vertebrates lose over 50% of the climatically determined geographic range at 1.5°C (18% of insects, 16% of plants and 8% of vertebrates at 2°C) (see Chapter 3, Section 3.4.3.3)		✓
Poverty	24–357 million people exposed to multi-sector climate risks and vulnerable to poverty at 1.5°C (86–1220 million at 2°C) (see Section 5.2.2)	✓	
Human health	Twice as many megacities exposed to heat stress at 1.5°C compared to present, potentially exposing 350 million additional people to deadly heat wave conditions by 2050 (see Chapter 3, Section 3.4.8)	✓	✓
Coastal livelihoods	Large-scale changes in oceanic systems (temperature and acidification) inflict damage and losses to livelihoods, income, cultural identity and health for coastal-dependent communities at 1.5°C (potential higher losses at 2°C) (see Chapter 3, Sections 3.4.4, 3.4.5, 3.4.6.3, Box 3.4, Box 3.5, Cross-Chapter Box 6, Chapter 4, Section 4.3.5; Section 5.2.3)	✓	✓
Small Island Developing States	Sea level rise and increased wave run up combined with increased aridity and decreased freshwater availability at 1.5°C warming potentially leaving several atoll islands uninhabitable (see Chapter 3, Sections 3.4.3, 3.4.5, Box 3.5, Chapter 4, Cross-Chapter Box 9)		✓

Cross-Chapter Box 12 (continued)

Approaches and policy options to address residual risk and loss and damage

Conceptual and applied work since the AR5 has highlighted the synergies and differences with adaptation and disaster risk reduction policies (van der Geest and Warner, 2015; Thomas and Benjamin, 2017), suggesting more integration of existing mechanisms, yet careful consideration is advised for slow-onset and potentially irreversible impacts and risk (Mechler and Schinko, 2016). Scholarship on justice and equity has provided insight on compensatory, distributive and procedural equity considerations for policy and practice to address loss and damage (Roser et al., 2015; Wallimann-Helmer, 2015; Huggel et al., 2016). A growing body of legal literature considers the role of litigation in preventing and addressing loss and damage and finds that litigation risks for governments and business are bound to increase with improved understanding of impacts and risks as climate science evolves (high confidence) (Mayer, 2016; Banda and Fulton, 2017; Marjanac and Patton, 2018; Wewerinke-Singh, 2018b). Policy proposals include international support for experienced losses and damages (Crosland et al., 2016; Page and Heyward, 2017), addressing climate displacement, donor-supported implementation of regional public insurance systems (Surminski et al., 2016) and new global governance systems under the UNFCCC (Biermann and Boas, 2017).

5.3 Climate Adaptation and Sustainable Development

Adaptation will be extremely important in a 1.5°C warmer world since substantial impacts will be felt in every region (*high confidence*) (Chapter 3, Section 3.3), even if adaptation needs will be lower than in a 2°C warmer world (see Chapter 4, Sections 4.3.1 to 4.3.5, 4.5.3, Cross-Chapter Box 10 in Chapter 4). Climate adaptation options comprise structural, physical, institutional and social responses, with their effectiveness depending largely on governance (see Glossary), political will, adaptive capacities and availability of finance (see Chapter 4, Sections 4.4.1 to 4.4.5) (Betzold and Weiler, 2017; Sonwa et al., 2017; Sovacool et al., 2017). Even though the literature is scarce on the expected impacts of future adaptation measures on sustainable development specific to warming experiences of 1.5°C, this section assesses available literature on how (i) prioritising sustainable development enhances or impedes climate adaptation efforts (Section 5.3.1); (ii) climate adaptation measures impact sustainable development and the SDGs in positive (synergies) or negative (trade-offs) ways (Section 5.3.2); and (iii) adaptation pathways towards a 1.5°C warmer world affect sustainable development, poverty and inequalities (Section 5.3.3). The section builds on Chapter 4 (see Section 4.3.5) regarding available adaptation options to reduce climate vulnerability and build resilience (see Glossary) in the context of 1.5°C-compatible trajectories, with emphasis on sustainable development implications.

5.3.1 Sustainable Development in Support of Climate Adaptation

Making sustainable development a priority, and meeting the SDGs, is consistent with efforts to adapt to climate change (*very high confidence*). Sustainable development is effective in building adaptive capacity if it addresses poverty and inequalities, social and economic exclusion, and inadequate institutional capacities (Noble et al., 2014; Abel et al., 2016; Colloff et al., 2017). Four ways in which sustainable development leads to effective adaptation are described below.

First, sustainable development enables transformational adaptation (see Chapter 4, Section 4.2.2.2) when an integrated approach is adopted, with inclusive, transparent decision-making, rather than addressing current vulnerabilities as stand-alone climate problems (Mathur et al., 2014; Arthurson and Baum, 2015; Shackleton et al., 2015; Lemos et al., 2016; Antwi-Agyei et al., 2017b). Ending poverty in its multiple dimensions (SDG 1) is often a highly effective form of climate adaptation (Fankhauser and McDermott, 2014; Leichenko and Silva, 2014; Hallegatte and Rozenberg, 2017). However, ending poverty is not sufficient, and the positive outcome as an adaptation strategy depends on whether increased household wealth is actually directed towards risk reduction and management strategies (Nelson et al., 2016), as shown in urban municipalities (Colenbrander et al., 2017; Rasch, 2017) and agrarian communities (Hashemi et al., 2017), and whether finance for adaptation is made available (Section 5.6.1).

Second, local participation is effective when wider socio-economic barriers are addressed via multiscale planning (McCubbin et al., 2015; Nyantakyi-Frimpong and Bezner-Kerr, 2015; Toole et al., 2016). This is the case, for instance, when national education efforts (SDG 4) (Muttarak and Lutz, 2014; Striessnig and Loichinger, 2015) and indigenous knowledge (Nkomwa et al., 2014; Pandey and Kumar, 2018) enhance information sharing, which also builds resilience (Santos et al., 2016; Martinez-Baron et al., 2018) and reduces risks for maladaptation (Antwi-Agyei et al., 2018; Gajjar et al., 2018).

Third, development promotes transformational adaptation when addressing social inequalities (Section 5.5.3, 5.6.4), as in SDGs 4, 5, 16 and 17 (O'Brien, 2016; O'Brien, 2017). For example, SDG 5 supports measures that reduce women's vulnerabilities and allow women to benefit from adaptation (Antwi-Agyei et al., 2015; Van Aelst and Holvoet, 2016; Cohen, 2017). Mobilization of climate finance, carbon taxation and environmentally motivated subsidies can reduce inequalities (SDG 10), advance climate mitigation and adaptation (Chancel and Picketty, 2015), and be conducive to strengthening and enabling environments for resilience building (Nhamo, 2016; Halonen et al., 2017).

Fourth, when sustainable development promotes livelihood security, it enhances the adaptive capacities of vulnerable communities and households. Examples include SDG 11 supporting adaptation in cities to reduce harm from disasters (Kelman, 2017; Parnell, 2017); access to water and sanitation (SDG 6) with strong institutions (SDG 16) (Rasul and Sharma, 2016); SDG 2 and its targets that promote adaptation in agricultural and food systems (Lipper et al., 2014); and targets for SDG 3 such as reducing infectious diseases and providing health cover are consistent with health-related adaptation (ICSU, 2017; Gomez-Echeverri, 2018).

Sustainable development has the potential to significantly reduce systemic vulnerability, enhance adaptive capacity and promote livelihood security for poor and disadvantaged populations (*high confidence*). Transformational adaptation (see Chapter 4, Sections 4.2.2.2 and 4.5.3) would require development that takes into consideration multidimensional poverty and entrenched inequalities, local cultural specificities and local knowledge in decision-making, thereby making it easier to achieve the SDGs in a 1.5°C warmer world (*medium evidence, high agreement*).

5.3.2 Synergies and Trade-Offs between Adaptation Options and Sustainable Development

There are short-, medium-, and long-term positive impacts (synergies) and negative impacts (trade-offs) between the dual goals of keeping temperatures below 1.5°C global warming and achieving sustainable development. The extent of synergies between development and adaptation goals will vary by the development process adopted for a particular SDG and underlying vulnerability contexts (*medium evidence, high agreement*). Overall, the impacts of adaptation on sustainable development, poverty eradication and reducing inequalities in general, and the SDGs specifically, are expected to be largely positive, given that the inherent purpose of adaptation is to lower risks. Building on Chapter 4 (see Section 4.3.5), this section examines synergies and trade-offs between adaptation and sustainable development for some key sectors and approaches.

Agricultural adaptation: The most direct synergy is between SDG 2 (zero hunger) and adaptation in cropping, livestock and food systems, designed to maintain or increase production (Lipper et al., 2014; Rockström et al., 2017). Farmers with effective adaptation strategies tend to enjoy higher food security and experience lower levels of poverty (FAO, 2015; Douxchamps et al., 2016; Ali and Erenstein, 2017). Vermeulen et al. (2016) report strong positive returns on investment across the world from agricultural adaptation with side benefits for environment and economic well-being. Well-adapted agricultural systems contribute to safe drinking water, health, biodiversity and equity goals (DeClerck et al., 2016; Myers et al., 2017). Climate-smart agriculture has synergies with food security, though it can be biased towards technological solutions, may not be gender sensitive, and can create specific challenges for institutional and distributional aspects (Lipper et al., 2014; Arakelyan et al., 2017; Taylor, 2017).

At the same time, adaptation options increase risks for human health, oceans and access to water if fertiliser and pesticides are used without regulation or when irrigation reduces water availability for other purposes (Shackleton et al., 2015; Campbell et al., 2016). When agricultural insurance and climate services overlook the poor, inequality may rise (Dinku et al., 2014; Carr and Owusu-Daaku, 2015; Georgeson et al., 2017a; Carr and Onzere, 2018). Agricultural adaptation measures may increase workloads, especially for women, while changes in crop mix can result in loss of income or culturally inappropriate food (Carr and Thompson, 2014; Thompson-Hall et al., 2016; Bryan et al., 2017), and they may benefit farmers with more land to the detriment of land-poor farmers, as seen in the Mekong River Basin (see Chapter 3, Cross-Chapter Box 6 in Chapter 3).

Adaptation to protect human health: Adaptation options in the health sector are expected to reduce morbidity and mortality (Arbuthnott et al., 2016; Ebi and Otmani del Barrio, 2017). Heat-early-warning systems help lower injuries, illnesses and deaths (Hess and Ebi, 2016), with positive impacts for SDG 3. Institutions better equipped to share information, indicators for detecting climate-sensitive diseases, improved provision of basic health care services and coordination with other sectors also improve risk management, thus reducing adverse health outcomes (Dasgupta et al., 2016; Dovie et al., 2017). Effective adaptation creates synergies via basic public health measures (K.R. Smith et al., 2014; Dasgupta, 2016) and health infrastructure protected from extreme weather events (Watts et al., 2015). Yet trade-offs can occur when adaptation in one sector leads to negative impacts in another sector. Examples include the creation of urban wetlands through flood control measures which can breed mosquitoes, and migration eroding physical and mental well-being, hence adversely affecting SDG 3 (K.R. Smith et al., 2014; Watts et al., 2015). Similarly, increased use of air conditioning enhances resilience to heat stress (Petkova et al., 2017), yet it can result in higher energy consumption, undermining SDG 13.

Coastal adaptation: Adaptation to sea level rise remains essential in coastal areas even under a climate stabilization scenario of 1.5°C (Nicholls et al., 2018). Coastal adaptation to restore ecosystems (for instance by planting mangrove forests) supports SDGs for enhancing life and livelihoods on land and oceans (see Chapter 4, Sections 4.3.2.3). Synergistic outcomes between development and relocation of coastal communities are enhanced by participatory decision-making and settlement designs that promote equity and sustainability (van der Voorn et al., 2017). Limits to coastal adaptation may rise, for instance in low-lying islands in the Pacific, Caribbean and Indian Ocean, with attendant implications for loss and damage (see Chapter 3 Box 3.5, Chapter 4, Cross-Chapter Box 9 in Chapter 4, Cross-Chapter Box 12 in Chapter 5, Box 5.3).

Migration as adaptation: Migration has been used in various contexts to protect livelihoods from challenges related to climate change (Marsh, 2015; Jha et al., 2017), including through remittances (Betzold and Weiler, 2017). Synergies between migration and the achievement of sustainable development depend on adaptive measures and conditions in both sending and receiving regions (Fatima et al., 2014; McNamara, 2015; Entzinger and Scholten, 2016; Ober and Sakdapolrak, 2017; Schwan and Yu, 2017). Adverse developmental impacts arise when vulnerable women or the elderly are left behind or if migration is culturally disruptive (Wilkinson et al., 2016; Albert et al., 2017; Islam and Shamsuddoha, 2017).

Ecosystem-based adaptation: Ecosystem-based adaptation (EBA) can offer synergies with sustainable development (Morita and Matsumoto, 2015; Ojea, 2015; Szabo et al., 2015; Brink et al., 2016; Butt et al., 2016; Conservation International, 2016; Huq et al., 2017), although assessments remain difficult (see Chapter 4, Section 4.3.2.2) (Doswald et al., 2014). Examples include mangrove restoration reducing coastal vulnerability, protecting marine and terrestrial ecosystems, and increasing local food security, as well as watershed management reducing flood risks and improving water quality (Chong, 2014). In drylands, EBA practices, combined with community-based adaptation, have shown how to link adaptation with mitigation to improve livelihood conditions of poor farmers (Box 5.1). Synergistic developmental outcomes arise where EBA is cost effective, inclusive of indigenous and local knowledge and easily accessible by the poor (Ojea, 2015; Daigneault et al., 2016; Estrella et al., 2016). Payment for ecosystem services can provide incentives to land owners and natural resource managers to preserve environmental services with synergies with SDGs 1 and 13 (Arriagada et al., 2015), when implementation challenges are overcome (Calvet-Mir et al., 2015; Wegner, 2016; Chan et al., 2017). Trade-offs include loss of other economic land use types, tension between biodiversity and adaptation priorities, and conflicts over governance (Wamsler et al., 2014; Ojea, 2015).

Community-based adaptation: Community-based adaptation (CBA) (see Chapter 4, Sections 4.3.3.2) enhances resilience and sustainability of adaptation plans (Ford et al., 2016; Fernandes-Jesus et al., 2017; Grantham and Rudd, 2017; Gustafson et al., 2017). Yet negative impacts occur if it fails to fairly represent vulnerable populations and to foster long-term social resilience (Ensor, 2016; Taylor Aiken et al., 2017). Mainstreaming CBA into planning and decision-making enables the attainment of SDGs 5, 10 and 16 (Archer et al., 2014; Reid and Huq, 2014; Vardakoulias and Nicholles, 2014; Cutter, 2016; Kim et al., 2017). Incorporating multiple forms of indigenous and local knowledge is an important element of CBA, as shown for instance in the Arctic region (see Chapter 4, Section 4.3.5.5, Box 4.3, Cross-Chapter Box 9) (Apgar et al., 2015; Armitage, 2015; Pearce et al., 2015; Chief et al., 2016; Cobbinah and Anane, 2016; Ford et al., 2016). Indigenous and local knowledge can be synergistic with achieving SDGs 2, 6 and 10 (Ayers et al., 2014; Lasage et al., 2015; Regmi and Star, 2015; Berner et al., 2016; Chief et al., 2016; Murtinho, 2016; Reid, 2016).

There are clear synergies between adaptation options and several SDGs, such as poverty eradication, elimination of hunger, clean water and health (*robust evidence, high agreement*), as well-integrated adaptation supports sustainable development (Eakin et al., 2014; Weisser et al., 2014; Adam, 2015; Smucker et al., 2015). Substantial synergies are observed in the agricultural and health sectors, and in ecosystem-based adaptations. However, particular adaptation strategies can lead to adverse consequences for developmental outcomes (*medium evidence, high agreement*). Adaptation strategies that advance one SDG can result in trade-offs with other SDGs; for instance, agricultural adaptation to enhance food security (SDG 2) causing negative impacts for health, equality and healthy ecosystems (SDGs 3, 5, 6, 10, 14 and 15), and resilience to heat stress increasing energy consumption (SDGs 3 and 7) and high-cost adaptation in resource-constrained contexts (*medium evidence, medium agreement*).

5.3.3 Adaptation Pathways towards a 1.5°C Warmer World and Implications for Inequalities

In a 1.5°C warmer world, adaptation measures and options would need to be intensified, accelerated and scaled up. This entails not only the right 'mix' of options (asking 'right for whom and for what?') but also a forward-looking understanding of dynamic trajectories, that is adaptation pathways (see Chapter 1, Cross-Chapter Box 1 in Chapter 1), best understood as decision-making processes over sets of potential action sequenced over time (Câmpeanu and Fazey, 2014; Wise et al., 2014). Given the scarcity of literature on adaptation pathways that navigate place-specific warming experiences at 1.5°C, this section presents insights into current local decision-making for adaptation futures. This grounded evidence shows that choices between possible pathways, at different scales and for different groups of people, are shaped by uneven power structures and historical legacies that create their own, often unforeseen change (Fazey et al., 2016; Bosomworth et al., 2017; Lin et al., 2017; Murphy et al., 2017; Pelling et al., 2018).

Pursuing a place-specific adaptation pathway approach towards a 1.5°C warmer world harbours the potential for significant positive outcomes, with synergies for well-being possibilities to 'leap-frog the SDGs' (J.R.A. Butler et al., 2016), in countries at all levels of development (*medium evidence, high agreement*). It allows for identifying local, socially salient tipping points before they are crossed, based on what people value and trade-offs that are acceptable to them (Barnett et al., 2014, 2016; Gorddard et al., 2016; Tschakert et al., 2017). Yet evidence also reveals adverse impacts that reinforce rather than reduce existing social inequalities and hence may lead to poverty traps (*medium evidence, high agreement*) (Nagoda, 2015; Warner et al., 2015; Barnett et al., 2016; J.R.A. Butler et al., 2016; Godfrey-Wood and Naess, 2016; Pelling et al., 2016; Albert et al., 2017; Murphy et al., 2017).

Past development trajectories as well as transformational adaptation plans can constrain adaptation futures by reinforcing dominant political-economic structures and processes, and narrowing option spaces; this leads to maladaptive pathways that preclude alternative, locally relevant and sustainable development initiatives and increase vulnerabilities (Warner and Kuzdas, 2017; Gajjar et al., 2018). Such dominant pathways tend to validate the practices, visions and values of existing governance regimes and powerful members of a community while devaluing those of less privileged stakeholders. Examples from Romania, the Solomon Islands and Australia illustrate such pathway dynamics in which individual economic gains and prosperity matter more than community cohesion and solidarity; this discourages innovation, exacerbates inequalities and further erodes adaptive capacities of the most vulnerable (Davies et al., 2014; Fazey et al., 2016; Bosomworth et al., 2017). In the city of London, United Kingdom, the dominant adaptation and disaster risk management pathway promotes resilience that emphasizes self-reliance; yet it intensifies the burden on low-income citizens, the elderly, migrants and others unable to afford flood insurance or protect themselves against heat waves (Pelling et al., 2016). Adaptation pathways in the Bolivian Altiplano have transformed subsistence farmers into world-leading quinoa producers, but loss of social cohesion and traditional values, dispossession and loss of ecosystem services now constitute undesirable trade-offs (Chelleri et al., 2016).

A narrow view of adaptation decision-making, for example focused on technical solutions, tends to crowd out more participatory processes (Lawrence and Haasnoot, 2017; Lin et al., 2017), obscures contested values and reinforces power asymmetries (Bosomworth et al., 2017; Singh, 2018). A situated and context-specific understanding of adaptation pathways that galvanizes diverse knowledge, values and joint initiatives helps to overcome dominant path dependencies, avoid trade-offs that intensify inequities and challenge policies detached from place (Fincher et al., 2014; Wyborn et al., 2015; Murphy et al., 2017; Gajjar et al., 2018). These insights suggest that adaptation pathway approaches to prepare for 1.5°C warmer futures would be difficult to achieve without considerations for inclusiveness, place-specific trade-off deliberations, redistributive measures and procedural justice mechanisms to facilitate equitable transformation (*medium evidence, high agreement*).

Box 5.1 | Ecosystem- and Community-Based Practices in Drylands

Drylands face severe challenges in building climate resilience (Fuller and Lain, 2017), yet small-scale farmers can play a crucial role as agents of change through ecosystem- and community-based practices that combine adaptation, mitigation and sustainable development.

Farmer managed natural regeneration (FMNR) of trees in cropland is practised in 18 countries across sub-Saharan Africa, Southeast Asia, Timor-Leste, India and Haiti and has, for example, permitted the restoration of over five million hectares of land in the Sahel (Niang et al., 2014; Bado et al., 2016). In Ethiopia, the Managing Environmental Resources to Enable Transitions programme, which entails community-based watershed rehabilitation in rural landscapes, supported around 648,000 people, resulting in the rehabilitation of 25,400,000 hectares of land in 72 severely food-insecure districts across Ethiopia between 2012 and 2015 (Gebrehaweria et al., 2016). In India, local farmers have benefitted from watershed programmes across different agro-ecological regions (Singh et al., 2014; Datta, 2015).

These low-cost, flexible community-based practices represent low-regrets adaptation and mitigation strategies. These strategies often contribute to strengthened ecosystem resilience and biodiversity, increased agricultural productivity and food security, reduced household poverty and drudgery for women, and enhanced agency and social capital (Niang et al., 2014; Francis et al., 2015; Kassie et al., 2015; Mbow et al., 2015; Reij and Winterbottom, 2015; Weston et al., 2015; Bado et al., 2016; Dumont et al., 2017). Small check dams in dryland areas and conservation agriculture can significantly increase agricultural output (Kumar et al., 2014; Agoramoorthy and Hsu, 2016; Pradhan et al., 2018). Mitigation benefits have also been quantified (Weston et al., 2015); for example, FMNR of more than five million hectares in Niger has sequestered 25–30 Mtonnes of carbon over 30 years (Stevens et al., 2014).

However, several constraints hinder scaling-up efforts: inadequate attention to the socio-technical processes of innovation (Grist et al., 2017; Scoones et al., 2017), difficulties in measuring the benefits of an innovation (Coe et al., 2017), farmers' inability to deal with long-term climate risk (Singh et al., 2017), and difficulties for matching practices with agro-ecological conditions and complementary modern inputs (Kassie et al., 2015). Key conditions to overcome these challenges include: developing agroforestry value chains and markets (Reij and Winterbottom, 2015) and adaptive planning and management (Gray et al., 2016). Others include inclusive processes giving greater voice to women and marginalized groups (MRFCJ, 2015a; UN Women and MRFCJ, 2016; Dumont et al., 2017), strengthening community land and forest rights (Stevens et al., 2014; Vermeulen et al., 2016), and co-learning among communities of practice at different scales (Coe et al., 2014; Reij and Winterbottom, 2015; Sinclair, 2016; Binam et al., 2017; Dumont et al., 2017; Epule et al., 2017).

5.4 Mitigation and Sustainable Development

The AR5 WGIII examined the potential of various mitigation options for specific sectors (energy supply, industry, buildings, transport, and agriculture, forestry, and other land use; AFOLU); it provided a narrative of dimensions of sustainable development and equity as a framing for evaluating climate responses and policies, respectively, in Chapters 4, 7, 8, 9, 10 and 11 (IPCC, 2014a). This section builds on the analyses of Chapters 2 and 4 of this report to re-assess mitigation and sustainable development in the context of 1.5°C global warming as well as the SDGs.

5.4.1 Synergies and Trade-Offs between Mitigation Options and Sustainable Development

Adopting stringent climate mitigation options can generate multiple positive non-climate benefits that have the potential to reduce the costs of achieving sustainable development (IPCC, 2014b; Ürge-Vorsatz et al., 2014, 2016; Schaeffer et al., 2015; von Stechow et al., 2015). Understanding the positive impacts (synergies) but also the negative impacts (trade-offs) is key for selecting mitigation options and policy choices that maximize the synergies between mitigation and developmental actions (Hildingsson and Johansson, 2015; Nilsson et al., 2016; Delponte et al., 2017; van Vuuren et al., 2017b; McCollum et al., 2018b). Aligning mitigation response options to sustainable development objectives can ensure public acceptance (IPCC, 2014a), encourage faster action (Lechtenboehmer and Knoop, 2017) and support the design of equitable mitigation (Holz et al., 2018; Winkler et al., 2018) that protect human rights (MRFCJ, 2015b) (Section 5.5.3).

This sub-section assesses available literature on the interactions of individual mitigation options (see Chapter 2, Section 2.3.1.2, Chapter 4, Sections 4.2 and 4.3) with sustainable development and the SDGs and underlying targets. Table 5.2 presents an assessment of these synergies and trade-offs and the strength of the interaction using an SDG-interaction score (see Glossary) (McCollum et al., 2018b), with evidence and agreements levels. Figure 5.2 presents the information of Table 5.2, showing gross (not net) interactions with the SDGs. This detailed assessment of synergies and trade-offs of individual mitigation options with the SDGs (Table 5.2 a–d and Figure 5.2) reveals that the number of synergies exceeds that of trade-offs. Mitigation response options in the energy demand sector, AFOLU and oceans have more positive interactions with a larger number of SDGs compared to those on the energy supply side (*robust evidence, high agreement*).

5.4.1.1 Energy Demand: Mitigation Options to Accelerate Reduction in Energy Use and Fuel Switch

For mitigation options in the energy demand sectors, the number of synergies with all sixteen SDGs exceeds the number of trade-offs (Figure 5.2 and Table 5.2) (*robust evidence, high agreement*). Most of the interactions are of a reinforcing nature, hence facilitating the achievement of the goals.

Accelerating energy efficiency in all sectors, which is a necessary condition for a 1.5°C warmer world (see Chapters 2 and 4), has synergies with a large number of SDGs (*robust evidence, high agreement*) (Figure 5.2 and Table 5.2). The diffusion of efficient equipment and appliances across end use sectors has synergies with international partnership (SDG 17) and participatory and transparent institutions (SDG 16) because innovations and deployment of new technologies require transnational capacity building and knowledge sharing. Resource and energy savings support sustainable production and consumption (SDG 12), energy access (SDG 7), innovation and infrastructure development (SDG 9) and sustainable city development (SDG 11). Energy efficiency supports the creation of decent jobs by new service companies providing services for energy efficiency, but the net employment effect of efficiency improvement remains uncertain due to macro-economic feedback (SDG 8) (McCollum et al., 2018b).

In the buildings sector, accelerating energy efficiency by way of, for example, enhancing the use of efficient appliances, refrigerant transition, insulation, retrofitting and low- or zero-energy buildings generates benefits across multiple SDG targets. For example, improved cook stoves make fuel endowments last longer and hence reduce deforestation (SDG 15), support equal opportunity by reducing school absences due to asthma among children (SDGs 3 and 4) and empower rural and indigenous women by reducing drudgery (SDG 5) (*robust evidence, high agreement*) (Derbez et al., 2014; Lucon et al., 2014; Maidment et al., 2014; Scott et al., 2014; Cameron et al., 2015; Fay et al., 2015; Liddell and Guiney, 2015; Shah et al., 2015; Sharpe et al., 2015; Wells et al., 2015; Willand et al., 2015; Hallegatte et al., 2016; Kusumaningtyas and Aldrian, 2016; Berrueta et al., 2017; McCollum et al., 2018a).

In energy-intensive processing industries, 1.5°C-compatible trajectories require radical technology innovation through maximum electrification, shift to other low emissions energy carriers such as hydrogen or biomass, integration of carbon capture and storage (CCS) and innovations for carbon capture and utilization (CCU) (see Chapter 4, Section 4.3.4.5). These transformations have strong synergies with innovation and sustainable industrialization (SDG 9), supranational partnerships (SDGs 16 and 17) and sustainable production (SDG 12). However, possible trade-offs due to risks of CCS-based carbon leakage, increased electricity demands, and associated price impacts affecting energy access and poverty (SDGs 7 and 1) would need careful regulatory attention (Wesseling et al., 2017). In the mining industry, energy efficiency can be synergetic or face trade-offs with sustainable management (SDG 6), depending on the option retained for water management (Nguyen et al., 2014). Substitution and recycling are also an important driver of 1.5°C-compatible trajectories in industrial systems (see Chapter 4, Section 4.3.4.2). Structural changes and reorganization of economic activities in industrial park/clusters following the principles of industrial symbiosis (circular economy) improves the overall sustainability by reducing energy and waste (Fan et al., 2017; Preston and Lehne, 2017) and reinforces responsible production and consumption (SDG 12) through recycling, water use efficiency (SDG 6), energy access (SDG 7) and ecosystem protection and restoration (SDG 15) (Karner et al., 2015; Zeng et al., 2017).

In the transport sector, deep electrification may trigger increases of electricity prices and adversely affect poor populations (SDG 1), unless pro-poor redistributive policies are in place (Klausbruckner et al., 2016). In cities, governments can lay the foundations for compact, connected low-carbon cities, which are an important component of 1.5°C-compatible transformations (see Chapter 4, Section 4.3.3) and show synergies with sustainable cities (SDG 11) (Colenbrander et al., 2016).

Behavioural responses are important determinants of the ultimate outcome of energy efficiency on emission reductions and energy access (SDG 7) and their management requires a detailed understanding of the drivers of consumption and the potential for and barriers to absolute reductions (Fuchs et al., 2016). Notably, the rebound effect tends to offset the benefits of efficiency for emissions reductions through growing demand for energy services (Sorrell, 2015; Suffolk and Poortinga, 2016). However, high rebound can help in providing faster access to affordable energy (SDG 7.1) where the goal is to reduce energy poverty and unmet energy demand (see Chapter 2, Section 2.4.3) (Chakravarty et al., 2013). Comprehensive policy design – including rebound supressing policies, such as carbon pricing and policies that encourage awareness building and promotional material design – is needed to tap the full potential of energy savings, as applicable to a 1.5°C warming context (Chakravarty and Tavoni, 2013; IPCC, 2014b; Karner et al., 2015; Zhang et al., 2015; Altieri et al., 2016; Santarius et al., 2016) and to address policy-related trade-offs and welfare-enhancing benefits (*robust evidence, high agreement*) (Chakravarty et al., 2013; Chakravarty and Roy, 2016; Gillingham et al., 2016).

Other behavioural responses will affect the interplay between energy efficiency and sustainable development. Building occupants reluctant to change their habits may miss out on welfare-enhancing energy efficiency opportunities (Zhao et al., 2017). Preferences for new products and premature obsolescence for appliances is expected to adversely affect sustainable consumption and production (SDG 12) with ramifications for resource use efficiency (Echegaray, 2016). Changes in user behaviour towards increased physical activity, less reliance on motorized travel over short distances and the use of public transport would help to decarbonize the transport sector in a synergetic manner with SDGs 3, 11 and 12 (Shaw et al., 2014; Ajanovic, 2015; Chakrabarti and Shin, 2017), while reducing inequality in access to basic facilities (SDG 10) (Lucas and Pangbourne, 2014; Kagawa et al., 2015). However, infrastructure design and regulations would need to ensure road safety and address risks of road accidents for pedestrians (Hwang et al., 2017; Khreis et al., 2017) to ensure sustainable infrastructure growth in human settlements (SDGs 9 and 11) (Lin et al., 2015; SLoCaT, 2017).

5.4.1.2 Energy Supply: Accelerated Decarbonization

Decreasing the share of coal in energy supply in line with 1.5°C-compatible scenarios (see Chapter 2, Section 2.4.2) reduces adverse impacts of upstream supply-chain activities, in particular air and water pollution and coal mining accidents, and enhances health by reducing air pollution, notably in cities, showing synergies with SDGs 3, 11 and 12 (Yang et al., 2016; UNEP, 2017).

Fast deployment of renewables such as solar, wind, hydro and modern biomass, together with the decrease of fossil fuels in energy supply (see Chapter 2, Section 2.4.2.1), is aligned with the doubling of renewables in the global energy mix (SDG 7.2). Renewables could also support progress on SDGs 1, 10, 11 and 12 and supplement new technology (*robust evidence, high agreement*) (Chaturvedi and Shukla, 2014; Rose et al., 2014; Smith and Sagar, 2014; Riahi et al., 2015; IEA, 2016; van Vuuren et al., 2017a; McCollum et al., 2018a). However, some trade-offs with the SDGs can emerge from offshore installations, particularly SDG 14 in local contexts (McCollum et al., 2018a). Moreover, trade-offs between renewable energy production and affordability (SDG 7) (Labordena et al., 2017) and other environmental objectives would need to be scrutinised for potential negative social outcomes. Policy interventions through regional cooperation-building (SDG 17) and institutional capacity (SDG 16) can enhance affordability (SDG 7) (Labordena et al., 2017). The deployment of small-scale renewables, or off-grid solutions for people in remote areas (Sánchez and Izzo, 2017), has strong potential for synergies with access to energy (SDG 7), but the actualization of these potentials requires measures to overcome technology and reliability risks associated with large-scale deployment of renewables (Giwa et al., 2017; Heard et al., 2017). Bundling energy-efficient appliances and lighting with off-grid renewables can lead to substantial cost reduction while increasing reliability (IEA, 2017). Low-income populations in industrialized countries are often left out of renewable energy generation schemes, either because of high start-up costs or lack of home ownership (UNRISD, 2016).

Nuclear energy, the share of which increases in most of the 1.5°C-compatible pathways (see Chapter 2, Section 2.4.2.1), can increase the risks of proliferation (SDG 16), have negative environmental effects (e.g., for water use; SDG 6) and have mixed effects for human health when replacing fossil fuels (SDGs 7 and 3) (see Table 5.2). The use of fossil CCS, which plays an important role in deep mitigation pathways (see Chapter 2, Section 2.4.2.3), implies continued adverse impacts of upstream supply-chain activities in the coal sector, and because of lower efficiency of CCS coal power plants (SDG 12), upstream impacts and local air pollution are likely to be exacerbated (SDG 3). Furthermore, there is a non-negligible risk of carbon dioxide leakage from geological storage and the carbon dioxide transport infrastructure (SDG 3) (Table 5.2).

Economies dependent upon fossil fuel-based energy generation and/or export revenue are expected to be disproportionally affected by future restrictions on the use of fossil fuels under stringent climate goals and higher carbon prices; this includes impacts on employment, stranded assets, resources left underground, lower capacity use and early phasing out of large infrastructure already under construction (*robust evidence, high agreement*) (Box 5.2) (Johnson et al., 2015; McGlade and Ekins, 2015; UNEP, 2017; Spencer et al., 2018). Investment in coal continues to be attractive in many countries as it is a mature technology and provides cheap energy supplies, large-scale employment and energy security (Jakob and Steckel, 2016; Vogt-Schilb and Hallegatte, 2017; Spencer et al., 2018). Hence, accompanying policies and measures would be required to ease job losses and correct for relatively higher prices of alternative energy (Oosterhuis and Ten Brink, 2014; Oei and Mendelevitch, 2016; Garg et al., 2017; HLCCP, 2017; Jordaan et al., 2017; OECD, 2017; UNEP, 2017; Blondeel and van de Graaf, 2018; Green, 2018). Research on historical transitions shows that managing the impacts on workers through retraining programmes is essential in order to align the phase-down of mining industries with meeting ambitious climate targets, and the objectives of a 'just transition' (Galgóczi, 2014; Caldecott et al., 2017; Healy and Barry, 2017). This aspect is even more important in developing countries where the mining workforce is largely semi- or unskilled (Altieri et al., 2016; Tung, 2016). Ambitious emissions reduction targets can unlock very strong decoupling potentials in industrialized fossil exporting economies (Hatfield-Dodds et al., 2015).

Box 5.2 | Challenges and Opportunities of Low-Carbon Pathways in Gulf Cooperative Council Countries

The Gulf Cooperative Council (GCC) region (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia and United Arab Emirates) is characterized by high dependency on hydrocarbon resources (natural oil and gas), with high risks of socio-economic impacts of policies and response measures to address climate change. The region is also vulnerable to the decrease of the global demand and price of hydrocarbons as a result of climate change response measures. The projected declining use of oil and gas under low emissions pathways creates risks of significant economic losses for the GCC region (e.g., Waisman et al., 2013; Van de Graaf and Verbruggen, 2015; Al-Maamary et al., 2016; Bauer et al., 2016), given that natural gas and oil revenues contributed to about 70% of government budgets and > 35% of the gross domestic product in 2010 (Callen et al., 2014).

The current high energy intensity of the domestic economies (Al-Maamary et al., 2017), triggered mainly by low domestic energy prices (Alshehry and Belloumi, 2015), suggests specific challenges for aligning mitigation towards 1.5°C-consistent trajectories, which would require strong energy efficiency and economic development for the region.

The region's economies are highly reliant on fossil fuel for their domestic activities. Yet the renewables deployment potentials are large, deployment is already happening (Cugurullo, 2013; IRENA, 2016) and positive economic benefits can be envisaged (Sgouridis et al., 2016). Nonetheless, the use of renewables is currently limited by economics and structural challenges (Lilliestam and Patt, 2015; Griffiths, 2017a). Carbon capture and storage (CCS) is also envisaged with concrete steps towards implementation (Alsheyab, 2017; Ustadi et al., 2017); yet the real potential of this technology in terms of scale and economic dimensions is still uncertain.

Beyond the above mitigation-related challenges, the region's human societies and fragile ecosystems are highly vulnerable to the impacts of climate change, such as water stress (Evans et al., 2004; Shaffrey et al., 2009), desertification (Bayram and Öztürk, 2014), sea level rise affecting vast low coastal lands, and high temperature and humidity with future levels potentially beyond adaptive capacities (Pal and Eltahir, 2016). A low-carbon pathway that manages climate-related risks within the context of sustainable development requires an approach that jointly addresses both types of vulnerabilities (Al Ansari, 2013; Lilliestam and Patt, 2015; Babiker, 2016; Griffiths, 2017b).

The Nationally Determined Contributions (NDCs) for GCC countries identified energy efficiency, deployment of renewables and technology transfer to enhance agriculture, food security, protection of marine resources, and management of water and costal zones (Babiker, 2016). Strategic vision documents, such as Saudi Arabia's 'Vision 2030', identify emergent opportunities for energy price reforms, energy efficiency, turning emissions into valuable products, and deployment of renewables and other clean technologies, if accompanied with appropriate policies to manage the transition and in the context of economic diversification (Luomi, 2014; Atalay et al., 2016; Griffiths, 2017b; Howarth et al., 2017).

5.4.1.3 Land-based agriculture, forestry and ocean: mitigation response options and carbon dioxide removal

In the AFOLU sector, dietary change towards global healthy diets, that is, a shift from over-consumption of animal-related to plant-related diets, and food waste reduction (see Chapter 4, Section 4.3.2.1) are in synergy with SDGs 2 and 6, and SDG 3 through lower consumption of animal products and reduced losses and waste throughout the food system, contributing to achieving SDGs 12 and 15 (Bajželj et al., 2014; Bustamante et al., 2014; Tilman and Clark, 2014; Hiç et al., 2016).

Power dynamics play an important role in achieving behavioural change and sustainable consumption (Fuchs et al., 2016). In forest management (see Chapter 4, Section 4.3.2.2), encouraging responsible sourcing of forest products and securing indigenous land tenure has the potential to increase economic benefits by creating decent jobs (SDG 8), maintaining biodiversity (SDG 15), facilitating innovation and upgrading technology (SDG 9), and encouraging responsible and just decision-making (SDG 16) (*medium evidence, high agreement*) (Ding et al., 2016; WWF, 2017).

Emerging evidence indicates that future mitigation efforts that would be required to reach stringent climate targets, particularly those associated with carbon dioxide removal (CDR) (e.g., afforestation and reforestation and bioenergy with carbon capture and storage; BECCS), may also impose significant constraints upon poor and vulnerable communities (SDG 1) via increased food prices and competition for arable land, land appropriation and dispossession (Cavanagh and Benjaminsen, 2014; Hunsberger et al., 2014; Work, 2015; Muratori et al., 2016; Smith et al., 2016; Burns and Nicholson, 2017; Corbera et al., 2017) with disproportionate negative impacts upon rural poor and indigenous populations (SDG 1) (*robust evidence, high agreement*) (Section 5.4.2.2, Table 5.2, Figure 5.2) (Grubert et al., 2014; Grill et al., 2015; Zhang and Chen, 2015; Fricko et al., 2016; Johansson et al., 2016; Aha and Ayitey, 2017; De Stefano et al., 2017; Shi et al., 2017). Crops for bioenergy may increase irrigation needs and exacerbate water stress with negative associated impacts on SDGs 6 and 10 (Boysen et al., 2017).

Ocean iron fertilization and enhanced weathering have two-way interactions with life under water and on land and food security (SDGs

2, 14 and 15) (Table 5.2). Development of blue carbon resources through coastal (mangrove) and marine (seaweed) vegetative ecosystems encourages: integrated water resource management (SDG 6) (Vierros, 2017); promotes life on land (SDG 15) (Potouroglou et al., 2017); poverty reduction (SDG 1) (Schirmer and Bull, 2014; Lamb et al., 2016); and food security (SDG 2) (Ahmed et al., 2017a, b; Duarte et al., 2017; Sondak et al., 2017; Vierros, 2017; Zhang et al., 2017).

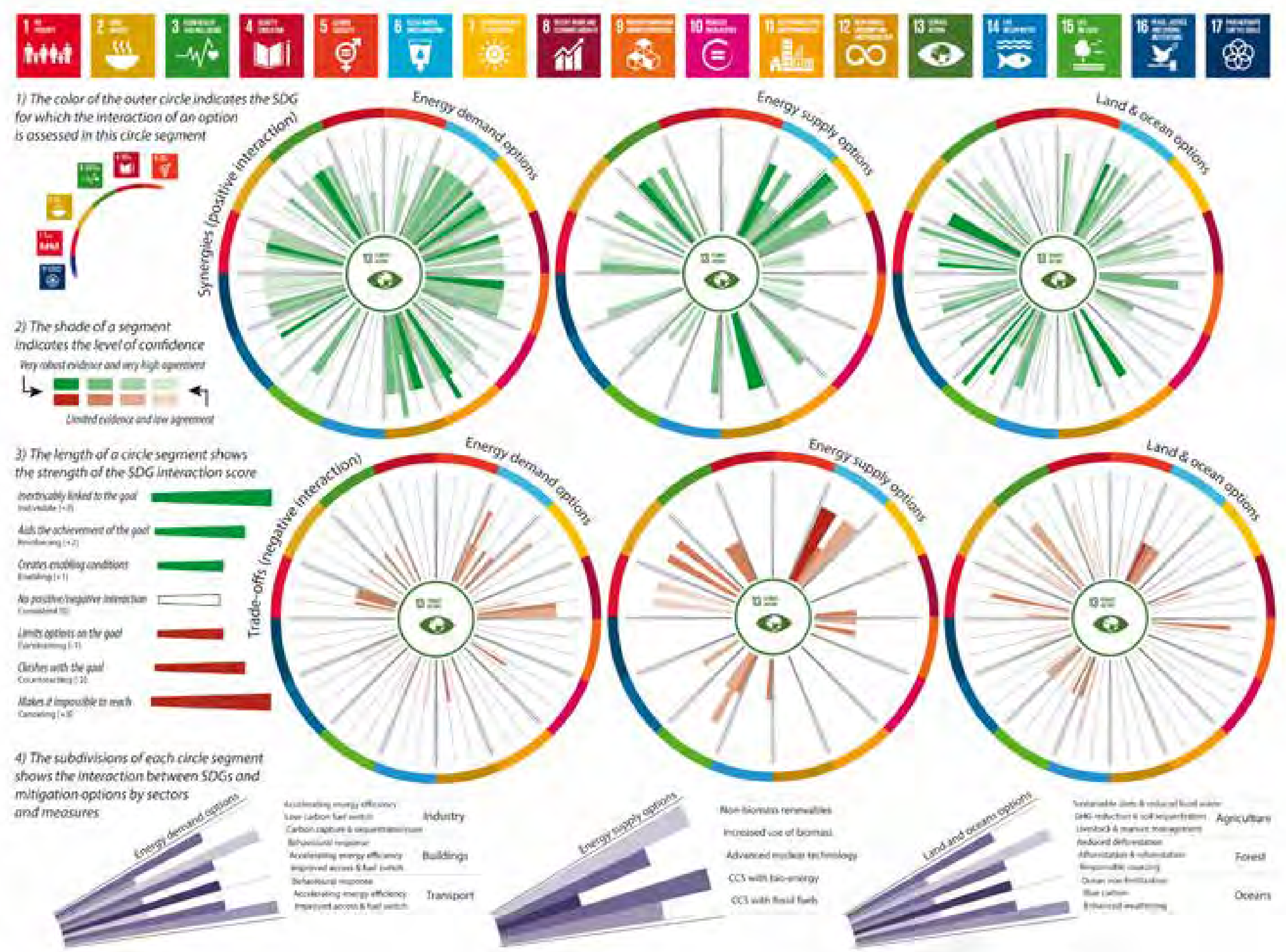


Figure 5.2 | Synergies and trade-offs and gross Sustainable Development Goal (SDG)-interaction with individual mitigation options. The top three wheels represent synergies and the bottom three wheels show trade-offs. The colours on the border of the wheels correspond to the SDGs listed above, starting at the 9 o'clock position, with reading guidance in the top-left corner with the quarter circle (Note 1). Mitigation (climate action, SDG 13) is at the centre of the circle. The coloured segments inside the circles can be counted to arrive at the number of synergies (green) and trade-offs (red). The length of the coloured segments shows the strength of the synergies or trade-offs (Note 3) and the shading indicates confidence (Note 2). Various mitigation options within the energy demand sector, energy supply sector, and land and ocean sector, and how to read them within a segment are shown in grey (Note 4). See also Table 5.2.

5.4.2 Sustainable Development Implications of 1.5°C and 2°C Mitigation Pathways

While previous sections have focused on individual mitigation options and their interaction with sustainable development and the SDGs, this section takes a systems perspective. Emphasis is on quantitative pathways depicting path-dependent evolutions of human and natural systems over time. Specifically, the focus is on fundamental transformations and thus stringent mitigation policies consistent with 1.5°C or 2°C, and the differential synergies and trade-offs with respect to the various sustainable development dimensions.

Both 1.5°C and 2°C pathways would require deep cuts in greenhouse gas (GHG) emissions and large-scale changes of energy supply and demand, as well as in agriculture and forestry systems (see Chapter 2, Section 2.4). For the assessment of the sustainable development implications of these pathways, this chapter draws upon studies that show the aggregated impact of mitigation for multiple sustainable development dimensions (Grubler et al., 2018; McCollum et al., 2018b; Rogelj et al., 2018) and across multiple integrated assessment modelling (IAM) frameworks. Often these tools are linked to disciplinary models covering specific SDGs in more detail (Cameron et al., 2016; Rao et al., 2017; Grubler et al., 2018; McCollum et al., 2018b). Using multiple IAMs and disciplinary models is important for a robust assessment of the sustainable development implications of different pathways. Emphasis is on multi-regional studies, which can be aggregated to the global scale. The recent literature on 1.5°C mitigation pathways has begun to provide quantifications for a range of sustainable development dimensions, including air pollution and health, food security and hunger, energy access, water security, and multidimensional poverty and equity.

5.4.2.1 Air pollution and health

GHGs and air pollutants are typically emitted by the same sources. Hence, mitigation strategies that reduce GHGs or the use of fossil fuels typically also reduce emissions of pollutants, such as particulate matter (e.g., PM2.5 and PM10), black carbon (BC), sulphur dioxide (SO_2), nitrogen oxides (NO_x) and other harmful species (Clarke et al., 2014) (Figure 5.3), causing adverse health and ecosystem effects at various scales (Kusumaningtyas and Aldrian, 2016).

Mitigation pathways typically show that there are significant synergies for air pollution, and that the synergies increase with the stringency of the mitigation policies (Amann et al., 2011; Rao et al., 2016; Klimont et al., 2017; Shindell et al., 2017; Markandya et al., 2018). Recent multimodel comparisons indicate that mitigation pathways consistent with 1.5°C would result in higher synergies with air pollution compared to pathways that are consistent with 2°C (Figures 5.4 and 5.5). Shindell et al. (2018) indicate that health benefits worldwide over the century of 1.5°C pathways could be in the range of 110 to 190 million fewer premature deaths compared to 2°C pathways. The synergies for air pollution are highest in the developing world, particularly in Asia. In addition to significant health benefits, there are also economic benefits from mitigation, reducing the investment needs in air pollution control technologies by about 35% globally (or about 100 billion USD2010 per year to 2030 in 1.5°C pathways; McCollum et al., 2018b) (Figure 5.4).

5.4.2.2 Food security and hunger

Stringent climate mitigation pathways in line with 'well below 2°C' or '1.5°C' goals often rely on the deployment of large-scale land-related measures, like afforestation and/or bioenergy supply (Popp et al., 2014; Rose et al., 2014; Creutzig et al., 2015). These land-related measures can compete with food production and hence raise food security concerns (Section 5.4.1.3) (P. Smith et al., 2014). Mitigation studies indicate that so-called 'single-minded' climate policy, aiming solely at limiting warming to 1.5°C or 2°C without concurrent measures in the food sector, can have negative impacts for global food security (Hasegawa et al., 2015; McCollum et al., 2018b). Impacts of 1.5°C mitigation pathways can be significantly higher than those of 2°C pathways (Figures 5.4 and 5.5). An important driver of the food security impacts in these scenarios is the increase of food prices and the effect of mitigation on disposable income and wealth due to GHG pricing. A recent study indicates that, on aggregate, the price and income effects on food may be bigger than the effect due to competition over land between food and bioenergy (Hasegawa et al., 2015).

In order to address the issue of trade-offs with food security, mitigation policies would need to be designed in a way that shields the population at risk of hunger, including through the adoption of different complementary measures, such as food price support. The investment needs of complementary food price policies are found to be globally relatively much smaller than the associated mitigation investments of 1.5°C pathways (Figure 5.3) (McCollum et al., 2018b). Besides food support price, other measures include improving productivity and efficiency of agricultural production systems (FAO and NZAGRC, 2017a, b; Frank et al., 2017) and programmes focusing on forest land-use change (Havlík et al., 2014). All these lead to additional benefits of mitigation, improving resilience and livelihoods.

Van Vuuren et al. (2018) and Grubler et al. (2018) show that 1.5°C pathways without reliance on BECCS can be achieved through a fundamental transformation of the service sectors which would significantly reduce energy and food demand (see Chapter 2, Sections 2.1.1, 2.3.1 and 2.4.3). Such low energy demand (LED) pathways would result in significantly reduced pressure on food security, lower food prices and fewer people at risk of hunger. Importantly, the trade-offs with food security would be reduced by the avoided impacts in the agricultural sector due to the reduced warming associated with the 1.5°C pathways (see Chapter 3, Section 3.5). However, such feedbacks are not comprehensively captured in the studies on mitigation.

5.4.2.3 Lack of energy access/energy poverty

A lack of access to clean and affordable energy (especially for cooking) is a major policy concern in many countries, especially in those in South Asia and Africa where major parts of the population still rely primarily on solid fuels for cooking (IEA and World Bank, 2017). Scenario studies which quantify the interactions between climate mitigation and energy access indicate that stringent climate policy which would affect energy prices could significantly slow down the transition to clean cooking fuels, such as liquefied petroleum gas or electricity (Cameron et al., 2016).

Estimates across six different IAMs (McCollum et al., 2018b) indicate that, in the absence of compensatory measures, the number of people without access to clean cooking fuels may increase. Redistributional measures, such as subsidies on cleaner fuels and stoves, could compensate for the negative effects of mitigation on energy access. Investment costs of the redistributional measures in 1.5°C pathways (on average around 120 billion USD2010 per year to 2030; Figure 5.4) are much smaller than the mitigation investments of 1.5°C pathways (McCollum et al., 2018b). The recycling of revenues from climate policy might act as a means to help finance the costs of providing energy access to the poor (Cameron et al., 2016).

5.4.2.4 Water security

Transformations towards low emissions energy and agricultural systems can have major implications for freshwater demand as well as water pollution. The scaling up of renewables and energy efficiency as depicted by low emissions pathways would, in most instances, lower water demands for thermal energy supply facilities ('water-for-energy') compared to fossil energy technologies, and thus reinforce targets related to water access and scarcity (see Chapter 4, Section 4.2.1). However, some low-carbon options such as bioenergy, centralized solar

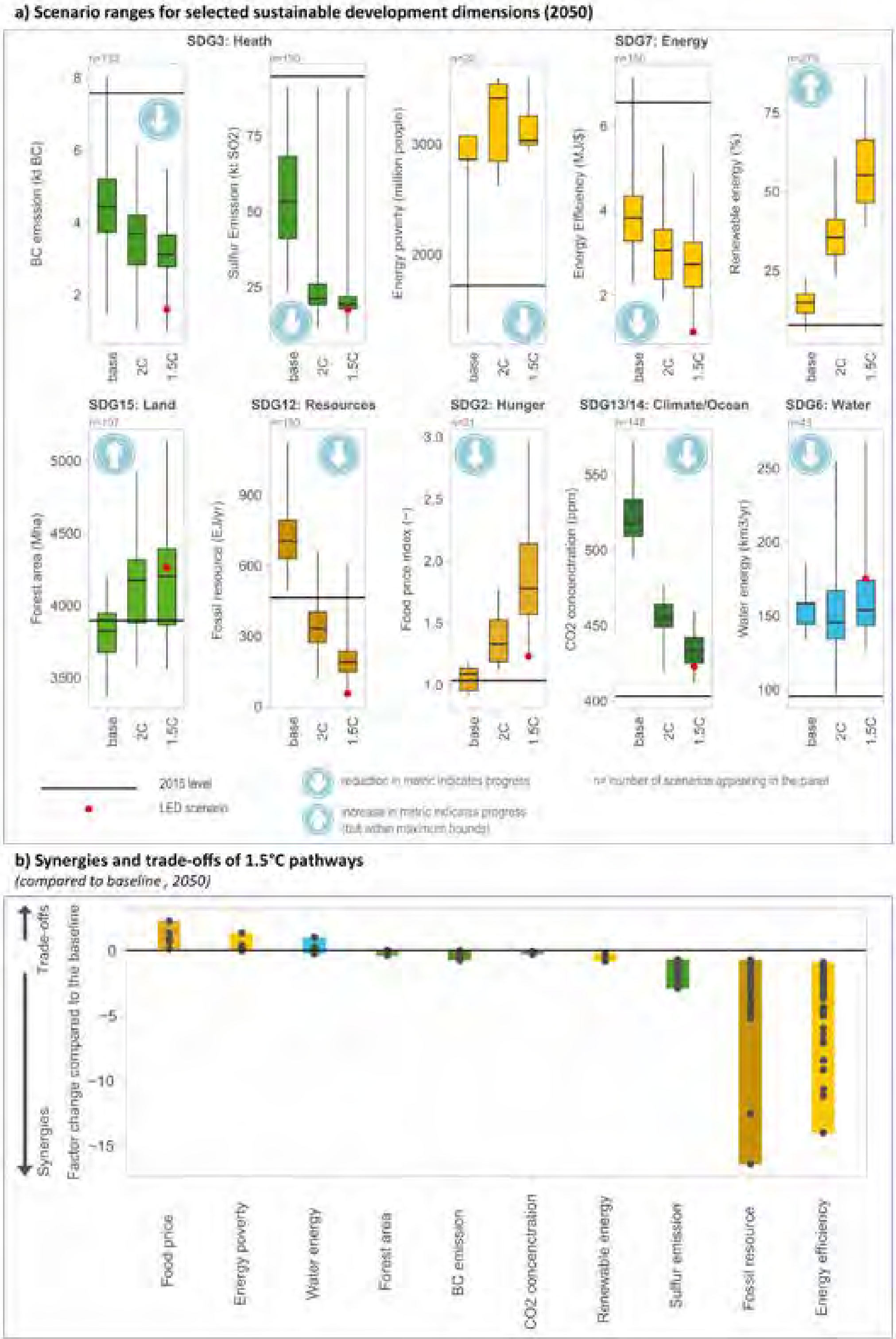


Figure 5.3 | Sustainable development implications of mitigation actions in 1.5°C pathways. Panel (a) shows ranges for 1.5°C pathways for selected sustainable development dimensions compared to the ranges of 2°C pathways and baseline pathways. The panel (a) depicts interquartile and the full range across the scenarios for Sustainable Development Goal (SDG) 2 (hunger), SDG 3 (health), SDG 6 (water), SDG 7 (energy), SDG 12 (resources), SDG 13/14 (climate/ocean) and SDG 15 (land). Progress towards achieving the SDGs is denoted by arrow symbols (increase or decrease of indicator). Black horizontal lines show 2015 values for comparison. Note that sustainable development effects are estimated for the effect of mitigation and do not include benefits from avoided impacts (see Chapter 3, Section 3.5). Low energy demand (LED) denotes estimates from a pathway with extremely low energy demand reaching 1.5°C without bioenergy with carbon capture and storage (BECCS). Panel (b) presents the resulting full range for synergies and trade-offs of 1.5°C pathways compared to the corresponding baseline scenarios. The y-axis in panel (b) indicates the factor change in the 1.5°C pathway compared to the baseline. Note that the figure shows gross impacts of mitigation and does not include feedbacks due to avoided impacts. The realization of the side effects will critically depend on local circumstances and implementation practice. Trade-offs across many sustainable development dimensions can be reduced through complementary/re-distributional measures. The figure is not comprehensive and focuses on those sustainable development dimensions for which quantifications across models are available. Sources: 1.5°C pathways database from Chapter 2 (Grubler et al., 2018; McCollum et al., 2018b).

power, nuclear and hydropower technologies could, if not managed properly, have counteracting effects that compound existing water-related problems in a given locale (Byers et al., 2014; Fricko et al., 2016; IEA, 2016; Fujimori et al., 2017a; Wang, 2017; McCollum et al., 2018a).

Under stringent mitigation efforts, the demand for bioenergy can result in a substantial increase of water demand for irrigation, thereby potentially contributing to water scarcity in water-stressed regions (Berger et al., 2015; Bonsch et al., 2016; Jägermeyr et al., 2017). However, this risk can be reduced by prioritizing rain-fed production of bioenergy (Hayashi et al., 2015, 2018; Bonsch et al., 2016), but might have adverse effects for food security (Boysen et al., 2017).

Reducing food and energy demand without compromising the needs of the poor emerges as a robust strategy for both water conservation and GHG emissions reductions (von Stechow et al., 2015; IEA, 2016; Parkinson et al., 2016; Grubler et al., 2018). The results underscore the importance of an integrated approach when developing water, energy and climate policy (IEA, 2016).

Estimates across different models for the impacts of stringent mitigation pathways on energy-related water uses seem ambiguous. Some pathways show synergies (Mouratiadou et al., 2018) while others indicate trade-offs and thus increases of water use due to mitigation (Fricko et al., 2016). The synergies depend on the adopted policy implementation or mitigation strategies and technology portfolio. A number of adaptation options exist (e.g., dry cooling), which can effectively reduce electricity-related water trade-offs (Fricko et al., 2016; IEA, 2016). Similarly, irrigation water use will depend on the regions where crops are produced, the sources of bioenergy (e.g., agriculture vs. forestry) and dietary change induced by climate policy. Overall, and also considering other water-related SDGs, including access to safe drinking water and sanitation as well as waste-water treatment, investments into the water sector seem to be only modestly affected by stringent climate policy compatible with 1.5°C (Figure 5.4) (McCollum et al., 2018b).

In summary, the assessment of mitigation pathways shows that to meet the 1.5°C target, a wide range of mitigation options would need to be deployed (see Chapter 2, Sections 2.3 and 2.4). While pathways aiming at 1.5°C are associated with high synergies for some sustainable development dimensions (such as human health and air pollution, forest preservation), the rapid pace and magnitude of the required changes would also lead to increased risks for trade-offs for other sustainable development dimensions (particularly food security) (Figures 5.4 and 5.5). Synergies and trade-offs are expected to be unevenly distributed between regions and nations (Box 5.2), though little literature has formally examined such distributions under 1.5°C-consistent mitigation scenarios. Reducing these risks requires smart policy designs and mechanisms that shield the poor and redistribute the burden so that the most vulnerable are not disproportionately affected. Recent scenario analyses show that associated investments for reducing the trade-offs for, for example, food, water and energy access to be significantly lower than the required mitigation investments (McCollum et al., 2018b). Fundamental transformation of demand, including efficiency and behavioural changes, can help to significantly reduce the reliance on risky technologies, such as BECCS, and thus reduce the risk of potential trade-offs between mitigation and other sustainable development dimensions (von Stechow et al., 2015; Grubler et al., 2018; van Vuuren et al., 2018). Reliance on demand-side measures only, however, would not be sufficient for meeting stringent targets, such as 1.5°C and 2°C (Clarke et al., 2014).

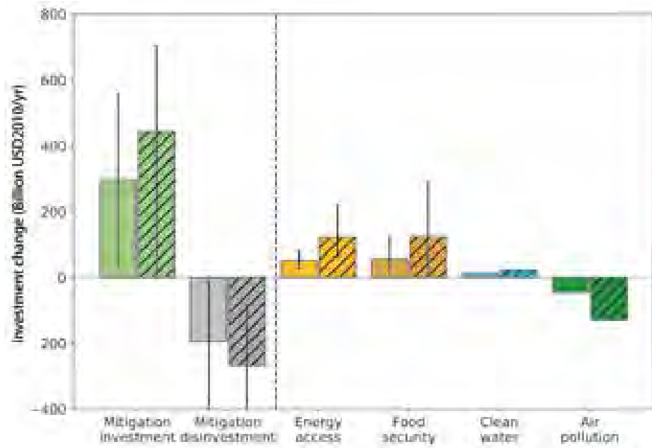


Figure 5.4 | Investment into mitigation up until 2030 and implications for investments for four sustainable development dimensions. Cross-hatched bars show the median investment in 1.5°C pathways across results from different models, and solid bars for 2°C pathways, respectively. Whiskers on bars represent minima and maxima across estimates from six models. Clean water and air pollution investments are available only from one model. Mitigation investments show the change in investments across mitigation options compared to the baseline. Negative mitigation investments (grey bars) denote disinvestment (reduced investment needs) into fossil fuel sectors compared to the baseline. Investments for different sustainable development dimensions denote the investment needs for complementary measures in order to avoid trade-offs (negative impacts) of mitigation. Negative sustainable development investments for air pollution indicate cost savings, and thus synergies of mitigation for air pollution control costs. The values compare to about 2 trillion USD2010 (range of 1.4 to 3 trillion) of total energy-related investments in the 1.5°C pathways. Source: Estimates from CD-LINKS scenarios summarised by McCollum et al., 2018b.

5.5 Sustainable Development Pathways to 1.5°C

This section assesses what is known in the literature on development pathways that are sustainable and climate-resilient and relevant to a 1.5°C warmer world. Pathways, transitions from today's world to achieving a set of future goals (see Chapter 1, Section 1.2.3, Cross-Chapter Box 1), follow broadly two main traditions: first, as integrated pathways describing the required societal and systems transformations, combining quantitative modelling and qualitative narratives at multiple spatial scales (global to sub-national); and second, as country- and community-level, solution-oriented trajectories and decision-making processes about context- and place-specific opportunities, challenges and trade-offs. These two notions of pathways offer different, though complementary, insights into the nature of 1.5°C-relevant trajectories and the short-term actions that enable long-term goals. Both highlight to varying degrees the urgency, ethics and equity dimensions of possible trajectories and society- and system-wide transformations, yet at different scales, building on Chapter 2 (see Section 2.4) and Chapter 4 (see Section 4.5).

5.5.1 Integration of Adaptation, Mitigation and Sustainable Development

Insights into climate-compatible development (see Glossary) illustrate how integration between adaptation, mitigation and sustainable development works in context-specific projects, how synergies are achieved and what challenges are encountered during implementation (Stringer et al., 2014; Suckall et al., 2014; Antwi-Agyei et al., 2017a; Bickersteth et al., 2017; Kalafatis, 2017; Nunan, 2017). The operationalization of climate-compatible development, including climate-smart agriculture and carbon-forestry projects (Lipper et al., 2014; Campbell et al., 2016; Quan et al., 2017), shows multilevel and multisector trade-offs involving 'winners' and 'losers' across governance levels (*high confidence*) (Kongsager and Corbera, 2015; Naess et al., 2015; Karlsson et al., 2017; Tanner et al., 2017; Taylor, 2017; Wood, 2017; Ficklin et al., 2018). Issues of power, participation, values, equity, inequality and justice transcend case study examples of attempted integrated approaches (Nunan, 2017; Phillips et al., 2017; Stringer et al., 2017; Wood, 2017), also reflected in policy frameworks for integrated outcomes (Stringer et al., 2014; Di Gregorio et al., 2017; Few et al., 2017; Tanner et al., 2017).

Ultimately, reconciling trade-offs between development needs and emissions reductions towards a 1.5°C warmer world requires a dynamic view of the interlinkages between adaptation, mitigation and sustainable development (Nunan, 2017). This entails recognition of the ways in which development contexts shape the choice and effectiveness of interventions, limit the range of responses afforded to communities and governments, and potentially impose injustices upon vulnerable groups (UNRISD, 2016; Thornton and Comberti, 2017). A variety of approaches, both quantitative and qualitative, exist to examine possible sustainable development pathways under which climate and sustainable development goals can be achieved, and synergies and trade-offs for transformation identified (Sections 5.3 and 5.4).

5.5.2 Pathways for Adaptation, Mitigation and Sustainable Development

This section focuses on the growing body of pathways literature describing the dynamic and systemic integration of mitigation and adaptation with sustainable development in the context of a 1.5°C warmer world. These studies are critically important for the identification of 'enabling' conditions under which climate and the SDGs can be achieved, and thus help the design of transformation strategies that maximize synergies and avoid potential trade-offs (Sections 5.3 and 5.4). Full integration of sustainable development dimensions is, however, challenging, given their diversity and the need for high temporal, spatial and social resolution to address local effects, including heterogeneity related to poverty and equity (von Stechow et al., 2015). Research on long-term climate change mitigation and adaptation pathways has covered individual SDGs to different degrees. Interactions between climate and other SDGs have been explored for SDGs 2, 3, 4, 6, 7, 8, 12, 14 and 15 (Clarke et al., 2014; Abel et al., 2016; von Stechow et al., 2016; Rao et al., 2017), while interactions with SDGs 1, 5, 11 and 16 remain largely underexplored in integrated long-term scenarios (Zimm et al., 2018).

Quantitative pathways studies now better represent 'nexus' approaches to assess sustainable development dimensions. In such approaches (see Chapter 4, Section 4.3.3.8), a subset of sustainable development dimensions are investigated together because of their close relationships (Welsch et al., 2014; Conway et al., 2015; Keairns et al., 2016; Parkinson et al., 2016; Rasul and Sharma, 2016; Howarth and Monasterolo, 2017). Compared to single-objective climate–SDG assessments (Section 5.4.2), nexus solutions attempt to integrate complex interdependencies across diverse sectors in a systems approach for consistent analysis. Recent pathways studies show how water, energy and climate (SDGs 6, 7 and 13) interact (Parkinson et al., 2016; McCollum et al., 2018b) and call for integrated water–energy investment decisions to manage systemic risks. For instance, the provision of bioenergy, important in many 1.5°C-consistent pathways, can help resolve 'nexus challenges' by alleviating energy security concerns, but can also have adverse 'nexus impacts' on food security, water use and biodiversity (Lotze-Campen et al., 2014; Bonsch et al., 2016). Policies that improve resource use efficiency across sectors can maximize synergies for sustainable development (Bartos and Chester, 2014; McCollum et al., 2018b; van Vuuren et al., 2018). Mitigation compatible with 1.5°C can significantly reduce impacts and adaptation needs in the nexus sectors compared to 2°C (Byers et al., 2018). In order to avoid trade-offs due to high carbon pricing of 1.5°C pathways, regulation in specific areas may complement price-based instruments. Such combined policies generally lead also to more early action maximizing synergies and avoiding some of the adverse climate effects for sustainable development (Bertram et al., 2018).

The comprehensive analysis of climate change in the context of sustainable development requires suitable reference scenarios that lend themselves to broader sustainable development analyses. The Shared Socio-Economic Pathways (SSPs) (Chapter 1, Cross-Chapter Box 1 in Chapter 1) (O'Neill et al., 2017a; Riahi et al., 2017) constitute an important first step in providing a framework for the integrated assessment of adaptation and mitigation and their climate–development linkages (Ebi et al., 2014). The five underlying SSP narratives (O'Neill et al., 2017a) map well into some of the key SDG dimensions, with one of the pathways (SSP1) explicitly depicting sustainability as the main theme (van Vuuren et al., 2017b).

To date, no pathway in the literature proves to achieve all 17 SDGs because several targets are not met or not sufficiently covered in the analysis, hence resulting in a sustainability gap (Zimm et al., 2018). The SSPs facilitate the systematic exploration of different sustainable dimensions under ambitious climate objectives. SSP1 proves to be in line with eight SDGs (3, 7, 8, 9, 10, 11, 13 and 15) and several of their targets in a 2°C warmer world (van Vuuren et al., 2017b; Zimm et al., 2018). However, important targets for SDGs 1, 2 and 4 (i.e., people living in extreme poverty, people living at the risk of hunger and gender gap in years of schooling) are not met in this scenario.

The SSPs show that sustainable socio-economic conditions will play a key role in reaching stringent climate targets (Riahi et al., 2017; Rogelj et al., 2018). Recent modelling work has examined 1.5°C-consistent, stringent mitigation scenarios for 2100 applied to the SSPs, using six different IAMs. Despite the limitations of these models, which are coarse approximations of reality, robust trends can be identified

(Rogelj et al., 2018). SSP1 – which depicts broader 'sustainability' as well as enhancing equity and poverty reductions – is the only pathway where all models could reach 1.5°C and is associated with the lowest mitigation costs across all SSPs. A decreasing number of models was successful for SSP2, SSP4 and SSP5, respectively, indicating distinctly higher risks of failure due to high growth and energy intensity as well as geographical and social inequalities and uneven regional development. And reaching 1.5°C has even been found infeasible in the less sustainable SSP3 – 'regional rivalry' (Fujimori et al., 2017b; Riahi et al., 2017). All these conclusions hold true if a 2°C objective is considered (Calvin et al., 2017; Fujimori et al., 2017b; Popp et al., 2017; Riahi et al., 2017). Rogelj et al. (2018) also show that fewer scenarios are, however, feasible across different SSPs in case of 1.5°C, and mitigation costs substantially increase in 1.5°C pathways compared to 2°C pathways.

There is a wide range of SSP-based studies focusing on the connections between adaptation/impacts and different sustainable development dimensions (Hasegawa et al., 2014; Ishida et al., 2014; Arnell et al., 2015; Bowyer et al., 2015; Burke et al., 2015; Lemoine and Kapnick, 2016; Rozenberg and Hallegatte, 2016; Blanco et al., 2017; Hallegatte and Rozenberg, 2017; O'Neill et al., 2017a; Rutledge et al., 2017; Byers et al., 2018). New methods for projecting inequality and poverty (downscaled to sub-national rural and urban levels as well as spatially explicit levels) have enabled advanced SSP-based assessments of locally sustainable development implications of avoided impacts and related adaptation needs. For instance, Byers et al. (2018) find that, in a 1.5°C warmer world, a focus on sustainable development can reduce the climate risk exposure of populations vulnerable to poverty by more than an order of magnitude (Section 5.2.2). Moreover, aggressive reductions in between-country inequality may decrease the emissions intensity of global economic growth (Rao and Min, 2018). This is due to the higher potential for decoupling of energy from income growth in lower-income countries, due to high potential for technological advancements that reduce the energy intensity of growth of poor countries – critical also for reaching 1.5°C in a socially and economically equitable way. Participatory downscaling of SSPs in several European Union countries and in Central Asia shows numerous possible pathways of solutions to the 2°C–1.5°C goal, depending on differential visions (Tàbara et al., 2018). Other participatory applications of the SSPs, for example in West Africa (Palazzo et al., 2017) and the southeastern United States (Absar and Preston, 2015), illustrate the potentially large differences in adaptive capacity within regions and between sectors.

Harnessing the full potential of the SSP framework to inform sustainable development requires: (i) further elaboration and extension of the current SSPs to cover sustainable development objectives explicitly; (ii) the development of new or variants of current narratives that would facilitate more SDG-focused analyses with climate as one objective (among other SDGs) (Riahi et al., 2017); (iii) scenarios with high regional resolution (Fujimori et al., 2017b); (iv) a more explicit representation of institutional and governance change associated with the SSPs (Zimm et al., 2018); and (v) a scale-up of localized and spatially explicit vulnerability, poverty and inequality estimates, which have emerged in recent publications based on the SSPs (Byers et al., 2018) and are essential to investigate equity dimensions (Klinsky and Winkler, 2018).

5.5.3 Climate-Resilient Development Pathways

This section assesses the literature on pathways as solution-oriented trajectories and decision-making processes for attaining transformative visions for a 1.5°C warmer world. It builds on climate-resilient development pathways (CRDPs) introduced in the AR5 (Section 5.1.2) (Olsson et al., 2014) as well as growing literature (e.g., Eriksen et al., 2017; Johnson, 2017; Orindi et al., 2017; Kirby and O'Mahony, 2018; Solecki et al., 2018) that uses CRDPs as a conceptual and aspirational idea for steering societies towards low-carbon, prosperous and ecologically safe futures. Such a notion of pathways foregrounds decision-making processes at local to national levels to situate transformation, resilience, equity and well-being in the complex reality of specific places, nations and communities (Harris et al., 2017; Ziervogel et al., 2017; Fazey et al., 2018; Gajjar et al., 2018; Klinsky and Winkler, 2018; Patterson et al., 2018; Tàbara et al., 2018).

Pathways compatible with 1.5°C warming are not merely scenarios to envision possible futures but processes of deliberation and implementation that address societal values, local priorities and inevitable trade-offs. This includes attention to politics and power that perpetuate business-as-usual trajectories (O'Brien, 2016; Harris et al., 2017), the politics that shape sustainability and capabilities of everyday life (Agyeman et al., 2016; Schlosberg et al., 2017), and ingredients for community resilience and transformative change (Fazey et al., 2018). Chartering CRDPs encourages locally situated and problem-solving processes to negotiate and operationalize resilience 'on the ground' (Beilin and Wilkinson, 2015; Harris et al., 2017; Ziervogel et al., 2017). This entails contestation, inclusive governance and iterative engagement of diverse populations with varied needs, aspirations, agency and rights claims, including those most affected, to deliberate trade-offs in a multiplicity of possible pathways (*high confidence*) (see Figure 5.5) (Stirling, 2014; Vale, 2014; Walsh-Dilley and Wolford, 2015; Biermann et al., 2016; J.R.A. Butler et al., 2016; O'Brien, 2016, 2018; Harris et al., 2017; Jones and Tanner, 2017; Mapfumo et al., 2017; Rosenbloom, 2017; Gajjar et al., 2018; Klinsky and Winkler, 2018; Lyon, 2018; Tàbara et al., 2018).

5.5.3.1 Transformations, equity and well-being

Most literature related to CRDPs invokes the concept of transformation, underscoring the need for urgent and far-reaching changes in practices, institutions and social relations in society. Transformations towards a 1.5°C warmer world would need to address considerations for equity and well-being, including in trade-off decisions (see Figure 5.1).

To attain the anticipated *transformations*, all countries as well as non-state actors would need to strengthen their contributions, through bolder and more committed cooperation and equitable effort-sharing (*medium evidence, high agreement*) (Rao, 2014; Frumhoff et al., 2015; Ekwurzel et al., 2017; Millar et al., 2017; Shue, 2017; Holz et al., 2018; Robinson and Shine, 2018). Sustaining decarbonization rates at a 1.5°C-compatible level would be unprecedented and not possible without rapid transformations to a net-zero-emissions global economy by mid-century or the later half of the century (see Chapters 2 and 4). Such efforts would entail overcoming technical, infrastructural, institutional and behavioural barriers across all sectors and levels

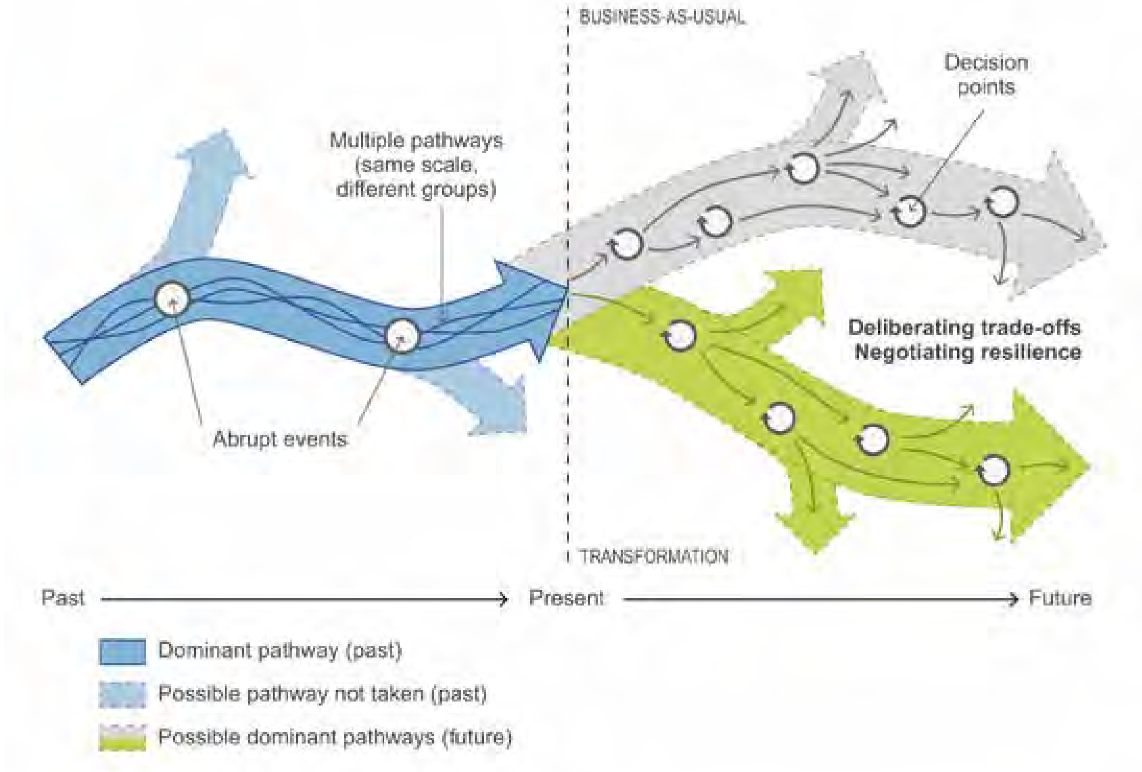


Figure 5.5 | Pathways into the future, with path dependencies and iterative problem-solving and decision-making (after Fazey et al., 2016).

of society (Pfeiffer et al., 2016; Seto et al., 2016) and defeating path dependencies, including poverty traps (Boonstra et al., 2016; Enqvist et al., 2016; Lade et al., 2017; Haider et al., 2018). Transformation also entails ensuring that 1.5°C-compatible pathways are inclusive and desirable, build solidarity and alliances, and protect vulnerable groups, including against disruptions of transformation (Patterson et al., 2018).

There is growing emphasis on the role of *equity, fairness* and *justice* (see Glossary) regarding context-specific transformations and pathways to a 1.5°C warmer world (*medium evidence, high agreement*) (Shue, 2014; Thorp, 2014; Dennig et al., 2015; Moellendorf, 2015; Klinsky et al., 2017b; Roser and Seidel, 2017; Sealey-Huggins, 2017; Klinsky and Winkler, 2018; Robinson and Shine, 2018). Consideration for what is equitable and fair suggests the need for stringent decarbonization and up-scaled adaptation that do not exacerbate social injustices, locally and at national levels (Okereke and Coventry, 2016), uphold human rights (Robinson and Shine, 2018), are socially desirable and acceptable (von Stechow et al., 2016; Rosenbloom, 2017), address values and beliefs (O'Brien, 2018), and overcome vested interests (Normann, 2015; Patterson et al., 2016). Attention is often drawn to huge disparities in the cost, benefits, opportunities and challenges involved in transformation within and between countries, and the fact that the suffering of already poor, vulnerable and disadvantaged populations may be worsened, if care to protect them is not taken (Holden et al., 2017; Klinsky and Winkler, 2018; Patterson et al., 2018).

Well-being for all (Dearing et al., 2014; Raworth, 2017) is at the core of an ecologically safe and socially just space for humanity, including health and housing, peace and justice, social equity, gender equality and political voices (Raworth, 2017). It is in alignment with transformative social development (UNRISD, 2016) and the 2030 Agenda of 'leaving no one behind'. The social conditions to enable well-being for all are to reduce entrenched inequalities within and between countries (Klinsky and Winkler, 2018); rethink prevailing values, ethics and behaviours (Holden et al., 2017); allow people to live a life in dignity while avoiding actions that undermine capabilities (Klinsky and Golub, 2016); transform economies (Popescu and Ciurlau, 2016; Tàbara et al., 2018); overcome uneven consumption and production patterns (Dearing et al., 2014; Häyhä et al., 2016; Raworth, 2017) and conceptualize development as well-being rather than mere economic growth (*medium evidence, high agreement*) (Gupta and Pouw, 2017).

5.5.3.2 Development trajectories, sharing of efforts and cooperation

The potential for pursuing sustainable and climate-resilient development pathways towards a 1.5°C warmer world differs between and within nations, due to differential development achievements and trajectories, and opportunities and challenges (*very high confidence*) (Figure 5.1). There are clear differences between high-income countries where social achievements are high, albeit often with negative effects on the environment, and most developing nations where vulnerabilities to climate change are high and social support and life satisfaction are low, especially in the Least Developed Countries (LDCs) (Sachs et al., 2017; O'Neill et al., 2018). Differential starting points for CRDPs between and within countries, including path dependencies (Figure 5.5), call for sensitivity to context (Klinsky and Winkler, 2018). For the developing world, limiting warming to 1.5°C also means potentially severely curtailed development prospects (Okereke and Coventry, 2016) and risks to human rights from both climate action and inaction to achieve this goal (Robinson and Shine, 2018) (Section 5.2). Within-country development differences remain, despite efforts to ensure inclusive societies (Gupta and Arts, 2017; Gupta and Pouw, 2017). Cole et al. (2017), for instance, show how differences between provinces in South Africa constitute barriers to sustainable development trajectories and for operationalising nation-level SDGs, across various dimensions of social deprivation and environmental stress, reflecting historic disadvantages.

Moreover, various equity and effort- or burden-sharing approaches to climate stabilization in the literature describe how to sketch national potentials for a 1.5°C warmer world (e.g., Anand, 2004; CSO Equity Review, 2015; Meinshausen et al., 2015; Okereke and Coventry, 2016; Bexell and Jönsson, 2017; Otto et al., 2017; Pan et al., 2017; Robiou du Pont et al., 2017; Holz et al., 2018; Kartha et al., 2018; Winkler et al., 2018;). Many approaches build on the AR5 'responsibility – capacity – need' assessment (Clarke et al., 2014), complement other proposed national-level metrics for capabilities, equity and fairness (Heyward and Roser, 2016; Klinsky et al., 2017a), or fall under the wider umbrella of fair share debates on responsibility, capability and the right to development in climate policy (Fuglestvedt and Kallbekken, 2016). Importantly, different principles and methodologies generate different calculated contributions, responsibilities and capacities (Skeie et al., 2017).

The notion of nation-level fair shares is now also discussed in the context of limiting global warming to 1.5°C and the Nationally Determined Contributions (NDCs) (see Chapter 4, Cross-Chapter Box 11 in Chapter 4) (CSO Equity Review, 2015; Mace, 2016; Pan et al., 2017; Robiou du Pont et al., 2017; Holz et al., 2018; Kartha et al., 2018; Winkler et al., 2018). A study by Pan et al. (2017) concluded that all countries would need to contribute to ambitious emissions reductions and that current pledges for 2030 by seven out of eight high-emitting countries would be insufficient to meet 1.5°C. Emerging literature on justice-centred pathways to 1.5°C points towards ambitious emissions reductions domestically and committed cooperation internationally whereby wealthier countries support poorer ones, technologically, financially and otherwise to enhance capacities (Okereke and Coventry, 2016; Holz et al., 2018; Robinson and Shine, 2018; Shue, 2018). These findings suggest that equitable and 1.5°C-compatible pathways would require fast action across all countries at all levels of development rather than late accession of developing countries (as assumed under SSP3, see Chapter 2), with external support for prompt mitigation and resilience-building efforts in the latter (*medium evidence, medium agreement*).

Scientific advances since the AR5 now also make it possible to determine contributions to climate change for non-state actors (see Chapter 4, Section 4.4.1) and their potential to contribute to CRDPs (*medium evidence, medium agreement*). These non-state actors includes cities (Bulkeley et al., 2013, 2014; Byrne et al., 2016), businesses (Heede, 2014; Frumhoff et al., 2015; Shue, 2017), transnational initiatives (Castro, 2016; Andonova et al., 2017) and industries. Recent work demonstrates the contributions of 90 industrial carbon producers to global temperature and sea level rise, and their responsibilities to contribute to investments in and support for mitigation and adaptation (Heede, 2014; Ekwurzel et al., 2017; Shue, 2017) (Sections 5.6.1 and 5.6.2).

At the level of groups and individuals, equity in pursuing climate resilience for a 1.5°C warmer world means addressing disadvantage, inequities and empowerment that shape transformative processes and pathways (Fazey et al., 2018), and deliberate efforts to strengthen the capabilities, capacities and well-being of poor, marginalized and vulnerable people (Byrnes, 2014; Tokar, 2014; Harris et al., 2017; Klinsky et al., 2017a; Klinsky and Winkler, 2018). Community-driven CRDPs can flag potential negative impacts of national trajectories on disadvantaged groups, such as low-income families and communities of colour (Rao, 2014). They emphasize social equity, participatory governance, social inclusion and human rights, as well as innovation, experimentation and social learning (see Glossary) (*medium evidence, high agreement*) (Sections 5.5.3.3 and 5.6).

5.5.3.3 Country and community strategies and experiences

There are many possible pathways towards climate-resilient futures (O'Brien, 2018; Tàbara et al., 2018). Literature depicting different sustainable development trajectories in line with CRDPs is growing, with some of it being specific to 1.5°C global warming. Most experiences to date are at local and sub-national levels (Cross-Chapter Box 13 in this chapter), while state-level efforts align largely with green economy trajectories or planning for climate resilience (Box 5.3). Due to the fact that these strategies are context-specific, the literature is scarce on comparisons, efforts to scale up and systematic monitoring.

States can play an enabling or hindering role in a transition to a 1.5°C warmer world (Patterson et al., 2018). The literature on strategies to reconcile low-carbon trajectories with sustainable development and ecological sustainability through green growth, inclusive growth, de-growth, post-growth and development as well-being *shows low agreement* (see Chapter 4, Section 4.5). Efforts that align best with CRDPs are described as 'transformational' and 'strong' (Ferguson, 2015). Some view 'thick green' perspectives as enabling equity, democracy and agency building (Lorek and Spangenberg, 2014; Stirling, 2014; Ehresman and Okereke, 2015; Buch-Hansen, 2018), others show how green economy and sustainable development pathways can align (Brown et al., 2014; Georgeson et al., 2017b), and how a green economy can help link the SDGs with NDCs, for instance in Mongolia, Kenya and Sweden (Shine, 2017). Others still critique the continuous reliance on market mechanisms (Wanner, 2014; Brockington and Ponte, 2015) and disregard for equity and distributional and procedural justice (Stirling, 2014; Bell, 2015).

Country-level pathways and achievements vary significantly (*robust evidence, medium agreement*). For instance, the Scandinavian countries rank at the top of the Global Green Economy Index (Dual Citizen LLC, 2016), although they also tend to show high spill-over effects (Holz et al., 2018) and transgress their biophysical boundaries (O'Neill et al., 2018). State-driven efforts in non-member countries of the Organisation for Economic Co-operation and Development include Ethiopia's 'Climate-resilient Green Economy Strategy', Mozambique's 'Green Economy Action Plan' and Costa Rica's ecosystem- and conservation-driven green transition paths. China and India have adopted technology and renewables pathways (Brown et al., 2014; Death, 2014, 2015, 2016; Khanna et al., 2014; Chen et al., 2015; Kim and Thurbon, 2015; Wang et al., 2015; Weng et al., 2015). Brazil promotes low per capita GHG emissions, clean energy sources, green jobs, renewables and sustainable transportation, while slowing rates of deforestation (see Chapter 4, Box 4.7) (Brown et al., 2014; La Rovere, 2017). Yet concerns remain regarding persistent inequalities, ecosystem monetization, lack of participation in green-style projects (Brown et al., 2014) and labour conditions and risk of displacement in the sugarcane ethanol sector (McKay et al., 2016). Experiences with low-carbon development pathways in LDCs highlight the crucial role of identifying synergies across scale, removing institutional barriers and ensuring equity and fairness in distributing benefits as part of the right to development (Rai and Fisher, 2017).

In small islands states, for many of which climate change hazards and impacts at 1.5°C pose significant risks to sustainable development (see Chapter 3 Box 3.5, Chapter 4 Box 4.3, Box 5.3), examples of CRDPs have emerged since the AR5. This includes the SAMOA Pathway: SIDS Accelerated Modalities of Action (see Chapter 4, Box 4.3) (UNGA, 2014; Government of Kiribati, 2016; Steering Committee on Partnerships for SIDS and UN DESA, 2016; Lefale et al., 2017) and the Framework for Resilient Development in the Pacific, a leading example of integrated regional climate change adaptation planning for mitigation and sustainable development, disaster risk management and low-carbon economies (SPC, 2016). Small islands of the Pacific vary significantly in their capacity and resources to support effective integrated planning (McCubbin et al., 2015; Barnett and Walters, 2016; Cvitanovic et al., 2016; Hemstock et al., 2017; Robinson and Dornan, 2017). Vanuatu (Box 5.3) has developed a significant coordinated national adaptation plan to advance the 2030 Agenda for Sustainable Development, respond to the Paris Agreement and reduce the risk of disasters in line with the Sendai targets (UNDP, 2016; Republic of Vanuatu, 2017).

Box 5.3 | Republic of Vanuatu – National Planning for Development and Climate Resilience

The Republic of Vanuatu is leading Pacific Small Island Developing States (SIDS) to develop a nationally coordinated plan for climate-resilient development in the context of high exposure to hazard risk (MoCC, 2016; UNU-EHS, 2016). The majority of the population depends on subsistence, rain-fed agriculture and coastal fisheries for food security (Sovacool et al., 2017). Sea level rise, increased prolonged drought, water shortages, intense storms, cyclone events and degraded coral reef environments threaten human security in a 1.5°C warmer world (see Chapter 3, Box 3.5) (SPC, 2015; Aipira et al., 2017). Given Vanuatu's long history of climate hazards and disasters, local adaptive capacity is relatively high, despite barriers to the use of local knowledge and technology, and low rates of literacy and women's participation (McNamara and Prasad, 2014; Aipira et al., 2017; Granderson, 2017). However, the adaptive capacity of Vanuatu and other SIDS is increasingly constrained due to more frequent severe weather events (see Chapter 3, Box 3.5, Chapter 4, Cross-Chapter Box 9 in Chapter 4) (Gero et al., 2013; Kuruppu and Willie, 2015; SPC, 2015; Sovacool et al., 2017).

Vanuatu has developed a national sustainable development plan for 2016–2030: the People's Plan (Republic of Vanuatu, 2016). This coordinated, inclusive plan of action on economy, environment and society aims to strengthen adaptive capacity and resilience to climate change and disasters. It emphasizes rights of all Ni-Vanuatu, including women, youth, the elderly and vulnerable groups (Nalau et al., 2016). Vanuatu has also developed a Coastal Adaptation Plan (Republic of Vanuatu, 2016), an integrated Climate Change and Disaster Risk Reduction Policy (2016–2030) (SPC, 2015) and the first South Pacific National Advisory Board on Climate Change & Disaster Risk Reduction (SPC, 2015; UNDP, 2016).

Vanuatu aims to integrate planning at multiple scales, and increase climate resilience by supporting local coping capacities and iterative processes of planning for sustainable development and integrated risk assessment (Aipira et al., 2017; Eriksson et al., 2017; Granderson, 2017). Climate-resilient development is also supported by non-state partnerships, for example, the 'Yumi stap redi long climate change'–the Vanuatu non-governmental organization Climate Change Adaptation Program (Maclellan, 2015). This programme focuses on equitable governance, with particular attention to supporting women's voices in decision-making through allied programmes addressing domestic violence, and rights-based education to reduce social marginalization; alongside institutional reforms for greater transparency, accountability and community participation in decision-making (Davies, 2015; Maclellan, 2015; Sterrett, 2015; Ensor, 2016; UN Women, 2016).

Power imbalances embedded in the political economy of development (Nunn et al., 2014), gender discrimination (Aipira et al., 2017) and the priorities of climate finance (Cabezon et al., 2016) may marginalize the priorities of local communities and influence how local risks are understood, prioritised and managed (Kuruppu and Willie, 2015; Baldacchino, 2017; Sovacool et al., 2017). However, the experience of the low death toll after Cyclone Pam suggests effective use of local knowledge in planning and early warning may support resilience at least in the absence of storm surge flooding (Handmer and Iveson, 2017; Nalau et al., 2017). Nevertheless, the very severe infrastructure damage of Cyclone Pam 2015 highlights the limits of individual Pacific SIDS efforts and the need for global and regional responses to a 1.5°C warmer world (see Chapter 3, Box 3.5, Chapter 4, Box 4.3) (Dilling et al., 2015; Ensor, 2016; Shultz et al., 2016; Rey et al., 2017).

Communities, towns and cities also contribute to low-carbon pathways, sustainable development and fair and equitable climate resilience, often focused on processes of power, learning and contestation as entry points to more localised CRDPs (*medium evidence, high agreement*) (Cross-Chapter Box 13 in this chapter, Box 5.2). In the Scottish Borders Climate Resilient Communities Project (United Kingdom), local flood management is linked with national policies to foster cross-scalar and inclusive governance, with attention to systemic disadvantages, shocks and stressors, capacity building, learning for change and climate narratives to inspire hope and action, all of which are essential for community resilience in a 1.5°C warmer world (Fazey et al., 2018). Narratives and storytelling are vital for realizing place-based 1.5°C futures as they create space for agency, deliberation, co-constructing meaning, imagination and desirable and dignified pathways (Veland et al., 2018). Engagement with possible futures, identity and self-reliance is also documented for Alaska, where warming has already exceeded 1.5°C and indigenous communities invest in renewable energy, greenhouses for food security and new fishing practices to overcome loss of sea ice, flooding and erosion (Chapin et al., 2016; Fazey et al., 2018). The Asian Cities Climate Change Resilience Network facilitates shared learning dialogues, risk-to-resilience workshops, and iterative, consultative planning in flood-prone cities in India; vulnerable communities, municipal governmental agents, entrepreneurs and technical experts negotiate different visions, trade-offs and local politics to identify desirable pathways (Harris et al., 2017).

Transforming our societies and systems to limit global warming to 1.5°C and ensuring equity and well-being for human populations and ecosystems in a 1.5°C warmer world would require ambitious and well-integrated adaptation–mitigation–development pathways that deviate fundamentally from high-carbon, business-as-usual futures (Okereke and Coventry, 2016; Arts, 2017; Gupta and Arts, 2017; Sealey-Huggins, 2017). Identifying and negotiating socially acceptable, inclusive and equitable pathways towards climate-resilient futures is a challenging, yet important, endeavour, fraught with complex moral, practical and political difficulties and inevitable trade-offs (*very high confidence*). The ultimate questions are: what futures do we want (Bai et al., 2016; Tàbara et al., 2017; Klinsky and Winkler, 2018; O'Brien, 2018; Veland et al., 2018), whose resilience matters, for what, where, when and why (Meerow and Newell, 2016), and 'whose vision … is being pursued and along which pathways' (Gillard et al., 2016).

Cross-Chapter Box 13 | Cities and Urban Transformation

Lead Authors:

Fernando Aragon-Durand (Mexico), Paolo Bertoldi (Italy), Anton Cartwright (South Africa), François Engelbrecht (South Africa), Bronwyn Hayward (New Zealand), Daniela Jacob (Germany), Debora Ley (Guatemala/Mexico), Shagun Mehrotra (USA/India), Peter Newman (Australia), Aromar Revi (India), Seth Schultz (USA), William Solecki (USA), Petra Tschakert (Australia/Austria)

Contributor:

Peter Marcotullio (USA)

Global Urbanization in a 1.5°C Warmer World

The concentration of economic activity, dense social networks, human resource capacity, investment in infrastructure and buildings, relatively nimble local governments, close connection to surrounding rural and natural environments, and a tradition of innovation provide urban areas with transformational potential (see Chapter 4, Section 4.3.3) (Castán Broto, 2017). In this sense, the urbanization megatrend that will take place over the next three decades, and add approximately 2 billion people to the global urban population (UN, 2014), offers opportunities for efforts to limit warming to 1.5°C.

Cities can also, however, concentrate the risks of flooding, landslides, fire and infectious and parasitic disease that are expected to heighten in a 1.5°C warmer world (Chapter 3). In African and Asian countries where urbanization rates are highest, these risks could expose and amplify pre-existing stresses related to poverty, exclusion, and governance (Gore, 2015; Dodman et al., 2017; Jiang and O'Neill, 2017; Pelling et al., 2018; Solecki et al., 2018). Through its impact on economic development and investment, urbanization often leads to increased consumption and environmental degradation and enhanced vulnerability and risk (Rosenzweig et al., 2018). In the absence of innovation, the combination of urbanization and urban economic development could contribute 226 $GtCO_2$ in emissions by 2050 (Bai et al., 2018). At the same time, some new urban developments are demonstrating combined carbon and Sustainable Development Goals (SDG) benefits (Wiktorowicz et al., 2018), and it is in towns and cities that building renovation rates can be most easily accelerated to support the transition to 1.5°C pathways (Kuramochi et al., 2018), including through voluntary programmes (Van der Heijden, 2018).

Urban transformations and emerging climate-resilient development pathways

The 1.5°C pathways require action in all cities and urban contexts. Recent literature emphasizes the need to deliberate and negotiate how resilience and climate-resilient pathways can be fostered in the context of people's daily lives, including the failings of everyday development such as unemployment, inadequate housing and a growing informal sector and settlements (informality), in order

Cross-Chapter Box 13 (continued)

to acknowledge local priorities and foster transformative learning (Vale, 2014; Shi et al., 2016; Harris et al., 2017; Ziervogel et al., 2017; Fazey et al., 2018; Macintyre et al., 2018). Enhancing deliberate transformative capacities in urban contexts also entails new and relational forms of envisioning agency, equity, resilience, social cohesion and well-being (Section 5.5.3) (Gillard et al., 2016; Ziervogel et al., 2016). Two examples of urban transformation are explored here.

The built environment, spatial planning, infrastructure, energy services, mobility and urban–rural linkages necessary in rapidly growing cities in South Asia and Africa in the next three decades present mitigation, adaptation and development opportunities that are crucial for a 1.5°C world (Newman et al., 2017; Lwasa et al., 2018; Teferi and Newman, 2018). Realizing these opportunities would require the structural challenges of poverty, weak and contested local governance, and low levels of local government investment to be addressed on an unprecedented scale (Wachsmuth et al., 2016; Chu et al., 2017; van Noorloos and Kloosterboer, 2017; Pelling et al., 2018).

Urban governance is critical to ensuring that the necessary urban transitions deliver economic growth and equity (Hughes et al., 2018). The proximity of local governments to citizens and their needs can make them powerful agents of climate action (Melica et al., 2018), but urban governance is enhanced when it involves multiple actors (Ziervogel et al., 2016; Pelling et al., 2018), supportive national governments (Tait and Euston-Brown, 2017), and sub-national climate networks (see Chapter 4, Section 4.4.1). Governance is complicated for the urban population currently living in informality. This population is expected to triple, to three billion, by 2050 (Satterthwaite et al., 2018), placing a significant portion of the world's population beyond the direct reach of formal climate mitigation and adaptation policies (Revi et al., 2014). How to address the co-evolved and structural conditions that lead to urban informality and associated vulnerability to 1.5°C of warming is a central question for this report. Brown and McGranahan (2016) cite evidence that the informal urban 'green economy' that has emerged out of necessity in the absence of formal service provisions is frequently low-carbon and resource-efficient.

Realising the potential for low carbon transitions in informal urban settlements would require an express recognition of the unpaid-for contributions of women in the informal economy, and new partnerships between the state and communities (Ziervogel et al., 2017; Pelling et al., 2018; Satterthwaite et al., 2018). There is no guarantee that these partnerships will evolve or cohere into the type of service delivery and climate governance system that could steer the change on a scale required to limit to warming to 1.5°C (Jaglin, 2014). However, work by transnational networks, such as Shack/Slum Dwellers International, C40, the Global Covenant of Mayors, and the International Council for Local Environmental Initiatives, as well as efforts to combine in-country planning for Nationally Determined Contributions (NDCs) (Andonova et al., 2017; Fuhr et al., 2018) with those taking place to support the New Urban Agenda and National Urban Policies, represent one step towards realizing the potential (Tait and Euston-Brown, 2017). So too do 'old urban agendas', such as slum upgrading and universal water and sanitation provision (McGranahan et al., 2016; Satterthwaite, 2016; Satterthwaite et al., 2018).

Transition Towns (TTs) are a type of urban transformation that have emerged mainly in high-income countries. The grassroots TT movement (origin in the United Kingdom) combines adaptation, mitigation and just transitions, mainly at the level of communities and small towns. It now has more than 1,300 registered local initiatives in more than 40 countries (Grossmann and Creamer, 2017), many of them in the United Kingdom, the United States, and other high-income countries. TTs are described as 'progressive localism' (Cretney et al., 2016), aiming to foster a 'communitarian ecological citizenship' that goes beyond changes in consumption and lifestyle (Kenis, 2016). They aspire to promote equitable communities resilient to the impacts of climate change, peak oil and unstable global markets; re-localization of production and consumption; and transition pathways to a post-carbon future (Feola and Nunes, 2014; Evans and Phelan, 2016; Grossmann and Creamer, 2017).

TT initiatives typically pursue lifestyle-related low-carbon living and economies, food self-sufficiency, energy efficiency through renewables, construction with locally sourced material and cottage industries (Barnes, 2015; Staggenborg and Ogrodnik, 2015; Taylor Aiken, 2016). Social and iterative learning through the collective involves dialogue, deliberation, capacity building, citizen science engagements, technical re-skilling to increase self-reliance, for example canning and preserving food and permaculture, future visioning and emotional training to share difficulties and loss (Feola and Nunes, 2014; Barnes, 2015; Boke, 2015; Taylor Aiken, 2015; Kenis, 2016; Mehmood, 2016; Grossmann and Creamer, 2017).

Important conditions for successful transition groups include flexibility, participatory democracy, care ethics, inclusiveness and consensus-building, assuming bridging or brokering roles, and community alliances and partnerships (Feola and Nunes, 2014; Mehmood, 2016; Taylor Aiken, 2016; Grossmann and Creamer, 2017). Smaller scale rural initiatives allow for more experimentation

Cross-Chapter Box 13 (continued)

(Cretney et al., 2016), while those in urban centres benefit from stronger networks and proximity to power structures (North and Longhurst, 2013; Nicolosi and Feola, 2016). Increasingly, TTs recognize the need to participate in policymaking (Kenis and Mathijs, 2014; Barnes, 2015).

Despite high self-ratings of success, some TT initiatives are too inwardly focused and geographically isolated (Feola and Nunes, 2014), while others have difficulties in engaging marginalized, non-white, non-middle-class community members (Evans and Phelan, 2016; Nicolosi and Feola, 2016; Grossmann and Creamer, 2017). In the United Kingdom, expectations of innovations growing in scale (Taylor Aiken, 2015) and carbon accounting methods required by funding bodies (Taylor Aiken, 2016) undermine local resilience building. Tension between explicit engagements with climate change action and efforts to appeal to more people have resulted in difficult trade-offs and strained member relations (Grossmann and Creamer, 2017) though the contribution to changing an urban culture that prioritizes climate change is sometimes underestimated (Wiktorowicz et al., 2018).

Urban actions that can highlight the 1.5°C agenda include individual actions within homes (Werfel, 2017; Buntaine and Prather, 2018); demonstration zero carbon developments (Wiktorowicz et al., 2018); new partnerships between communities, government and business to build mass transit and electrify transport (Glazebrook and Newman, 2018); city plans to include climate outcomes (Millard-Ball, 2013); and support for transformative change across political, professional and sectoral divides (Bai et al., 2018).

5.6 Conditions for Achieving Sustainable Development, Eradicating Poverty and Reducing Inequalities in 1.5°C Warmer Worlds

This chapter has described the fundamental, urgent and systemic transformations that would be needed to achieve sustainable development, eradicate poverty and reduce inequalities in a 1.5°C warmer world, in various contexts and across scales. In particular, it has highlighted the societal dimensions, putting at the centre people's needs and aspirations in their specific contexts. Here we synthesize some of the most pertinent enabling conditions (see Glossary) to support these profound transformations. These conditions are closely interlinked and connected by the overarching concept of governance, which broadly includes institutional, socio-economic, cultural and technological elements (see Chapter 1, Cross-Chapter Box 4 in Chapter 1).

5.6.1 Finance and Technology Aligned with Local Needs

Significant gaps in green investment constrain transitions to a low-carbon economy aligned with development objectives (Volz et al., 2015; Campiglio, 2016). Hence, unlocking new forms of public, private and public–private financing is essential to support environmental sustainability of the economic system (Croce et al., 2011; Blyth et al., 2015; Falcone et al., 2018) (see Chapter 4, Section 4.4.5). To avoid risks of undesirable trade-offs with the SDGs caused by national budget constraints, improved access to international climate finance is essential for supporting adaptation, mitigation and sustainable development, especially for LDCs and SIDS (*medium evidence, high agreement*) (Shine and Campillo, 2016; Wood, 2017). Care needs to be taken when international donors or partnership arrangements influence project financing structures (Kongsager and Corbera, 2015; Purdon, 2015; Phillips et al., 2017; Ficklin et al., 2018). Conventional climate funding schemes, especially the Clean Development Mechanism (CDM), have shown positive effects on sustainable development but also adverse consequences, for example, on adaptive capacities of rural households and uneven distribution of costs and benefits, often exacerbating inequalities (*robust evidence, high agreement*) (Aggarwal, 2014; Brohé, 2014; He et al., 2014; Schade and Obergassel, 2014; Smits and Middleton, 2014; Wood et al., 2016a; Horstmann and Hein, 2017; Kreibich et al., 2017). Close consideration of recipients' context-specific needs when designing financial support helps to overcome these limitations as it better aligns community needs, national policy objectives and donors' priorities; puts the emphasis on the increase of transparency and predictability of support; and fosters local capacity building (*medium evidence, high agreement*) (Barrett, 2013; Boyle et al., 2013; Shine and Campillo, 2016; Ley, 2017; Sánchez and Izzo, 2017).

The development and transfer of technologies is another enabler for developing countries to contribute to the requirements of the 1.5°C objective while achieving climate resilience and their socio-economic development goals (see Chapter 4, Section 4.4.4). International-level governance would be needed to boost domestic innovation and the deployment of new technologies, such as negative emission technologies, towards the 1.5°C objective (see Chapter 4, Section 4.3.7), but the alignment with local needs depends on close consideration of the specificities of the domestic context in countries at all levels of development (de Coninck and Sagar, 2015; IEA, 2015; Parikh et al., 2018). Technology transfer supporting development in developing countries would require an understanding of local and national actors and institutions (de Coninck and Puig, 2015; de Coninck and Sagar, 2017; Michaelowa et al., 2018), careful attention to the capacities in the entire innovation chain (Khosla et al., 2017; Olawuyi, 2017) and transfer of not only equipment but also knowledge (*medium evidence, high agreement*) (Murphy et al., 2015).

5.6.2 Integration of Institutions

Multilevel governance in climate change has emerged as a key enabler for systemic transformation and effective governance (see Chapter 4, Section 4.4.1). On the one hand, low-carbon and climate-resilient development actions are often well aligned at the lowest scale possible (Suckall et al., 2015; Sánchez and Izzo, 2017), and informal, local institutions are critical in enhancing the adaptive capacity of countries and marginalized communities (Yaro et al., 2015). On the other hand, international and national institutions can provide incentives for projects to harness synergies and avoid trade-offs (Kongsager et al., 2016).

Governance approaches that coordinate and monitor multiscale policy actions and trade-offs across sectoral, local, national, regional and international levels are therefore best suited to implement goals towards 1.5°C warmer conditions and sustainable development (Ayers et al., 2014; Stringer et al., 2014; von Stechow et al., 2016; Gwimbi, 2017; Hayward, 2017; Maor et al., 2017; Roger et al., 2017; Michaelowa et al., 2018). Vertical and horizontal policy integration and coordination is essential to take into account the interplay and trade-offs between sectors and spatial scales (Duguma et al., 2014; Naess et al., 2015; von Stechow et al., 2015; Antwi-Agyei et al., 2017a; Di Gregorio et al., 2017; Runhaar et al., 2018), enable the dialogue between local communities and institutional bodies (Colenbrander et al., 2016), and involve non-state actors such as business, local governments and civil society operating across different scales (*robust evidence, high agreement*) (Hajer et al., 2015; Labriet et al., 2015; Hale, 2016; Pelling et al., 2016; Kalafatis, 2017; Lyon, 2018).

5.6.3 Inclusive Processes

Inclusive governance processes are critical for preparing for a 1.5°C warmer world (Fazey et al., 2018; O'Brien, 2018; Patterson et al., 2018). These processes have been shown to serve the interests of diverse groups of people and enhance empowerment of often excluded stakeholders, notably women and youth (MRFCJ, 2015a; Dumont et al., 2017). They also enhance social- and co-learning which, in turn, facilitates accelerated and adaptive management and the scaling up of capacities for resilience building (Ensor and Harvey, 2015; Reij and Winterbottom, 2015; Tschakert et al., 2016; Binam et al., 2017; Dumont et al., 2017; Fazey et al., 2018; Lyon, 2018; O'Brien, 2018), and provides opportunities to blend indigenous, local and scientific knowledge (*robust evidence, high agreement*) (see Chapter 4, Section 4.3.5.5, Box 4.3, Section 5.3) (Antwi-Agyei et al., 2017a; Coe et al., 2017; Thornton and Comberti, 2017) . Such co-learning has been effective in improving deliberative decision-making processes that incorporate different values and world views (Cundill et al., 2014; C. Butler et al., 2016; Ensor, 2016; Fazey et al., 2016; Gorddard et al., 2016; Aipira et al., 2017; Chung Tiam Fook, 2017; Maor et al., 2017), and create space for negotiating diverse interests and preferences (*robust evidence, high agreement*) (O'Brien et al., 2015; Gillard et al., 2016; DeCaro et al., 2017; Harris et al., 2017; Lahn, 2018).

5.6.4 Attention to Issues of Power and Inequality

Societal transformations to limit global warming to 1.5°C and strive for equity and well-being for all are not power neutral (Section 5.5.3). Development preferences are often shaped by powerful interests that determine the direction and pace of change, anticipated benefits and beneficiaries, and acceptable and unacceptable trade-offs (Newell et al., 2014; Fazey et al., 2016; Tschakert et al., 2016; Winkler and Dubash, 2016; Wood et al., 2016b; Karlsson et al., 2017; Quan et al., 2017; Tanner et al., 2017). Each development pathway, including legacies and path dependencies, creates its own set of opportunities and challenges and winners and losers, both within and across countries (Figure 5.5) (*robust evidence, high agreement*) (Mathur et al., 2014; Phillips et al., 2017; Stringer et al., 2017; Wood, 2017; Ficklin et al., 2018; Gajjar et al., 2018).

Addressing the uneven distribution of power is critical to ensure that societal transformation towards a 1.5°C warmer world does not exacerbate poverty and vulnerability or create new injustices but rather encourages equitable transformational change (Patterson et al., 2018). Equitable outcomes are enhanced when they pay attention to just outcomes for those negatively affected by change (Newell et al., 2014; Dilling et al., 2015; Naess et al., 2015; Sovacool et al., 2015; Cervigni and Morris, 2016; Keohane and Victor, 2016) and promote human rights, increase equality and reduce power asymmetries within societies (*robust evidence, high agreement*) (UNRISD, 2016; Robinson and Shine, 2018).

5.6.5 Reconsidering Values

The profound transformations that would be needed to integrate sustainable development and 1.5°C-compatible pathways call for examining the values, ethics, attitudes and behaviours that underpin societies (Hartzell-Nichols, 2017; O'Brien, 2018; Patterson et al., 2018). Infusing values that promote sustainable development (Holden et al., 2017), overcome individual economic interests and go beyond economic growth (Hackmann, 2016), encourage desirable and transformative visions (Tàbara et al., 2018), and care for the less fortunate (Howell and Allen, 2017) is part and parcel of climate-resilient and sustainable development pathways. This entails helping societies and individuals to strive for sufficiency in resource consumption within planetary boundaries alongside sustainable and equitable well-being (O'Neill et al., 2018). Navigating 1.5°C societal transformations, characterized by action from local to global, stresses the core commitment to social justice, solidarity and cooperation, particularly regarding the distribution of responsibilities, rights and mutual obligations between nations (*medium evidence, high agreement*) (Patterson et al., 2018; Robinson and Shine, 2018).

5.7 Synthesis and Research Gaps

The assessment in Chapter 5 illustrates that limiting global warming to 1.5°C above pre-industrial levels is fundamentally connected with achieving sustainable development, poverty eradication and reducing inequalities. It shows that avoided impacts between 1.5°C and 2°C temperature stabilization would make it easier to achieve many aspects of sustainable development, although important risks would remain at 1.5°C (Section 5.2). Synergies between adaptation and mitigation response measures with sustainable development and the SDGs can often be enhanced when attention is paid to well-being and equity while, when unaddressed, poverty and inequalities may be exacerbated (Section 5.3 and 5.4). Climate-resilient development pathways (CRDPs) open up routes towards socially desirable futures that are sustainable and liveable, but concrete evidence reveals complex trade-offs along a continuum of different pathways, highlighting the role of societal values, internal contestations and political dynamics (Section 5.5). The transformations towards sustainable development in a 1.5°C warmer world, in all contexts, involve fundamental societal and systemic changes over time and across scale, and a set of enabling conditions without which the dual goal is difficult if not impossible to achieve (Sections 5.5 and 5.6).

This assessment is supported by growing knowledge on the linkages between a 1.5°C warmer world and different dimensions of sustainable development. However, several gaps in the literature remain:

Limited evidence exists that explicitly examines the real-world implications of a 1.5°C warmer world (and overshoots) as well as avoided impacts between 1.5°C versus 2°C for the SDGs and sustainable development more broadly. Few projections are available for households, livelihoods and communities. And literature on differential localized impacts and their cross-sector interacting and cascading effects with multidimensional patterns of societal vulnerability, poverty and inequalities remains scarce. Hence, caution is needed when global-level conclusions about adaptation and mitigation measures in a 1.5°C warmer world are applied to sustainable development in local, national and regional settings.

Limited literature has systematically evaluated context-specific synergies and trade-offs between and across adaptation and mitigation response measures in 1.5°C-compatible pathways and the SDGs. This hampers the ability to inform decision-making and fair and robust policy packages adapted to different local, regional or national circumstances. More research is required to understand how trade-offs and synergies will intensify or decrease, differentially across geographic regions and time, in a 1.5°C warmer world and as compared to higher temperatures.

Limited availability of interdisciplinary studies also poses a challenge for connecting the socio-economic transformations and the governance aspects of low emissions, climate-resilient transformations. For example, it remains unclear how governance structures enable or hinder different groups of people and countries to negotiate pathway options, values and priorities.

The literature does not demonstrate the existence of 1.5°C-compatible pathways achieving the 'universal and indivisible' agenda of the 17 SDGs, and hence does not show whether and how the nature and pace of changes that would be required to meet 1.5°C climate stabilization could be fully synergetic with all the SDGs.

The literature on low emissions and CRDPs in local, regional and national contexts is growing. Yet the lack of standard indicators to monitor such pathways makes it difficult to compare evidence grounded in specific contexts with differential circumstances, and therefore to derive generic lessons on the outcome of decisions on specific indicators. This knowledge gap poses a challenge for connecting local-level visions with global-level trajectories to better understand key conditions for societal and systems transformations that reconcile urgent climate action with well-being for all.

Frequently Asked Questions

FAQ 5.1 | What are the Connections between Sustainable Development and Limiting Global Warming to 1.5°C above Pre-Industrial Levels?

Summary: *Sustainable development seeks to meet the needs of people living today without compromising the needs of future generations, while balancing social, economic and environmental considerations. The 17 UN Sustainable Development Goals (SDGs) include targets for eradicating poverty; ensuring health, energy and food security; reducing inequality; protecting ecosystems; pursuing sustainable cities and economies; and a goal for climate action (SDG 13). Climate change affects the ability to achieve sustainable development goals, and limiting warming to 1.5°C will help meet some sustainable development targets. Pursuing sustainable development will influence emissions, impacts and vulnerabilities. Responses to climate change in the form of adaptation and mitigation will also interact with sustainable development with positive effects, known as synergies, or negative effects, known as trade-offs. Responses to climate change can be planned to maximize synergies and limit trade-offs with sustainable development.*

For more than 25 years, the United Nations (UN) and other international organizations have embraced the concept of sustainable development to promote well-being and meet the needs of today's population without compromising the needs of future generations. This concept spans economic, social and environmental objectives including poverty and hunger alleviation, equitable economic growth, access to resources, and the protection of water, air and ecosystems. Between 1990 and 2015, the UN monitored a set of eight Millennium Development Goals (MDGs). They reported progress in reducing poverty, easing hunger and child mortality, and improving access to clean water and sanitation. But with millions remaining in poor health, living in poverty and facing serious problems associated with climate change, pollution and land-use change, the UN decided that more needed to be done. In 2015, the UN Sustainable Development Goals (SDGs) were endorsed as part of the 2030 Agenda for Sustainable Development. The 17 SDGs (Figure FAQ 5.1) apply to all countries and have a timeline for success by 2030. The SDGs seek to eliminate extreme poverty and hunger; ensure health, education, peace, safe water and clean energy for all; promote inclusive and sustainable consumption, cities, infrastructure and economic growth; reduce inequality including gender inequality; combat climate change and protect oceans and terrestrial ecosystems.

Climate change and sustainable development are fundamentally connected. Previous IPCC reports found that climate change can undermine sustainable development, and that well-designed mitigation and adaptation responses can support poverty alleviation, food security, healthy ecosystems, equality and other dimensions of sustainable development. Limiting global warming to 1.5°C would require mitigation actions and adaptation measures to be taken at all levels. These adaptation and mitigation actions would include reducing emissions and increasing resilience through technology and infrastructure choices, as well as changing behaviour and policy.

These actions can interact with sustainable development objectives in positive ways that strengthen sustainable development, known as synergies. Or they can interact in negative ways, where sustainable development is hindered or reversed, known as trade-offs.

An example of a synergy is sustainable forest management, which can prevent emissions from deforestation and take up carbon to reduce warming at reasonable cost. It can work synergistically with other dimensions of sustainable development by providing food (SDG 2) and clean water (SDG 6) and protecting ecosystems (SDG 15). Other examples of synergies are when climate adaptation measures, such as coastal or agricultural projects, empower women and benefit local incomes, health and ecosystems.

An example of a trade-off can occur if ambitious climate change mitigation compatible with 1.5°C changes land use in ways that have negative impacts on sustainable development. An example could be turning natural forests, agricultural areas, or land under indigenous or local ownership to plantations for bioenergy production. If not managed carefully, such changes could undermine dimensions of sustainable development by threatening food and water security, creating conflict over land rights and causing biodiversity loss. Another trade-off could occur for some countries, assets, workers and infrastructure already in place if a switch is made from fossil fuels to other energy sources without adequate planning for such a transition. Trade-offs can be minimized if effectively managed, as when care is taken to improve bioenergy crop yields to reduce harmful land-use change or where workers are retrained for employment in lower carbon sectors.

(continued on next page)

5

FAQ 5.1 (continued)

Limiting temperature increase to 1.5°C can make it much easier to achieve the SDGs, but it is also possible that pursuing the SDGs could result in trade-offs with efforts to limit climate change. There are trade-offs when people escaping from poverty and hunger consume more energy or land and thus increase emissions, or if goals for economic growth and industrialization increase fossil fuel consumption and greenhouse gas emissions. Conversely, efforts to reduce poverty and gender inequalities and to enhance food, health and water security can reduce vulnerability to climate change. Other synergies can occur when coastal and ocean ecosystem protection reduces the impacts of climate change on these systems. The sustainable development goal of affordable and clean energy (SDG 7) specifically targets access to renewable energy and energy efficiency, which are important to ambitious mitigation and limiting warming to 1.5°C.

The link between sustainable development and limiting global warming to 1.5°C is recognized by the SDG for climate action (SDG 13), which seeks to combat climate change and its impacts while acknowledging that the United Nations Framework Convention on Climate Change (UNFCCC) is the primary international, intergovernmental forum for negotiating the global response to climate change.

The challenge is to put in place sustainable development policies and actions that reduce deprivation, alleviate poverty and ease ecosystem degradation while also lowering emissions, reducing climate change impacts and facilitating adaptation. It is important to strengthen synergies and minimize trade-offs when planning climate change adaptation and mitigation actions. Unfortunately, not all trade-offs can be avoided or minimized, but careful planning and implementation can build the enabling conditions for long-term sustainable development.

FAQ 5.1, Figure 1 | Climate change action is one of the United Nations Sustainable Development Goals (SDGs) and is connected to sustainable development more broadly. Actions to reduce climate risk can interact with other sustainable development objectives in positive ways (synergies) and negative ways (trade-offs).

Frequently Asked Questions

FAQ 5.2 | What are the Pathways to Achieving Poverty Reduction and Reducing Inequalities while Reaching a 1.5°C World?

Summary: *There are ways to limit global warming to 1.5°C above pre-industrial levels. Of the pathways that exist, some simultaneously achieve sustainable development. They entail a mix of measures that lower emissions and reduce the impacts of climate change, while contributing to poverty eradication and reducing inequalities. Which pathways are possible and desirable will differ between and within regions and nations. This is due to the fact that development progress to date has been uneven and climate-related risks are unevenly distributed. Flexible governance would be needed to ensure that such pathways are inclusive, fair and equitable to avoid poor and disadvantaged populations becoming worse off. Climate-resilient development pathways (CRDPs) offer possibilities to achieve both equitable and low-carbon futures.*

Issues of equity and fairness have long been central to climate change and sustainable development. Equity, like equality, aims to promote justness and fairness for all. This is not necessarily the same as treating everyone equally, since not everyone comes from the same starting point. Often used interchangeably with fairness and justice, equity implies implementing different actions in different places, all with a view to creating an equal world that is fair for all and where no one is left behind.

The Paris Agreement states that it 'will be implemented to reflect equity… in the light of different national circumstances' and calls for 'rapid reductions' of greenhouse gases to be achieved 'on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty'. Similarly, the UN SDGs include targets to reduce poverty and inequalities, and to ensure equitable and affordable access to health, water and energy for all.

Equity and fairness are important for considering pathways that limit warming to 1.5°C in a way that is liveable for every person and species. They recognize the uneven development status between richer and poorer nations, the uneven distribution of climate impacts (including on future generations) and the uneven capacity of different nations and people to respond to climate risks. This is particularly true for those who are highly vulnerable to climate change, such as indigenous communities in the Arctic, people whose livelihoods depend on agriculture or coastal and marine ecosystems, and inhabitants of small island developing states. The poorest people will continue to experience climate change through the loss of income and livelihood opportunities, hunger, adverse health effects and displacement.

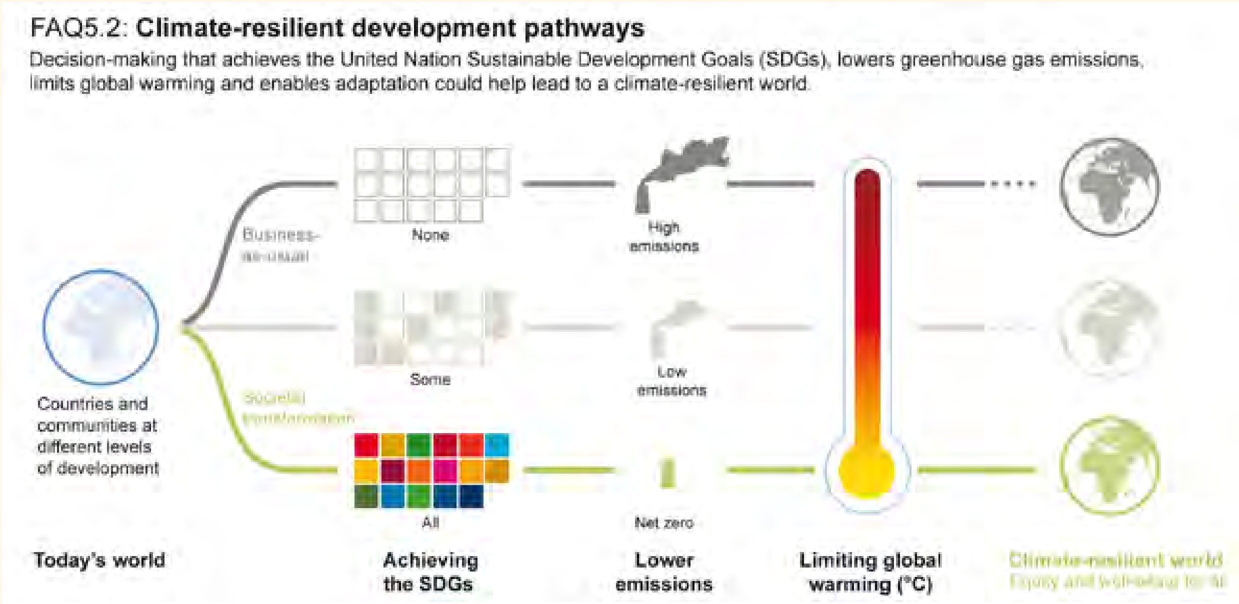
Well-planned adaptation and mitigation measures are essential to avoid exacerbating inequalities or creating new injustices. Pathways that are compatible with limiting warming to 1.5°C and aligned with the SDGs consider mitigation and adaptation options that reduce inequalities in terms of who benefits, who pays the costs and who is affected by possible negative consequences. Attention to equity ensures that disadvantaged people can secure their livelihoods and live in dignity, and that those who experience mitigation or adaptation costs have financial and technical support to enable fair transitions.

CRDPs describe trajectories that pursue the dual goal of limiting warming to 1.5°C while strengthening sustainable development. This includes eradicating poverty as well as reducing vulnerabilities and inequalities for regions, countries, communities, businesses and cities. These trajectories entail a mix of adaptation and mitigation measures consistent with profound societal and systems transformations. The goals are to meet the short-term SDGs, achieve longer-term sustainable development, reduce emissions towards net zero around the middle of the century, build resilience and enhance human capacities to adapt, all while paying close attention to equity and well-being for all.

The characteristics of CRDPs will differ across communities and nations, and will be based on deliberations with a diverse range of people, including those most affected by climate change and by possible routes towards transformation. For this reason, there are no standard methods for designing CRDPs or for monitoring their progress towards climate-resilient futures. However, examples from around the world demonstrate that flexible and inclusive governance structures and broad participation often help support iterative decision-making, continuous learning and experimentation. Such inclusive processes can also help to overcome weak institutional arrangements and power structures that may further exacerbate inequalities.

(continued on next page)

FAQ 5.2 (continued)



FAQ 5.2, Figure 1 | Climate-resilient development pathways (CRDPs) describe trajectories that pursue the dual goals of limiting warming to 1.5°C while strengthening sustainable development. Decision-making that achieves the SDGs, lowers greenhouse gas emissions and limits global warming could help lead to a climate-resilient world, within the context of enhancing adaptation.

Ambitious actions already underway around the world can offer insight into CRDPs for limiting warming to 1.5°C. For example, some countries have adopted clean energy and sustainable transport while creating environmentally friendly jobs and supporting social welfare programmes to reduce domestic poverty. Other examples teach us about different ways to promote development through practices inspired by community values. For instance, *Buen Vivir*, a Latin American concept based on indigenous ideas of communities living in harmony with nature, is aligned with peace; diversity; solidarity; rights to education, health, and safe food, water, and energy; and well-being and justice for all. The Transition Movement, with origins in Europe, promotes equitable and resilient communities through low-carbon living, food self-sufficiency and citizen science. Such examples indicate that pathways that reduce poverty and inequalities while limiting warming to 1.5°C are possible and that they can provide guidance on pathways towards socially desirable, equitable and low-carbon futures.

5

Table 5.2 | Mitigation – SDG table

Social-Demand

1 NO POVERTY

Sector	Mitigation measure	Target	Interaction	Score	Evidence	Agreement	Confidence	Description	References
Industry	Accelerating Energy Efficiency Improvement	Reduces Poverty	↑	[+2]	📖	☺	★	% of people living below poverty line declines from 49% to 18% in South African context.	Altieri et al., 2016
Industry	Low-carbon Fuel Switch			[0]				No direct interaction	
Industry	Decarbonization/CCS/CCU			[0]				No direct interaction	

2 ZERO HUNGER

Sector	Mitigation measure	Target	Interaction	Score	Evidence	Agreement	Confidence	Description	References
Industry	Accelerating Energy Efficiency Improvement			[0]				No direct interaction	
Industry	Low-carbon Fuel Switch			[0]				No direct interaction	
Industry	Decarbonization/CCS/CCU			[0]				No direct interaction	

3 GOOD HEALTH AND WELL-BEING

Sector	Mitigation measure	Target	Interaction	Score	Evidence	Agreement	Confidence	Description	References
Industry	Accelerating Energy Efficiency Improvement	Air, Water Pollution Reduction and Better Health (3.9)	↑	[+2]	📖📖	☺☺	★★	People living in deprived communities feel positive and predict considerable financial savings. Efficiency changes in the industrial sector that lead to reduced energy demand can lead to reduced requirements on energy supply. As water is used to convert energy into useful forms, the reduction in industrial demand is anticipated to reduce water consumption and wastewater, resulting in more clean water for other sectors and the environment. In extractive industries there are trade-off unless strategically managed. Behavioural changes in the industrial sector that lead to reduced energy demand can lead to reduced requirements on energy supply. As water is used to convert energy into useful forms, the reduction in industrial demand is anticipated to reduce water consumption and wastewater, resulting in more clean water for other sectors and the environment.	Vassolo and Döll, 2005; Xi et al., 2013; Nguyen et al., 2014; Holland et al., 2015; Zhang et al., 2015; Fricko et al., 2016
Industry	Low-carbon Fuel Switch	Water and Air Pollution Reduction and Better Health (3.9)	↑	[+2]	📖📖	☺☺	★★	Industries are becoming suppliers of energy, waste heat, water and roof tops for solar energy generation, and hence helping to improve air and water quality.	Vassolo and Döll, 2005; Nguyen et al., 2014; Holland et al., 2015; Karner et al., 2015; Fricko et al., 2016
Industry	Decarbonization/CCS/CCU	Disease and Mortality (3.1/3.2/3.3/3.4)	↓	[-1]	📖📖	☺☺☺	★★★	There is a risk of CO_2 leakage both from geological formations as well as from the transportation infrastructure from source to sequestration locations.	Wang and Jaffe, 2004; Hertwich et al., 2008; Apps et al., 2010; Veltman et al., 2010; Koornneef et al., 2011; Singh et al., 2011; Siirila et al., 2012; Atchley et al., 2013; Corsten et al., 2013; IPCC, 2014

4 QUALITY EDUCATION

Sector	Mitigation measure	Target	Interaction	Score	Evidence	Agreement	Confidence	Description	References
Industry	Accelerating Energy Efficiency Improvement	Technical Education, Vocational Training, Education for Sustainability (4.3/4.4/4.5/4.7)	↑	[+1]	📖📖	☺☺	★★	Awareness, knowledge, technical and managerial capability are closely linked, energy audit, information for trade unions, product/appliance labeling help in sustainability education.	Apeaning and Thollander, 2013; Fernando and Evans, 2015; Roy et al., 2018
Industry	Low-carbon Fuel Switch	Technical Education, Vocational Training, Education for Sustainability (4.b/4.7)	↑	[+1]	📖📖	☺☺	★★	New technology deployment creates demand for awareness and knowledge with technical and managerial capability; otherwise acts as barrier for rapid expansion.	Apeaning and Thollander, 2013; Fernando and Evans, 2015; Roy et al., 2018
Industry	Decarbonization/CCS/CCU			[0]				No direct interaction	

Social-Demand (continued)

Sector	Mitigation option	SDG	Interaction	Score	Evidence	Agreement	Confidence	Interaction description	References
Buildings	Behavioural Response	1 No Poverty: Poverty Reduction via Financial Savings (1.1)	↑	[+2]	📖	☺	★	People living in deprived communities feel positive and predict considerable financial savings.	Scott et al., 2014
Buildings	Behavioural Response	2 Zero Hunger		[0]				No direct interaction	
Buildings	Behavioural Response	3 Good Health and Well-being: Improved Warmth and Comforts	↑	[+2]	📖📖📖	☺☺☺	★★★	Home occupants reported warmth as the most important aspect of comfort which was largely temperature-related and low in energy costs. Residents living in deprived areas expect improved warmth in their properties after energy efficiency measures are employed.	Huebner et al., 2013; Yue et al., 2013; Scott et al., 2014; Zhao et al., 2017
Buildings	Behavioural Response	4 Quality Education		[0]				No direct interaction	
Buildings	Accelerating Energy Efficiency Improvement	1 No Poverty: Poverty and Development (1.1/1.2/1.3/1.4)	↑ / ↓	[+2,-1]	📖📖📖	☺☺☺	★★★	Energy efficiency interventions lead to cost savings which are realized due to reduced energy bills that further lead to poverty reduction. Participants with low incomes experience greater benefits. 'Energy efficiency and biomass strategies benefitted the poor more than wind and solar, whose benefits are captured by industry. Carbon mitigation can increase or decrease inequalities. The distributional costs of new energy policies (e.g., supporting renewables and energy efficiency) are dependent on instrument design. If costs fall disproportionately on the poor, then this could impair progress towards universal energy access and, by extension, counteract the fight to eliminate poverty. (Quote from McCollum et al., 2018).	Casillas and Kammen, 2012; Hirth and Ueckerdt, 2013; Jakob and Steckel, 2014; Maidment et al., 2014; Scott et al., 2014; Fay et al., 2015; Cameron et al., 2016; Hallegatte et al., 2016b; Berrueta et al., 2017; McCollum et al., 2018
Buildings	Accelerating Energy Efficiency Improvement	2 Zero Hunger: Food Security (2.1)	↑	[+2]	📖	☺	★	Using the improved stoves supports local food security and has significantly impacted on food security. By making fuel last longer, the improved stoves help improve food security and also provide a better buffer against fuel shortages induced by climate change-related events such as droughts, floods or hurricanes (Berrueta et al. 2017).	Berrueta et al., 2017
Buildings	Accelerating Energy Efficiency Improvement	3 Good Health and Well-being: Healthy Lives and Well-being for All at All Ages (3.2/3.9)	↑	[+2]	📖📖📖📖	☺☺☺☺	★★★★	Efficient stoves improve health, especially for indigenous and poor rural communities. Household energy efficiency has positive health impacts on children's respiratory health, weight and susceptibility to illness, and the mental health of adults. Household energy efficiency improves winter warmth, lowers relative humidity with benefits for cardiovascular and respiratory health. Further improved indoor air quality by thermal regulation and occupant comfort are realised. However, in one instance, negative health impacts (asthma) of increased household energy efficiency were also noted when housing upgrades took place without changes in occupant behaviours. Home occupants reported warmth as the most important aspect of comfort which was largely temperature-related and low in energy costs. Residents living in the deprived areas expect improved warmth in their properties after energy efficiency measures are employed.	Djamila et al., 2013; Huebner et al., 2013; Yue et al., 2013; Bhojvaid et al., 2014; Derbez et al., 2014; Maidment et al., 2014; Scott et al., 2014; Cameron et al., 2015; Liddell and Guiney, 2015; Sharpe et al., 2015; Wells et al., 2015; Willand et al., 2015; Berrueta et al., 2017; Zhao et al., 2017
Buildings	Accelerating Energy Efficiency Improvement	4 Quality Education: Equal Access to Educational Institutions (4.1/4.2/4.3/4.5)	↑	[+2]	📖	☺	★	Household energy efficiency measures reduce school absences for children with asthma due to indoor pollution.	Maidment et al., 2014
Buildings	Improved Access and Fuel Switch to Modern Low-carbon Energy	1 No Poverty: Poverty and Development (1.1/1.2/1.3/1.4)	↑	[+2]	📖📖📖	☺☺☺	★★★★	Access to modern energy forms (electricity, clean stoves, high-quality lighting) is fundamental to human development since the energy services made possible by them help alleviate chronic and persistent poverty. Strength of the impact varies in the literature. (Quote from McCollum et al., 2018)	Kirubi et al., 2009; Casillas and Kammen, 2010; Cook, 2011; Pachauri et al., 2012; Pode, 2013; Pueyo et al., 2013; Zulu and Richardson, 2013; Bonan et al., 2014; Rao et al., 2014; Burlig and Preonas, 2016; McCollum et al., 2018
Buildings	Improved Access and Fuel Switch to Modern Low-carbon Energy	2 Zero Hunger: Food Security and Agricultural Productivity (2.1/2.4)	~ / ↓	[0,-1]	📖📖	☺☺☺	★★	Modern energy access is critical to enhance agricultural yields/productivity, decrease post-harvest losses and mechanize agri-processing – all of which can aid food security. However, large-scale bioenergy and food production may compete for scarce land and other inputs (e.g., water, fertilizers), depending on how and where biomass supplies are grown and the indirect land use change impacts that result. If not implemented thoughtfully, this could lead to higher food prices globally, and thus reduce access to affordable food for the poor. Enhanced agricultural productivities can ameliorate the situation by allowing as much bioenergy to be produced on as little land as possible.	Cabraal et al., 2005; Tilman et al., 2009; van Vuuren et al., 2009; Asaduzzaman et al., 2010; Finco and Doppler, 2010; Msangi et al., 2010; Smith et al., 2013, 2014; Lotze-Campen et al., 2014; Hasegawa et al., 2015; Sola et al., 2016; McCollum et al., 2018
Buildings	Improved Access and Fuel Switch to Modern Low-carbon Energy	3 Good Health and Well-being: Disease and Mortality (3.1/3.2/3.3/3.4)	↑	[+2]	📖📖📖	☺☺☺	★★★★	Access to modern energy services can contribute to fewer injuries and diseases related to traditional solid fuel collection and burning, as well as utilization of kerosene lanterns. Access to modern energy services can facilitate improved health care provision, medicine and vaccine storage, utilization of powered medical equipment, and dissemination of health-related information and education. Such services can also enable thermal comfort in homes and contribute to food preservation and safety. (Quote from McCollum et al., 2018)	Lam et al., 2012; Lim et al., 2012; Smith et al., 2013; Aranda et al., 2014; McCollum et al., 2018
Buildings	Improved Access and Fuel Switch to Modern Low-carbon Energy	4 Quality Education: Equal Access to Educational Institutions (4.1/4.2/4.3/4.5)	↑	[+1]	📖	☺☺☺	★★	Access to modern energy is necessary for schools to have quality lighting and thermal comfort, as well as modern information and communication technologies. Access to modern lighting and energy allows for studying after sundown and frees constraints on time management that allow for higher school enrolment rates and better literacy outcomes. (Quote from McCollum et al., 2018)	Lipscomb et al., 2013; van de Walle et al., 2013; McCollum et al., 2018

Transport	SDG	Target	Interaction	Score	Evidence	Agreement	Confidence	Description	References
Behavioural Response	SDG 1 (No Poverty)	Equal Right to Economic Resources Access Basic Services (1.1/1.4/1.a/1.b)	↑/↓	[+2,-1]	📖📖📖	☺☺☺	★★★	The costs of daily mobility can have important economic stress impacts, not only impacting carless families with low-mobility, but in countries with high levels of car dependence, the costs of motoring can be burdensome, raising questions of affordability for households with limited economic resources. During economic crisis, public transport authorities may react by reducing levels of service and increasing fares, likely exacerbating the situation for low-income households.	Dodson et al., 2004; Cascajo et al., 2017
Behavioural Response	SDG 2 (Zero Hunger)	Ensure Access to Safe Nutritious Food (2.1/2.2)	↑	[+2]	📖	☺	★★★	Low-income community residents (non-white) who lack local access to affordable, quality sources of nutrition have to travel outside their immediate neighbourhood to find better sources of food to feed themselves and their families. Lack of locally available healthy food often exacerbates the rates of obesity in many of these communities since it is often difficult or expensive to travel long distances on a regular basis to shop for food.	Clifton, 2004; Hillier, 2011; Krukowski et al., 2013; LeDoux and Vojnovic, 2013; Ghosh-Dastidar et al., 2014; Zenk et al., 2015; Lowery et al., 2016
Behavioural Response	SDG 3 (Good Health and Well-being)	Road Traffic Accidents (3.4/3.6)	↑/↓	[+2,-1]	📖📖📖	☺☺☺	★★	Active travel modes, such as walking and cycling, represent strategies not only for boosting energy efficiency but also, potentially, for improving health and well-being (e.g., lowering rates of diabetes, obesity, heart disease, dementia and some cancers). However, a risk associated with these measures is that they could increase rates of road traffic accidents, if the existing infrastructure is unsatisfactory. Overall health effects will depend on the severity of the injuries sustained from these potential accidents relative to the health benefits accruing from increased exercise (McCollum et al., 2018).	Woodcock et al., 2009; Creutzig et al., 2012; Haines and Dora, 2012; Saunders et al., 2013; Shaw et al., 2014, 2017; Chakrabarti and Shin, 2017; Hwang et al., 2017; McCollum et al., 2018
Behavioural Response	SDG 4 (Quality Education)	Equal Safe Access to Educational Institutions (4.1/4.2/4.3/4.5)	↑	[+1]	📖	☺☺☺	★★	Poor road quality affects school travel safety, so collaborative efforts need to address safety issues from a dual perspective, first by working to change the existing infrastructure and use of roads to better address the traffic problems that children currently face walking to school, and then to better situate schools and control the roadways and land uses around them in the future.	Yu, 2015
Accelerating Energy Efficiency Improvement	SDG 1 (No Poverty)	End Poverty in all its Forms Everywhere (1.1/1.4/1.a/1.b)	↑/↓	[+2,-1]	📖📖📖	☺☺☺	★★★	Decarbonization of public buses in Sweden is receiving attention more than efficiency improvement. With more electrification, electricity prices go up and affordability can worsen for the poor unless redistributive policies are in place.	Xylia and Silveira, 2017
Accelerating Energy Efficiency Improvement	SDG 2 (Zero Hunger)			[0]				No direct interaction	
Accelerating Energy Efficiency Improvement	SDG 3 (Good Health and Well-being)	Reduce Illnesses from Hazardous Air, Water and Soil Pollution (3.9)	↑	[+2]	📖📖📖	☺☺☺	★★★	Locally relevant policies targeting traffic reductions and ambitious diffusion of electric vehicles results in measured changes in non-climatic exposure for population, including ambient air pollution, physical activity and noise. The transition to low-carbon equitable and sustainable transport can be fostered by numerous short- and medium-term strategies that would benefit energy security, health, productivity and sustainability. An evidence-based approach that takes into account GHG emissions, ambient air pollutants, economic factors (affordability, cost optimization), social factors (poverty alleviations, public health benefits) and political acceptability is needed to tackle these challenges.	Figueroa et al., 2014; Schucht et al., 2015; Klausbruckner et al., 2016; Peng et al., 2017
Accelerating Energy Efficiency Improvement	SDG 4 (Quality Education)			[0]				No direct interaction	
Improved Access and Fuel Switch to Modern Low-carbon Energy	SDG 1 (No Poverty)	End Poverty in all its Forms Everywhere (1.1/1.4/1.a/1.b)	↑/↓	[+2,-1]	📖📖📖	☺☺☺	★★★	Increasingly volatile global oil prices have raised concerns for the vulnerability of households to fuel price increases. Pricing measures as a key component of sustainable transport policy need to consider equity. Pro-poor mitigation policies are needed to reduce climate impact and reduce threat; for example, investing more and better in infrastructure by leveraging private resources and using designs that account for future climate change and the related uncertainty. Communities in poor areas cope with and adapt to multiple-stressors including climate change. Coping strategies provide short-term relief but in the long-term may negatively affect development goals. And responses generate a trade-off between adaptation, mitigation and development. For African cities with slums, due to high commuting costs, many walk to work places which limit access. In Latin America triple informality leading to low productivity and living standards.	Dodson and Sipe, 2008; Suckall et al., 2014; Hallegatte et al., 2016a; Klausbruckner et al., 2016; CAF, 2017; Lall et al., 2017
Improved Access and Fuel Switch to Modern Low-carbon Energy	SDG 2 (Zero Hunger)	Ensure Access to Food Security (2.1/2.3/2.a/2.b/2.c)	~	[0]	📖	☺	★	21 projects aiming at resilient transport infrastructure development to improve access (e.g., C40 Cities Clean Bus Declaration, UITP Declaration on Climate Leadership, Cycling Delivers on the Global Goals, Global Sidewalk Challenge) do not substantially contribute to realizing the (indirect) transport targets with mostly a rural focus: agricultural productivity (SDG 2) and access to safe drinking water (SDG 6).	SLoCaT, 2017
Improved Access and Fuel Switch to Modern Low-carbon Energy	SDG 3 (Good Health and Well-being)	Reduce Illnesses from Hazardous Air Pollution (3.9)	↑	[+2]	📖	☺	★	Projects aiming at resilient transport infrastructure development (e.g., C40 Cities Clean Bus Declaration, UITP Declaration on Climate Leadership, Cycling Delivers on the Global Goals, Global Sidewalk Challenge) are targeted at reducing air pollution; electric vehicles using electricity from renewables or low carbon sources combined with e-mobility options such as trolley buses, metros, trams and electro buses, as well as promoting walking and biking, especially for short distances, need consideration.	Ajanovic, 2015; SLoCaT, 2017
Improved Access and Fuel Switch to Modern Low-carbon Energy	SDG 4 (Quality Education)			[0]				No direct interaction	

Replacing Coal	SDG	Targets	Interaction	Score	Evidence	Agreement	Confidence	Text	References
Non-biomass Renewables - solar, wind, hydro	1 No Poverty	Poverty and Development (1.1/1.2/1.3/1.4)	↑	[+2]	🕮🕮🕮	☺☺☺	★★★	Deployment of renewable energy and improvements in energy efficiency globally will aid climate change mitigation efforts, and this, in turn, can help to reduce the exposure of the world's poor to climate-related extreme events, negative health impacts and other environmental shocks (McCollum et al., 2018).	Riahi et al., 2012; IPCC, 2014; Hallegatte et al., 2016b; McCollum et al., 2018
Non-biomass Renewables - solar, wind, hydro	2 Zero Hunger			[0]				No direct interaction	
Non-biomass Renewables - solar, wind, hydro	3 Good Health and Well-being	Air Pollution (3.9)	↑	[+2]	🕮🕮🕮	☺☺☺	★★★★	Promoting most types of renewables and boosting efficiency greatly aids the achievement of targets to reduce local air pollution and improve air quality; however, the order of magnitude of the effects, both in terms of avoided emissions and monetary valuation, varies significantly between different parts of the world. Benefits would especially accrue to those living in the dense urban centres of rapidly developing countries. Utilization of biomass and biofuels might not lead to any air pollution benefits, however, depending on the control measures applied. In addition, household air quality can be significantly improved through lowered particulate emissions from access to modern energy services (McCollum et al., 2018).	Haines et al., 2007; Nemet et al., 2010; Kaygusuz, 2011; Riahi et al., 2012; van Vliet et al., 2012; Anenberg et al., 2013; Rafaj et al., 2013; Rao et al., 2013, 2016; West et al., 2013; Chaturvedi and Shukla, 2014; Rose et al., 2014; Smith and Sagar, 2014; IEA, 2016; McCollum et al., 2018
Non-biomass Renewables - solar, wind, hydro	4 Quality Education	Vocational Trainig, Education for Sustainability (4.b/4.7)	↑	[+1]	🕮	☺	★	Decentralized renewable energy systems (e.g., home- or village-scale solar power) can support education and vocational training.	Anderson et al., 2017
Increased Use of Biomass	1 No Poverty	Poverty and Development (1.1/1.2/1.3/1.4)	↑/↓	[+2,-2]	🕮🕮	☺☺	★	Large-scale bioenergy production could lead to the creation of agricultural jobs, as well as higher farm wages and more diversified income streams for farmers. Modern energy access can make marginal lands more cultivable, thus potentially generating on-farm jobs and incomes; on the other hand, greater farm mechanization can also displace labour. However, large-scale bioenergy production could alter the structure of global agricultural markets in a way that is, potentially, unfavourable to small-scale food producers. See SDG2 (McCollum et al., 2018).	Balishter and Singh, 1991; Gohin, 2008; de Moraes et al., 2010; van der Horst and Vermeylen, 2011; Corbera and Pascual, 2012; Rud, 2012; Creutzig et al., 2013; Davis et al., 2013; Satolo and Bacchi, 2013; Muys et al., 2014; Ertem et al., 2017; McCollum et al., 2018
Increased Use of Biomass	2 Zero Hunger	Farm Employment and Incomes (2.3)	↑/↓	[+2,-2]	🕮🕮🕮	☺☺☺	★★★	Large-scale bioenergy production could lead to the creation of agricultural jobs, as well as higher farm wages and more diversified income streams for farmers. Modern energy access can make marginal lands more cultivable, thus potentially generating on-farm jobs and incomes; on the other hand, greater farm mechanization can also displace labour. However, large-scale bioenergy production could alter the structure of global agricultural markets in a way that is, potentially, unfavourable to small-scale food producers. The distributional effects of bioenergy production are underexplored in the literature (McCollum et al., 2018).	Balishter and Singh, 1991; Gohin, 2008; de Moraes et al., 2010; van der Horst and Vermeylen, 2011; Corbera and Pascual, 2012; Rud, 2012; Creutzig et al., 2013; Davis et al., 2013; Satolo and Bacchi, 2013; Muys et al., 2014; Ertem et al., 2017; McCollum et al., 2018
Increased Use of Biomass	3 Good Health and Well-being	Disease and Mortality (3.1/3.2/3.3/3.4), Air Pollution (3.9)	↑	[+2]	🕮🕮🕮	☺☺☺	★★★	Replacing coal by biomass can reduce adverse impacts of upstream supply-chain activities, in particular local air and water pollution, and prevent coal mining accidents. Improvements to local air pollution in power generation compared to coal-fired power plants depend on the technology and fuel of biomass power plants, but could be significant when switching from outdated coal combustion technologies to state-of-the-art biogas power generation.	IPCC, 2005, 2014; Miller et al., 2007; Hertwich et al., 2008; de Best-Waldhober et al., 2009; Shackley et al., 2009; Wallquist et al., 2009, 2010; Wong-Parodi and Ray, 2009; Chan and Griffiths, 2010; Veltman et al., 2010; Epstein et al., 2011; Koornneef et al., 2011; Reiner and Nuttall, 2011; Singh et al., 2011; Ashworth et al., 2012; Burgherr et al., 2012; Chen et al., 2012; Asfaw et al., 2013; Corsten et al., 2013; Einsiedel et al., 2013
Increased Use of Biomass	4 Quality Education			[0]				No direct interaction	

Social-Supply (continued)

		1 No Poverty					2 Zero Hunger					3 Good Health and Well-Being					4 Quality Education				
		Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence
Replacing Coal	**Nuclear/Advanced Nuclear**											**Disease and Mortality (3.1/3.2/3.3/3.4)**									
			[0]					[0]				↓	[-1]	📖📖📖	☺☺☺	★★★		[0]			
				No direct interaction					No direct interaction			In spite of the industry's overall safety track record, a non-negligible risk for accidents in nuclear power plants and waste treatment facilities remains. The long-term storage of nuclear waste is a politically fraught subject, with no large-scale long-term storage operational worldwide. Negative impacts from upstream uranium mining and milling are comparable to those of coal, hence replacing fossil fuel combustion by nuclear power would be neutral in that aspect. Increased occurrence of childhood leukaemia in populations living within 5 km of nuclear power plants was identified by some studies, even though a direct causal relation to ionizing radiation could not be established and other studies could not confirm any correlation (*low evidence/agreement* on this issue).							No direct interaction		
												Abdelouas, 2006; Cardis et al., 2006; Kaatsch et al., 2008; Al-Zoughool and Krewski, 2009; Heinävaara et al., 2010; Schnelzer et al., 2010; Brugge and Buchner, 2011; Møller and Mousseau, 2011; Møller et al., 2011, 2012; Moomaw et al., 2011; UNSCEAR, 2011; Sermage-Faure et al., 2012; Ten Hoeve and Jacobson, 2012; Tirmarche et al., 2012; Hiyama et al., 2013; Mousseau and Møller, 2013; Smith et al., 2013; WHO, 2013; IPCC, 2014; von Stechow et al., 2016									
	CCS: Bioenergy	**Poverty and Development (1.1/1.2/1.3/1.4)**					**Farm Employment and Incomes (2.3)**					**Disease and Mortality (3.1/3.2/3.3/3.4)**									
		↑/↓	[+2,-2]	📖📖	☺☺	★	↑/↓	[+1,-2]	📖📖📖	☺☺☺	★★★	↑/↓	[+2,-1]	📖📖	☺☺☺	★★★		[0]			
		See effects of increased bioenergy use.					See increased use of biomass effects. In addition, the concern that more bioenergy (for BECCS) necessarily leads to unacceptably high food prices is not founded on large agreement in the literature. AR5, for example, finds a significantly lower effect of large-scale bioenergy deployment on food prices by mid-century than the effect of climate change on crop yields. Also, Muratori et al. (2016) show that BECCS reduces the upward pressure on food crop prices by lowering carbon prices and lowering the total biomass demand in climate change mitigation scenarios. On the other hand, competition for land use may increase food prices and thereby increase risk of hunger. Use of agricultural residue for bioenergy can reduce soil carbon, thereby threatening agricultural productivity.					See positive impacts of increased biomass use. At the same time, there is a non-negligible risk of CO_2 leakage both from geological formations as well as from the transportation infrastructure from source to sequestration locations.							No direct interaction		
							See literature on increased biomass use: IPCC, 2014; Muratori et al., 2016; Dooley and Kartha, 2018					Wang and Jaffe, 2004; Hertwich et al., 2008; Apps et al., 2010; Veltman et al., 2010; Koornneef et al., 2011; Singh et al., 2011; Siirila et al., 2012; Atchley et al., 2013; Corsten et al., 2013; IPCC, 2014									
Advanced Coal	**CCS: Fossil**											**Disease and Mortality (3.1/3.2/3.3/3.4)**									
			[0]					[0]				↓	[-1]	📖📖	☺☺☺	★★★		[0]			
				No direct interaction					No direct interaction			The use of fossil CCS implies continued adverse impacts of upstream supply-chain activities in the coal sector, and because of lower efficiency of CCS coal power plants, upstream impacts and local air pollution are likely to be exacerbated. Furthermore, there is a non-negligible risk of CO_2 leakage from geological storage or the CO_2 transport infrastructure from source to sequestration location.							No direct interaction		
												Wang and Jaffe, 2004; Hertwich et al., 2008; Apps et al., 2010; Veltman et al., 2010; Koornneef et al., 2011; Singh et al., 2011; Siirila et al., 2012; Atchley et al., 2013; Corsten et al., 2013; IPCC, 2014									

1 NO POVERTY

Agriculture and Livestock	Target	Interaction	Score	Evidence	Agreement	Confidence	Description	References
Behavioural Response: Sustainable Healthy Diets and Reduced Food Waste	Poverty and Development (1.1/1.2/1.3/1.4)	~ / ↓	[0,-1]	📖📖	☺☺☺	★★	Cutting livestock consumption can increase food security for some if land grows food not feed, but can also undermine livelihoods and culture where livestock has long been the best use of land, such as in parts of Sub-Saharan Africa.	IPCC, 2014
Land-based GHG Reduction and Soil Carbon Sequestration	Poverty and Development (1.1/1.2/1.3/1.4)	↑	[+2]	📖📖📖📖	☺☺☺☺	★★★★	Many CSA interventions aim to improve rural livelihoods, thereby contributing to poverty alleviation. Agroforestry or integrated crop–livestock–biogas systems can substitute costly, external inputs, saving on household expenditures – or even lead to the selling of some of the manure, providing the farmer with extra income, leading to increased adaptive capacity (Bogdanski, 2012).	Branca et al., 2011; Bogdanski, 2012; Scherr et al., 2012; Vermeulen et al., 2012; Campbell et al., 2014; Lipper et al., 2014; Mbow et al., 2014; Steenwerth et al., 2014; Hammond et al., 2017
Greenhouse Gas Reduction from Improved Livestock Production and Manure Management Systems	Poverty Reduction and Minimize Exposure to Risk (1.5)	↑	[+2]	&	J	«	With mixed-farming systems farmers can not only mitigate risks by producing a multitude of commodities, but they can also increase the productivity of both crops and animals in a more profitable and sustainable way.	Sansoucy, 1995

2 ZERO HUNGER

Agriculture and Livestock	Target	Interaction	Score	Evidence	Agreement	Confidence	Description	References
Behavioural Response: Sustainable Healthy Diets and Reduced Food Waste	Food Security, Promoting Sustainable Agriculture (2.1/2.4/2a)	↑	[+2]	📖📖📖📖	☺☺☺☺	★★★★	Curbing consumer waste of major food crops (i.e., wheat, rice and vegetables) and meats (i.e., beef, pork and poultry) in China, USA and India alone could feed ~413 million people per year (West et al., 2014). One billion extra people could be fed if food crop losses could be halved (Kummu et al., 2012). Reducing waste, especially from meat and dairy, could play a role in delivering food security and reduce the need for sustainable intensification (Smith, 2013). Dietary change toward global healthy diets could improve nutritional health, food security and reduce emissions.	Garnett, 2011; Beddington et al., 2012; Kummu et al., 2012; Smith, 2013; Bajželj et al., 2014; Tilman and Clark, 2014; West et al., 2014; Lamb et al., 2016
Land-based GHG Reduction and Soil Carbon Sequestration	Food Security, Promoting Sustainable Agriculture (2.1/2.4/2a)	↑	[+2]	📖📖📖📖	☺☺☺☺	★★★★	Safe application of biotechnology, both conventional and modern methods, can help to improve agricultural productivity, improving crop adaptability and thereby catering to food security. Reducing tillage, eliminating fallow and keeping the soil covered with residue, cover crops or perennial vegetation helps prevent soil erosion and has the potential to increase soil organic matter. Efficient land-management techniques can help in increasing crop yields, and so food security issues can be addressed. Yield projections are actually higher for developing countries than for developed countries, reflecting the fact that they have more 'catch-up' potential (Evenson, 1999). Action is needed throughout the food system on moderating demand, reducing waste, improving governance and producing more food (Godfray and Garnett, 2014). Improving cropland management is the key to increase crop productivity without further degrading soil and water resources (Branca et al., 2011). CSA practices increase productivity and prioritize food security.	Evenson, 1999; West and Post, 2002; Johnson et al., 2007; Branca et al., 2011; McCarthy et al., 2011; Behnassi et al., 2014; Campbell et al., 2014; Godfray and Garnett, 2014; Harvey et al., 2014; Lipper et al., 2014
Greenhouse Gas Reduction from Improved Livestock Production and Manure Management Systems	Food Security, Promoting Sustainable Agriculture (2.1/2.4/2a)	↑	[+2]	&&&&	JJJJ	««««	Fostering transitions towards more productive livestock production systems targeting land-use change appears to be the most efficient lever to deliver food availability outcomes. Genomic selection should be able to at least double the rate of genetic gain in the dairy industry. Given the prevalence of mixed crop–livestock systems in many parts of the world, closer integration of crops and livestock in such systems can give rise to increased productivity and increased soil fertility (Thornton, 2010). Managing the indirect effects of livestock systems intensification is critical for the sustainability of the global food system: such as improving productivity and the close link to land sparing (Herrero and Thornton, 2013). In East Africa pastoralists have shifted from cows to camels, which are better adapted to survive periods of water scarcity and able to consistently provide more milk (Steenwerth et al., 2014). Scenarios where zero human-edible concentrate feed is used for livestock, soil erosion potential reduces by 12%.	Thornton, 2010, 2013; Herrero and Thornton, 2013; Havlík et al., 2014; Steenwerth et al., 2014; Schader et al., 2015

3 GOOD HEALTH AND WELL-BEING

Agriculture and Livestock	Target	Interaction	Score	Evidence	Agreement	Confidence	Description	References
Behavioural Response: Sustainable Healthy Diets and Reduced Food Waste	Tobacco Control (3.a/3.a.1)	↑	[+1]	📖	☺	★	Consume fewer foods with low nutritional value, e.g., alcohol (Garnett, 2011). Demand-side measures aimed at reducing the proportion of livestock products in human diets, where the consumption of animal products is higher than recommended, are associated with multiple health benefits, especially in industrialized countries (Bustamante et al., 2014).	Garnett, 2011; Bustamante et al., 2014
Land-based GHG Reduction and Soil Carbon Sequestration	Ensure Healthy Lives (3.c)	↑ / ↓	[+2,-2]	📖📖	☺☺	★★	Growing crops such as cassava, sorghum and millet, even in harsh conditions, is important to the diets of very poor people. Policy scenarios show that reduced research support, delayed industrialization, delayed biotechnology and climate change will delay progress in reducing childhood malnutrition. The global effects are small, but local effects for some countries, e.g., Bangladesh and Nigeria, are significant (Evenson, 1999).	Evenson, 1999; Godfray and Garnett, 2014
Greenhouse Gas Reduction from Improved Livestock Production and Manure Management Systems	Ensure Healthy Lives (3.c)	↑ / ↓	[+2,-2]	&&	JJ	««	Biodigestion, which has positive public health aspects, particularly where toilets are coupled with the biodigester; anaerobic conditions kill pathogenic organisms as well as digestive toxins. Separation processes can improve or worsen health risks related to food crops or to livestock.	Sansoucy, 1995; Burton, 2007

4 QUALITY EDUCATION

Agriculture and Livestock	Target	Interaction	Score	Evidence	Agreement	Confidence	Description	References
Behavioural Response: Sustainable Healthy Diets and Reduced Food Waste			[0]				No direct interaction	
Land-based GHG Reduction and Soil Carbon Sequestration	Ensure Inclusive and Quality Education (4.4/4.7)	↑ / ↓	[+2,-2]	📖📖	☺	★	Science-based action within CSA is required to integrate data sets and sound metrics for testing hypotheses about feedback regarding climate, weather data products and agricultural productivity, such as the nonlinearity of temperature effects on crop yield and the assessment of trade-offs and synergies that arise from different agricultural intensification strategies (Steenwerth et al., 2014). Low commodity prices have led to declining investment in research and development, farmer education, etc. (Lamb et al., 2016).	Steenwerth et al., 2014; Lamb et al., 2016
Greenhouse Gas Reduction from Improved Livestock Production and Manure Management Systems			[0]				No direct interaction	

Social-Other (continued)

		Interaction / Score / Evidence / Agreement / Confidence	Interaction / Score / Evidence / Agreement / Confidence	Interaction / Score / Evidence / Agreement / Confidence	Interaction / Score / Evidence / Agreement / Confidence
Forest	**Reduced Deforestation, REDD+**	**Poverty Reduction (1.5)** ↑ [+2] 🕮 ☺ ★ Partnerships between local forest managers, community enterprises and private sector companies can support local economies and livelihoods, and boost regional and national economic growth. Katila et al., 2017	**Food Security, Promoting Sustainable Agriculture (2.1/2.4/2a)** ↑/↓ [+1,-2] 🕮🕮 ☺ ★ Food security may lead to the conversion of productive land under forest, including community forests, into agricultural production. In a similar fashion, the production of biomass for energy purposes (SDG 7) may reduce land available for food production and/or for community forest activities . Efforts by the Government of Zambia to reduce emissions by REDD+ have contributed erosion control, ecotourism and pollination valued at 2.5% of the country's GDP. Turpie et al., 2015; Epstein and Theuer, 2017; Katila et al., 2017; Dooley and Kartha, 2018	[0] No direct interaction	**Ensure Inclusive and Quality Education (4.4/4.7)** ↑ [+1] 🕮 ☺ ★ Local forest users learn to understand laws, regulations and policies which facilitate their participation in society. Education and capacity building provide technical skill and knowledge (Katila et al., 2017). Katila et al., 2017
	Afforestation and Reforestation	**Poverty and Development (1.1/1.2/1.3/1.4)** ↑/↓ [+2,-2] 🕮🕮 ☺☺ ★★★ Clean Development Mechanism (CDM) can have different implications on local community livelihoods. For example, willingness to adopt afforestation is influenced in particular by Australian landholder's perceptions of its potential to provide a diversified income stream, and its impacts on flexibility of land management ; land sparing would have far reaching implications for the UK countryside and would affect landowners and rural communities ; and livelihoods could be threatened if subsistence agriculture is targeted . Zomer et al., 2008; Schirmer and Bull, 2014; Lamb et al., 2016; Dooley and Kartha, 2018	**Food Security (2.1)** ↑/↓ [+1,-1] 🕮 ☺ ★ CDM can have different implications on local to regional food security and local community livelihoods. Zomer et al., 2008; Dooley and Kartha, 2018	**Ensure Healthy Lives (3.c)** ↑ [+1] 🕮 ☺ ★ Urban trees are increasingly seen as a way to reduce harmful air pollutants and therefore improve cardio-respiratory health. Jones and McDermott, 2018	**Promote Knowledge and Skill to Promote SD (4.7)** ↓ [-1] 🕮 ☺ ★ Most landholders reported having low levels of knowledge about tree planting for carbon sequestration – particularly available programmes, prices and markets, and government rules and regulations . Schirmer and Bull, 2014
	Behavioural Response (Responsible	[0] No direct interaction	[0] No direct interaction	[0] No direct interaction	[0] No direct interaction
Oceans	**Ocean Iron Fertilization**	[0] No direct interaction	**Food Security (2.2/2.3)** ↑/↓ [+1,-1] 🕮🕮 ☺ ★ OIF can have different implications on fish stocks and aquaculture, and it might actually increase food availability for fish stocks (increasing yields); but potentially at the cost of reducing the yields of fisheries outside the enhancement region by depleting other nutrients. Lampitt et al., 2008; Smetacek and Naqvi, 2008; Williamson et al., 2012	[0] No direct interaction	[0] No direct interaction
	Blue Carbon	**Poverty and Development (1.1/1.2/1.5)** ↑ [+3] 🕮🕮🕮 ☺☺☺ ★★★ Avoiding loss of mangroves and maintaining the 2000 stock could save a value of ecosystem services from mangroves in South East Asia of approximately 2.16 billion USD until 2050 (2007 prices), with a 95% prediction interval of 1.58–2.76 billion USD (case study area South East Asia); seaweed aquaculture will enhance carbon uptake and provide employment; traditional management systems provide benefits for blue carbon and support livelihoods for local communities; greening of aquaculture can significantly enhance carbon storage; PES schemes could help capture the benefits derived from multiple ecosystem services beyond carbon sequestration. Zomer et al., 2008; Schirmer and Bull, 2014; Lamb et al., 2016	**Food Production (2.3/2.4)** ↑ [+3] 🕮🕮🕮 ☺☺☺ ★★★ Avoiding loss of mangroves and maintaining the 2000 stock could save a value of ecosystem services from mangroves in South East Asia including fisheries; seaweed aquaculture will provide employment; traditional management systems provide livelihoods for local communities; greening of aquaculture can increase income and well-being; and mariculture is a promising approach for China. Brander et al., 2012; Ahmed et al., 2017a, 2017b; Duarte et al., 2017; Sondak et al., 2017; Vierros, 2017; Zhang et al., 2017	[0] No direct interaction	[0] No direct interaction
	Enhanced Weathering	[0] No direct interaction	[0] No direct interaction	[0] No direct interaction	[0] No direct interaction

SDG 5 Gender Equality

		Interaction	Score	Evidence	Agreement	Confidence
Industry	Accelerating Energy Efficiency Improvement		[0]	No direct interaction		
Industry	Low-carbon Fuel Switch		[0]	No direct interaction		
Industry	Decarbonization/CCS/CCU		[0]	No direct interaction		

SDG 10 Reduced Inequalities

		Interaction	Score	Evidence	Agreement	Confidence
Industry	Accelerating Energy Efficiency Improvement	Knowledge and Skills Needed to Promote SD (4.7) ↑	[+1]	📖	☺☺☺	★★★
		There is need for skill in managing in-house energy efficiency. Sometimes ESCOs also help. Energy audits, but many times absence of skill acts as barrier for energy efficiency improvement. In many countries, especially developing countries, these act as barriers.				
		Apeaning and Thollander, 2013; Johansson and Thollander, 2018				
Industry	Low-carbon Fuel Switch		[0]	No direct interaction		
Industry	Decarbonization/CCS/CCU		[0]	No direct interaction		

SDG 16 Peace, Justice and Strong Institutions

		Interaction	Score	Evidence	Agreement	Confidence
Industry	Accelerating Energy Efficiency Improvement		[0]	No direct interaction		
Industry	Low-carbon Fuel Switch		[0]	No direct interaction		
Industry	Decarbonization/CCS/CCU		[0]	No direct interaction		

SDG 17 Partnerships for the Goals

		Interaction	Score	Evidence	Agreement	Confidence
Industry	Accelerating Energy Efficiency Improvement	Global Partnership (17.6/17.7) ↑	[+2]	📖📖	☺☺☺	★★★
		A driving force for energy efficiency is collaboration among companies, networks, experience sharing and management tools. Sharing among countries can help accelerate managerial action. Absence of information, budgetary funding, lack of access to capital, etc. are				
		Apeaning and Thollander, 2013; Griffin et al., 2018; Johansson and Thollander, 2018; Lawrence et al., 2018				
Industry	Low-carbon Fuel Switch	Global Partnership (17.6/17.7) ↑	[+2]	📖	☺☺	★★
		Ultra-low carbon steel making and breakthrough technologies are under trial across many countries and helping in enhancing the learning.				
		Abdul Quader et al., 2016				
Industry	Decarbonization/CCS/CCU	Global Partnership (17.6/17.7) ↑	[+2]	📖	☺☺☺	★★★
		EPI plants are capital intensive and are mostly operated by multinationals with long investment cycles. In developed countries new innovation investments are happening in brown fields. Such large innovation investments need strong collaboration among partners/competitors which can be facilitated by public funds. They happen at national and supranational scales and across sectors, needs fresh revisit at Intellectual Property Rights issues. Global production of bio-based polymers increasingly need public support and incentives to push forward.				
		Wesseling et al., 2017; Griffin et al., 2018				

Social 2-Demand (continued)

SDG 5

Sector	Option	Target	Interaction	Score	Evidence	Agreement	Confidence	Description	References
Buildings	Behavioural Response			[0]				No direct interaction	
Buildings	Accelerating Energy Efficiency Improvement	Gender Equality and Women's Empowerment (5.1/5.4)	↑	[+1]	🕮	☺☺	★★	Efficient stoves lead to empowerment of rural and indigenous women.	Bhojvaid et al., 2014; Berrueta et al., 2017
Buildings	Improved Access and Fuel Switch to Modern Low-carbon Energy	Women's Safety and Worth (5.1/5.2/5.4)/Opportunities for Women (5.1/5.5)	↑	[+1]	🕮🕮	☺☺	★★	Improved access to electric lighting can improve women's safety and girls' school enrolment. Cleaner cooking fuel and lighting access can reduce health risks and drudgery, which women disproportionately face. Access to modern energy services has the potential to empower women by improving their income-earning and entrepreneurial opportunities and reducing drudgery. Participating in energy supply chains can increase women's opportunities and agency and improve business outcomes.	Chowdhury, 2010; Dinkelman, 2011; Kaygusuz, 2011; Köhlin et al., 2011; Clancy et al., 2012; Haves, 2012; Matinga, 2012; Anenberg et al., 2013; Pachauri and Rao, 2013; Burney et al., 2017; McCollum et al.,

SDG 10

Sector	Option	Target	Interaction	Score	Evidence	Agreement	Confidence	Description	References
Buildings	Behavioural Response			[0]				No direct interaction	
Buildings	Accelerating Energy Efficiency Improvement	Empowerment and Inclusion (10.1/10.2/10.3/10.4)	↑/↓	[1,-1]	🕮🕮🕮	☺☺☺	★★★	Energy efficiency measures and the provision of energy access can free up resources that can then be put towards other productive uses (e.g., educational and employment opportunities), especially for women and children in poor, rural areas. The distributional costs of new energy policies are dependent on instrument design. If costs fall disproportionately on the poor, then this could work against the promotion of social, economic and political equality for all. The impacts of energy efficiency measures and policies on inequality can be both positive, if they reduce energy costs, or negative, if mandatory standards increase the need for purchasing more expensive equipment and appliances.	Dinkelman, 2011; Casillas and Kammen, 2012; Pachauri et al., 2012; Cayla and Osso, 2013; Hirth and Ueckerdt, 2013; Pueyo et al., 2013; Jakob and Steckel, 2014; Fay et al., 2015; Cameron et al., 2016; Hallegatte et al., 2016b; McCollum et al., 2018
Buildings	Improved Access and Fuel Switch to Modern Low-carbon Energy			[0]				No direct interaction	

SDG 16

Sector	Option	Target	Interaction	Score	Evidence	Agreement	Confidence	Description	References
Buildings	Behavioural Response	Environmental Justice (16.7)	↑	[+2]	🕮	☺	★	Consumption perspectives strengthen environmental justice discourse (as it claims to be a more just way of calculating global and local environmental effects) while possibly also increasing the participatory environmental discourse.	Hult and Larsson, 2016
Buildings	Accelerating Energy Efficiency Improvement	Capacity and Accountability (16.1/16.3/16.5/16.6/16.7/16.8)	↑	[+2]	🕮🕮🕮	☺☺☺	★★★★	Institutions that are effective, accountable and transparent are needed at all levels of government (local to national to international) for providing energy access, promoting modern renewables and boosting efficiency. Strengthening the participation of developing countries in international institutions (e.g., international energy agencies, UN organizations, WTO, regional development banks and beyond) will be important for issues related to energy trade, foreign direct investment, labour migration and knowledge and technology transfer. Reducing corruption, where it exists, will help these bodies and related domestic institutions maximize their societal impacts. Limiting armed conflict and violence will aid most efforts related to sustainable development, including progress in the energy dimension.	Acemoglu, 2009; Tabellini, 2010; Acemoglu et al., 2014; ICSU and ISSC, 2015; McCollum et al., 2018
Buildings	Improved Access and Fuel Switch to Modern Low-carbon Energy	Capacity and Accountability (16.1/16.3/16.5/16.6/16.7/16.8)	↑	[+2]	🕮🕮🕮	☺☺☺	★★★★	Institutions that are effective, accountable and transparent are needed at all levels of government (local to national to international) for providing energy access, promoting modern renewables and boosting efficiency. Strengthening the participation of developing countries in international institutions (e.g., international energy agencies, UN organizations, WTO, regional development banks and beyond) will be important for issues related to energy trade, foreign direct investment, labour migration, and knowledge and technology transfer. Reducing corruption, where it exists, will help these bodies and related domestic institutions maximize their societal impacts. Limiting armed conflict and violence will aid most efforts related to sustainable development, including progress in the energy dimension.	Acemoglu, 2009; Tabellini, 2010; Acemoglu et al., 2014; ICSU and ISSC, 2015; McCollum et al., 2018

SDG 17

Sector	Option	Target	Interaction	Score	Evidence	Agreement	Confidence	Description	References
Buildings	Behavioural Response			[0]				No direct interaction	
Buildings	Accelerating Energy Efficiency Improvement	Enhance Policy Coherence for Sustainable Development (17.4)	↑	[+2]	🕮	☺	★	Implementing refrigerant transition and energy efficiency improvement policies in parallel for room ACs, roughly doubles the benefit of either policy implemented in isolation.	Shah et al., 2015
Buildings	Improved Access and Fuel Switch to Modern Low-carbon Energy	Promote Transfer and Diffusion of Technology (17.6/17.7)	↑	[+2]	🕮	☺	★	Green building technology in Kazakhstan was based on transfer of knowledge among various parties.	Kim and Sun, 2017

Social 2-Demand (continued)

SDG 5 – Gender Equality

Sector	Option	Target	Interaction	Score	Evidence	Agreement	Confidence	Description	References
Transport	Behavioural response	Recognize Women's Unpaid Work (5.1/5.4)/Opportunities for Women (5.1/5.5)	↑	[+1]	📖📖	☺☺	★★	The woman's average trip to work differs markedly from the man's average trip. Working-poor women rely on extensive social networks creating communities of spatial necessity, bartering for basic needs to overcome transportation constraints. Women earn lower wages and so are less likely to justify longer commutes. Many women need to manage dual roles as workers and mothers. Women tend to perform multi-purpose commuting, combining both work and household needs .	Crane, 2007; Rogalsky, 2010
Transport	Accelerating Energy Efficiency Improvement			[0]				No direct interaction	
Transport	Improved Access and Fuel Switch to Modern Low-carbon Energy			[0]				No direct interaction	

SDG 10 – Reduced Inequalities

Sector	Option	Target	Interaction	Score	Evidence	Agreement	Confidence	Description	References
Transport	Behavioural response	Reduce Inequality (10.2)	↑	[+2]	📖📖	☺☺	★★	The equity impacts of climate change mitigation measures for transport, and indeed of transport policy intervention overall, are poorly understood by policymakers. This is in large part because standard assessment of these impacts is not a statutory requirement of current policymaking. Managing transport energy demand growth will have to be advanced alongside efforts in passenger travel towards reducing the deep inequalities in access to transport services that currently affect the poor worldwide. Free provision of roads and parking spaces converts vast amounts of public land and capital into under-priced space for cars, in extreme cases like Los Angeles, USA, roads and streets free for parking and driving are 20% of land area; as governments give drivers free land, people drive more than they would otherwise. High levels of car dependence and the costs of motoring can be burdensome, and lead to increasing debt, raising questions of affordability for households with limited resources, particularly low-income houses located in suburban areas.	Figueroa et al., 2014; Lucas and Pangbourne, 2014; Walks, 2015; Manville, 2017; Belton Chevallier et al., 2018
Transport	Accelerating Energy Efficiency Improvement			[0]				No direct interaction	
Transport	Improved Access and Fuel Switch to Modern Low-carbon Energy	Reduce Inequality (10.2)	↑	[+2]	📖📖	☺☺	★★	The equity impacts of climate change mitigation measures for transport, and indeed of transport policy intervention overall, are poorly understood by policymakers. This is in large part because standard assessment of these impacts is not a statutory requirement of current policymaking. Managing transport energy demand growth will have to be advanced alongside efforts in passenger travel towards reducing the deep inequalities in access to transport services that currently affect the poor worldwide.	Figueroa et al., 2014; Lucas and Pangbourne, 2014

SDG 16 – Peace, Justice and Strong Institutions

Sector	Option	Target	Interaction	Score	Evidence	Agreement	Confidence	Description	References
Transport	Behavioural response	Accountable and Transparent Institutions at All Levels (16.6/16.8)	↑/↓	[+1, -1]	📖	☺	★	With behavioural change towards walking for short distances, pedestrian safety on the road might reduce, unless public policy is appropriately formulated. Prevalence of high levels of triple forms of informality, in jobs, housing and transportation, are responsible for low productivity and low standards of living, and are a major challenge for policies targeting urban growth in Latin America.	CAF, 2017; SLoCaT, 2017
Transport	Accelerating Energy Efficiency Improvement	Responsive, Inclusive, Participatory Decision-making (16.7)	↑	[+2]	📖📖	☺☺	★★	In transport mitigation it is necessary to conduct needs assessments and stakeholder consultation to determine plausible challenges, prior to introducing desired planning reforms. Further, the involved personnel should actively engage transport-based stakeholders during policy identification and its implementation to achieve the desired results. User behaviour and stakeholder integration are key for successful transport policy implementation.	Aggarwal, 2017; AlSabbagh et al., 2017
Transport	Improved Access and Fuel Switch to Modern Low-carbon Energy	Responsive, Inclusive, Participatory Decision-making (16.7)	↑/↓	[+1, -1]	📖	☺	★	Formal transport infrastructure improvement in many cities in developing countries leads to eviction from informal settlements; need for appropriate redistributive policies and cooperation and partnerships with all stakeholders.	Colenbrander et al., 2016

SDG 17 – Partnerships for the Goals

Sector	Option	Target	Interaction	Score	Evidence	Agreement	Confidence	Description	References
Transport	Behavioural response	Help Promote Global Partnership (17.1/17.3/17.5/17.6/17.7)	↑	[+2]	📖	☺	★	Projects aiming at resilient transport infrastructure development (e.g., C40 Cities Clean Bus Declaration, UITP Declaration on Climate Leadership, Cycling Delivers on the Global Goals, Global Sidewalk Challenge) are happening through multi-stakeholder coalitions.	SLoCaT, 2017
Transport	Accelerating Energy Efficiency Improvement	Help Promote Global Partnership (17.1/17.3/17.5/17.6/17.7)	↑	[+2]	📖	☺	★	Projects aiming at resilient transport infrastructure development and technology adoption (e.g. C40 Cities Clean Bus Declaration, UITP Declaration on Climate Leadership, Cycling Delivers on the Global Goals, Global Sidewalk Challenge) are happening through multi-stakeholder coalitions.	SLoCaT, 2017
Transport	Improved Access and Fuel Switch to Modern Low-carbon Energy	Help Promote Global Partnership (17.1/17.3/17.5/17.6/17.7)	↑	[+2]	📖	☺	★	Projects aiming at resilient transport infrastructure development (e.g. C40 Cities Clean Bus Declaration, UITP Declaration on Climate Leadership, Cycling Delivers on the Global Goals, Global Sidewalk Challenge) are happening through multi-stakeholder coalitions.	SLoCaT, 2017

SDG 5 – Gender Equality

		Interaction	Score	Evidence	Agreement	Confidence
Replacing Coal	Non-biomass Renewables - solar, wind, hydro	**Gender Equality and Women's Empowerment (5.1/5.4)** ↑	[+1]	📖	☺	★
		Decentralized renewable energy systems (e.g., home- or village-scale solar power) can reduce the burden on girls and women of procuring traditional biomass.				
		Schwerhoff and Sy, 2017				
	Increased use of Biomass		[0]	No direct interaction		
	Nuclear/Advanced Nuclear		[0]	No direct interaction		
	CCS: Bioenergy		[0]	No direct interaction		
Advanced Coal	CCS: Fossil		[0]	No direct interaction		

SDG 10 – Reduced Inequalities

		Interaction	Score	Evidence	Agreement	Confidence
Replacing Coal	Non-biomass Renewables - solar, wind, hydro	**Empowerment and Inclusion (10.1/10.2/10.3/10.4)** ↑	[+1]	📖📖	☺☺	★★
		Decentralized renewable energy systems (e.g., home- or village-scale solar power) can enable a more participatory, democratic process for managing energy-related decisions within communities.				
		Walker and Devine-Wright, 2008; Cass et al., 2010; Cumbers, 2012; Kunze and Becker, 2015; McCollum et al., 2018				
	Increased use of Biomass		[0]	No direct interaction		
	Nuclear/Advanced Nuclear		[0]	No direct interaction		
	CCS: Bioenergy		[0]	No direct interaction		
Advanced Coal	CCS: Fossil		[0]	No direct interaction		

SDG 16 – Peace, Justice and Strong Institutions

		Interaction	Score	Evidence	Agreement	Confidence
Replacing Coal	Non-biomass Renewables - solar, wind, hydro	**Energy Justice** ↑	[+2]	📖	☺	★
		The energy justice framework serves as an important decision-making tool in order to understand how different principles of justice can inform energy systems and policies. Islar et al. (2017) state that off-grid and micro-scale energy development offers an alternative path to fossil-fuel use and top-down resource management as they democratize the grid and increase marginalized communities' access to renewable energy, education and health care.				
		Islar et al., 2017				
	Increased use of Biomass		[0]	No direct interaction		
	Nuclear/Advanced Nuclear	**Reduce Illicit Arms Trade (16.4)** ↓	[-1]	📖📖	☺☺	★★
		Continued use of nuclear power poses a constant risk of proliferation.				
		Adamantiades and Kessides, 2009; Rogner, 2010; Sagan, 2011; von Hippel et al., 2011, 2012; Yim and Li, 2013; IPCC, 2014				
	CCS: Bioenergy		[0]	No direct interaction		
Advanced Coal	CCS: Fossil		[0]	No direct interaction		

SDG 17 – Partnerships for the Goals

		Interaction	Score	Evidence	Agreement	Confidence
Replacing Coal	Non-biomass Renewables - solar, wind, hydro	**International Cooperation (All Goals)** ↑ / ~	[+2,0]	📖📖	☺☺	★★
		International cooperation (in policy) and collaboration (in science) is required for the protection of shared resources. Fragmented approaches have been shown to be more costly. Specific to SDG7, to achieve the targets for energy access, renewables and efficiency, it will be critical that all countries: (i) are able to mobilize the necessary financial resources (e.g., via taxes on fossil energy, sustainable financing, foreign direct investment, financial transfers from industrialized to developing countries); (ii) are willing to disseminate knowledge and share innovative technologies between each other; (iii) follow recognized international trade rules while at the same time ensuring that the least developed countries are able to take part in that trade; (iv) respect each other's policy space and decisions; (v) forge new partnerships between their public and private entities and within civil society; and (vi) support the collection of high-quality, timely and reliable data relevant to furthering their missions. There is some disagreement in the literature on the effect of some of the above strategies, such as free trade. Regarding international agreements, 'no-regrets options', where all sides gain through cooperation, are seen as particularly beneficial (e.g., nuclear test ban treaties) (McCollum et al., 2018).				
		UN, 1989; Ramaker et al., 2003; Clarke et al., 2009; NCE, 2015; Riahi et al., 2015, 2017; Eis et al., 2016; O'Neill et al., 2017; McCollum et al., 2018				
	Increased use of Biomass		[0]	No direct interaction		
	Nuclear/Advanced Nuclear		[0]	No direct interaction		
	CCS: Bioenergy		[0]	No direct interaction		
Advanced Coal	CCS: Fossil		[0]	No direct interaction		

		SDG 5 (Interaction / Score / Evidence / Agreement / Confidence)	SDG 10 (Interaction / Score / Evidence / Agreement / Confidence)	SDG 16 (Interaction / Score / Evidence / Agreement / Confidence)	SDG 17 (Interaction / Score / Evidence / Agreement / Confidence)
Agriculture and Livestock	Behavioural Response: Sustainable Healthy Diets and Reduced Food Waste	[0] No direct interaction	[0] No direct interaction	**making (16.6/16.7/16.a)** ↑ / ↓	[+1,-1]	📖📖📖	☺☺	★★ Appropriate incentives to reduce food waste may require some policy innovation and experimentation, but a strong commitment for devising and monitoring them seems essential. A financial incentive to minimize waste could be created through effective taxation (e.g., by taxing foods with the highest wastage rates, or by increasing taxes on waste disposal). Decision makers should try to integrate agricultural, environmental and nutritional objectives through appropriate policy measures to achieve sustainable healthy diets coupled with reduction in food waste. It is surprising that politicians and policymakers demonstrate little regarding the need to have strategies to reduce meat consumption and to encourage more sustainable eating practices. Garnett, 2011; Dagevos and Voordouw, 2013; Bajželj et al., 2014; Lamb et al., 2016	**Resource Mobilization and Strengthen Partnership** ↑ / ↓	[+1,-1]	📖	☺	★ Decision makers should try to integrate agricultural, environmental and nutritional objectives through appropriate policy measures to achieve sustainable healthy diets coupled with reduction in food waste. It is surprising that politicians and policymakers demonstrate little regarding the need to have strategies to reduce meat consumption and to encourage more sustainable eating practices . Garnett, 2011; Dagevos and Voordouw, 2013
	Land-based Greenhouse Gas Reduction and Soil Carbon Sequestration	**Equal Access, Empowerment of Women (5.5)** ↑ / ~	[+2,0]	📖📖	☺☺	★★★ Many programmes for CSA have been used to empower women and to improve gender equality. Women often have an especially important role to play in adaptation, because of their gendered indigenous knowledge on matters such as agriculture (Terry, 2009). Without access to land, credit and agricultural technologies, women farmers face major constraints in their capacity to diversify into alternative livelihoods (Demetriades and Esplen, 2008). Denton, 2002; Nelson et al., 2002; Morton, 2007; Demetriades and Esplen, 2009; Terry, 2009; Bernier et al., 2013; Jost et al., 2016	**Empower Economic and Political Inclusion of All, Irrespective of Sex (10.2)** ↑ / ~	[+1,0]	📖📖	☺☺	★★ In many rural societies women are side-lined from decisions regarding agriculture even when male household heads are absent, and they often lack access to important inputs such as irrigation water, credit, tools and fertilizer. To be effective, agricultural mitigation strategies need to take these and other aspects of local gender relations into account (Terry, 2009). Women's key role in maintaining biodiversity, through conserving and domesticating wild edible plant seed, and in food crop breeding, is not sufficiently recognized in agricultural and economic policymaking; nor is the importance of biodiversity to sustainable rural livelihoods in the face of predicted climate changes (Nelson et al., 2002). Nelson et al., 2002; Demetriades and Esplen, 2009; Terry, 2009	**Build Effective, Accountable and Inclusive Institutions (16.6/16.7/16.8)** ~ / ↓	[0,-1]	📖📖📖	☺☺	★★ Action is needed throughout the food system for improving governance and producing more food (Godfray and Garnett, 2014). CSA requires policy intervention for careful adjustment of agricultural practices to natural conditions, a knowledge-intensive approach, huge financial investment, etc., so having strong institutional frameworks is very important. The main source of climate finance for CSA in developing countries is the public sector. Lack of institutional capacity (as a means for securing creation of equal institutions among social groups and individuals) can reduce feasibility of AFOLU mitigation measures in the near future, especially in areas where small-scale farmers or forest users are the main stakeholders (Bustamante et al., 2014). Behnassi et al., 2014; Bustamante et al., 2014; Godfray and Garnett, 2014; Lipper et al., 2014; Steenwerth et al., 2014	**Resource Mobilization and Strengthen Multi-stakeholder Partnership (17.1/ 17.3/17.5/17.17)** ↑	[+2]	📖📖📖	☺☺☺	★★★ CSA requires more careful adjustment of agricultural practices to natural conditions, a knowledge-intensive approach, huge financial investment and policy and institutional innovation, etc. Besides private investment, quality of public investment is also important (Behnass et al., 2014). Sources of climate finance for CSA in developing countries include bilateral donors and multilateral financial institutions, besides public sector finance. CSA is committed to new ways of engaging in participatory research and partnerships with producers (Steenwerth et al., 2014). Behnassi et al., 2014; Lipper et al., 2014; Steenwerth et al., 2014
	Greenhouse Gas Reduction from Improved Livestock Production and Manure Management Systems	**Equal Access to Economic Resources, Promote Empowerment of Women (5.5/5.a/5.b)** ↑ / ~	[+2,0]	📖	☺	★ Most of the animal farming activities such as fodder collection and feeding are performed by women. Alongside the considerable involvement and contribution of women, gender inequalities are pervasive in Indian villages in terms of accessing natural resources, extension services, marketing opportunities and financial services as well as in exercising their decision-making powers. Therefore, there is a need to correct gender bias in the farming sector. Efforts are needed to increase the capacity of women to negotiate with confidence and meet their strategic needs. Access to and control and management of small ruminants, grazing areas and feed resources empower women and lead to an overall positive impact on the welfare of the household. Patel et al., 2016	**Empower Economic and Political Inclusion of All, Irrespective of Sex (10.2)** ↑ / ~	[+1,0]	📖	☺	★ Livestock ownership is increasing women's decision-making and economic power within both the household and the community. Access to and control and management of small ruminants, grazing areas and feed resources empower women and lead to an overall positive impact on the welfare of the household. Patel et al., 2016	**Responsible Decision-making (16.7)** ↑	[+1]	📖	☺	★ To minimize the economic and social cost, policies should target emissions at their source—on the supply side—rather than on the demand side as supply-side policies have lower calorie cost than demand-side policies. The role of livestock system transitions in emission reductions depends on the level of the carbon price and which emissions sector is targeted by the policies. Havlík et al., 2014	**Improve Domestic Capacity for Tax Collection (17.1)** ↑	[+2]	📖📖	☺☺	★★ The role of livestock system transitions in emission reductions depends on the level of the carbon price and which emissions sector is targeted by the policies (Havlík et al., 2014). Mechanisms for affecting behavioural change in livestock systems need to be better understood by implementing combinations of incentives and taxes simultaneously in different parts of the world (Herrero and Thornton, 2013). Herrero and Thornton, 2013; Havlík et al., 2014

Social 2-Other (continued)

		5 Gender Equality (Interaction / Score / Evidence / Agreement / Confidence)	10 Reduced Inequalities (Interaction / Score / Evidence / Agreement / Confidence)	16 Peace, Justice and Strong Institutions (Interaction / Score / Evidence / Agreement / Confidence)	17 Partnerships for the Goals (Interaction / Score / Evidence / Agreement / Confidence)
Forest	Reduced Deforestation, REDD+	**Opportunities for Women (5.1/5.5)** ↑/↓ [+1,-1] 📖 ☺ ★ Women have been less involved in REDD+ initiative (pilot project) design decisions and processes than men. Girls and women have an important role in forestry activities, related to fuel-wood, forest-food and pharmaceutical. Their empowerment contributes to sustainable forestry as well as reducing inequality . Brown, 2011; Larson et al., 2014; Katila et al., 2017	**Reduced Inequality, Empowerment and Inclusion (10.1/10.2/10.3/10.4)** ↑ [+2] 📖 ☺ ★ Urges developed countries to support, through multilateral and bilateral channels, the development of REDD+ national strategies or action plans and implementation . Girls and women have an important role in forestry activities, related to fuel-wood, forest-food and medicine. Their empowerment contributes to sustainable forestry as well as reducing inequality . Bastos Lima et al., 2017; Katila et al., 2017	**Build Effective, Accountable and Inclusive Institutions, Responsible Decision-making (16.6/16.7/16.8)** ↑ [+2] 📖📖 ☺☺☺ ★★★ Institutional building (National Forest Monitoring Systems, Safeguard Information Systems, etc.), with full and effective participation of all relevant countries . REDD+ actions also deliver non-carbon benefits (e.g. local socioeconomic benefits, governance improvements). Forest governance is another central aspect in recent studies, including the debate on decentralization of forest management, logging concessions in public-owned commercially valuable forests and timber certification, primarily in temperate forests . Bustamante et al., 2014; Bastos Lima et al., 2015, 2017	**Resource Mobilization and Strengthen Multi-stakeholder Partnership (17.1/ 17.3/17.5/17.17)** ↑/↓ [+1,-1] 📖 ☺ ★ To provide finance and technology to developing countries to support emissions reductions. Be supported by adequate and predictable financial and technology support, including support for capacity building . Partnerships in the form of significant aid money from, e.g., Norway, other bilateral donors and the World Bank's Forest Carbon Partnership Facility (FCPF) are forthcoming . Estimates of opportunity cost for REDD+ are very low. Lower costs and/or higher carbon prices could combine to protect more forests, including those with lower carbon content. Conversely, where the cost of action is high, a large amount of additional funding would be required for the forest to be protected (Miles and Kapos, 2008). Forest governance is another central aspect in recent studies, including debate on decentralization of forest management, logging concessions in public-owned commercially valuable forests and timber certification, primarily in temperate forests . Partnerships between local forest managers, community enterprises and private sector companies can support local economies and livelihoods and boost regional and national economic growth . Miles and Kapos, 2008; Bustamante et al., 2014; Andrew, 2017; Bastos Lima et al., 2017; Katila et al., 2017
	Afforestation and Reforestation	**Opportunities for Women (5.1/5.5)** ↑ [+1] 📖 ☺ ★ Many women in developing countries are already prominently engaged in economic sectors related to climate adaptation and mitigation efforts such as agriculture, renewable energy and forest management and are important drivers and leaders in climate responses that are innovative and effective, benefitting not only their families but also their wider communities. Women's participation in the decision-making process of forest management, for example, has been shown to increase rates of reforestation while decreasing the illegal extraction of forest products. UN-Women et al., 2015	**Empower Economic and Political Inclusion of All, Irrespective of Sex (10.2)** ↑ [+1] 📖 ☺ ★ Women's participation in the decision-making process of forest management, for example, has been shown to increase rates of reforestation while decreasing the illegal extraction of forest products. UN-Women et al., 2015	**Responsible Decision-making (16.7)** ↑ [+1] 📖 ☺ ★ Land-related mitigation, such as biofuel production, as well as conservation and reforestation action can increase competition for land and natural resources, so these measures should be accompanied by complementary policies. (Quoted from Epstein and Theur, 2017) Epstein and Theuer, 2017	**Resource Mobilization and Strengthen Partnership (17.1/17.14)** ↑ [+2] 📖📖 ☺☺ ★★ Financing at the national and international level is required to grow more seedlings/sapling, restore land, create awareness and education factsheets, provide training to local communities regarding the benefits of afforestation and reforestation. Article 12 of the Kyoto Protocol further sets a Clean Development Mechanism through which countries in Annex I earn 'certified emissions reductions' through projects implemented in developing countries (Montanarella and Alva, 2015). Afforestation and reforestation in India are being carried out under various programmes, namely social forestry initiated in the early 1980s, the Joint Forest Management Programme initiated in 1990, afforestation under National Afforestation and Eco-development Board programmes since 1992, and private farmer and industry initiated plantation forestry. If the current rate of afforestation and reforestation is assumed to continue, the carbon stock could increase by 11% by 2030 (Ravindranath et al., 2008). Ravindranath et al., 2008; Kibria, 2015; Montanarella and Alva, 2015
	Behavioural Response (Responsible Sourcing)	[0] No direct interaction	[0] No direct interaction	**Responsible Decision-making (16.7)** ↑ [+1] 📖📖 ☺☺ ★★ Indonesian factories may seek advantages through non-price competition—perhaps by highlighting decent working conditions or the existence of a union—or to see trade associations or government agencies promoting the country as a responsible sourcing location (Bartley, 2010). In the absence of domestic legal instruments providing incentives to improve sustainability of sourcing, it appears that initiatives to engage the major importing enterprises in developing responsible sourcing practices and policies is a practical approach. Unless initiatives involve all the major importers, they are unlikely to be successful since the high costs associated with accreditation would increase production costs for these firms relative to their competitors (Huang et al., 2013). Bartley, 2010; Huang et al., 2013	**Finance and Trade (17.1/17.10)** ↑ [+1] 📖📖 ☺☺ ★★ Private certification initiatives for wood product and biomass sourcing may extend their schemes with criteria for 'leakage' (external GHG effects). Also recycling of waste wood in pellets is not yet practiced, due to unclear rules in the EU Waste Directive about overseas shipping (Sikkema et al., 2014). Engagement of Chinese government and private sector stakeholders in supply-country sustainability initiatives may be the best way to support this gradual process of improvement. Although carrying out due diligence in timber sourcing can require considerable internal resources, it may be substantially less of a financial burden than the potential fines and reputational damage resulting from sourcing unknown or controversial timber (Huang et al., 2013). Huang et al., 2013; Sikkema et al., 2014

Social 2-Other (continued)

		5 Gender Equality					10 Reduced Inequalities					16 Peace, Justice and Strong Institutions					17 Partnerships for the Goals				
		Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence
Oceans	Ocean Iron Fertilization		[0]	No direct interaction				[0]	No direct interaction				[0]	No direct interaction				[0]	No direct interaction		
	Blue Carbon		[0]	No direct interaction				[0]	No direct interaction				[0]	No direct interaction				[0]	No direct interaction		
	Enhanced Weathering		[0]	No direct interaction				[0]	No direct interaction				[0]	No direct interaction				[0]	No direct interaction		

Industry	SDG / Target	Interaction	Score	Evidence	Agreement	Confidence	Description	References
Accelerating Energy Efficiency Improvement	**Water Efficiency and Pollution Prevention (6.3/6.4/6.6)**	↑/↓	[+2,-1]	📖📖	☺☺	★★	Efficiency and behavioural changes in the industrial sector that lead to reduced energy demand can lead to reduced requirements on energy supply. As water is used to convert energy into useful forms, the reduction in industrial demand is anticipated to reduce water consumption and waste water, resulting in more clean water for other sectors and the environment. Likewise, reducing material inputs for industrial processes through efficiency and behavioural changes will reduce water inputs in the material supply chains. In extractive industries there can be a trade-off with production unless strategically managed.	Vassolo and Döll, 2005; Nguyen et al., 2014; Holland et al., 2015; Fricko et al., 2016
Accelerating Energy Efficiency Improvement	**Sustainable and Efficient Resource (12.2/12.5/12.6/12.7/12.a)**	↑	[+1]	📖📖📖	☺☺☺	★★★	Once started leads to chain of actions within the sector and policy space to sustain the effort. Helps in expansion of sustainable industrial production (Ghana).	Apeaning and Thollander, 2013; Fernando et al., 2017
Accelerating Energy Efficiency Improvement	SDG 14		[0]				No direct interaction	
Accelerating Energy Efficiency Improvement	SDG 15		[0]				No direct interaction	
Low-carbon Fuel Switch	**Water Efficiency and Pollution Prevention (6.3/6.4/6.6)**	↑/↓	[+2,-2]	📖📖	☺☺	★★★	A switch to low-carbon fuels can lead to a reduction in water demand and waste water if the existing higher-carbon fuel is associated with a higher water intensity than the lower-carbon fuel. However, in some situations the switch to a low-carbon fuel such as, for example, biofuel could increase water use compared to existing conditions if the biofuel comes from a water-intensive feedstock.	Hejazi et al., 2015; Fricko et al., 2016; Song et al., 2016
Low-carbon Fuel Switch	**Sustainable Production (12.2/12.3/12.a)**	↑	[+2]	📖📖📖📖📖	☺☺☺☺	★★★★	A circular economy instead of linear global economy can achieve climate goals and can help in economic growth through industrialization which saves on resources, the environment and supports small, medium and even large industries, and can lead to employment generation. So new regulations, incentives and a tax regime can help in achieving the goal, especially in newly emerging developing countries - although also applicable for large industrialized countries.	Liu and Bai, 2014; Lieder and Rashid, 2016; Stahel, 2016; Supino et al., 2016; Fan et al., 2017; Shi et al., 2017; Zeng et al., 2017
Low-carbon Fuel Switch	SDG 14		[0]				No direct interaction	
Low-carbon Fuel Switch	**Sustainable Production (15.1/15.5/15.9/15.10)**	↑	[+1,-1]	📖	☺	★	A circular economy help in managing local biodiversity better by having less resource use footprint	Shi et al., 2017
Decarbonisation/CCS/CCU	**Water Efficiency and Pollution Prevention (6.3/6.4/6.6)**	↑/↓	[+1,-1]	📖📖📖	☺	★★	CCU/S requires access to water for cooling and processing which could contribute to localized water stress. CCS/U processes can potentially be configured for increased water efficiency compared to a system without carbon capture via process integration.	Meldrum et al., 2013; Byers et al., 2016; Fricko et al., 2016; Brandl et al., 2017
Decarbonisation/CCS/CCU	**Sustainable Production and Consumption (12.1/12.6/12.a)**	↑	[+2]	📖	☺☺☺☺	★★★★	EPI plants are capital intensive and are mostly operated by multinationals with long investment cycles. In developed countries new investments are happening in brown fields, while in developing countries these are in green fields. Collaboration among partners and user demand change, policy change is essential for encouraging these large risky investments.	Wesseling et al., 2017
Decarbonisation/CCS/CCU	**Conserve and Sustainably Use Ocean (14.1/14.5)**	↓	[-1]	📖	☺	★	CCU/S in the chemical industry faces challenges for transport costs and storage. In the UK cluster region have been identified for storage under sea.	Griffin et al., 2018
Decarbonisation/CCS/CCU	SDG 15		[0]				No direct interaction	

Environment-Demand (continued)

SDG 6 (Clean Water and Sanitation)

Sector	Option	Interaction	Score	Evidence	Agreement	Confidence
Buildings	**Behavioural Response**	**Water Efficiency and Pollution Prevention (6.3/6.4/6.6)**				
		↑	[+2]	📖📖	☺☺☺	★★★
		Behavioural changes in the residential sector that lead to reduced energy demand can lead to reduced requirements on energy supply. As water is used to convert energy into useful forms, the reduction in residential demand is anticipated to reduce water consumption and waste water, resulting in more clean water for other sectors and the environment.				
		Bartos and Chester (2014); Fricko et al. (2016); Holland et al. (2016)				
	Accelerating Energy Efficiency Improvement	**Water Efficiency and Pollution Prevention (6.3/6.4/6.6)**				
		↑	[+2]	📖📖📖	☺☺☺	★★★
		Efficiency changes in the residential sector that lead to reduced energy demand can lead to reduced requirements on energy supply. As water is used to convert energy into useful forms, the reduction in residential demand is anticipated to reduce water consumption and waste water, resulting in more clean water for other sectors and the environment. A switch to low-carbon fuels in the residential sector can lead to a reduction in water demand and waste water if the existing higher-carbon fuel is associated with a higher water intensity than the lower-carbon fuel. However, in some situations the switch to a low-carbon fuel such as, for example, biofuel could increase water use compared to existing conditions if the biofuel comes from a water-intensive feedstock. As water is used to convert energy into useful forms, energy efficiency is anticipated to reduce water consumption and waste water, resulting in more clean water for other sectors and the environment. Subsidies for renewables are anticipated to lead to the benefits and trade-offs outlined when deploying renewables. Subsidies for renewables could lead to improved water access and treatment if subsidies support projects that provide both water and energy services (e.g., solar desalination).				
		Bilton et al., 2011; Scott, 2011; Kumar et al., 2012; Meldrum et al., 2013; Bartos and Chester, 2014; Hendrickson and Horvath, 2014; Kern et al., 2014; Holland et al., 2015; Fricko et al., 2016; Kim et al., 2017				

SDG 12 (Responsible Consumption and Production)

Sector	Option	Interaction	Score	Evidence	Agreement	Confidence
Buildings	**Behavioural Response**	**Responsible and Sustainable Consumption**				
		↑	[+2]	📖📖📖	☺☺☺	★★★
		Technological improvements alone are not sufficient to increase energy savings. Zhao et al. (2017) found that building technology and occupant behaviours interact with each other and finally affect energy consumption from home. They found that occupant habits could not take advantage of more than 50% of energy efficiency potential allowed by an efficient building. In the electronic segment, product obsolescence represents a key challenge for sustainability. Echegaray (2016) discusses the dissonance between consumers' product durability experience, orientations to replace devices before terminal technical failure, and perceptions of industry responsibility and performance. The results from their urban sample survey indicate that technical failure is far surpassed by subjective obsolescence as a cause for fast product replacement. At the same time Liu et al. (2017) suggest that we need to go beyond individualist and structuralist perspectives to analyse sustainable consumption (i.e., combines both human agency paradigm and social structural perspective).				
		Sweeney et al., 2013; Webb et al., 2013; Allen et al., 2015; Echegaray (2015); He et al., 2016; Hult and Larsson, 2016; Isenhour and Feng, 2016; van Sluisveld et al., 2016; Zhao et al., 2017; Liu et al., 2017; Sommerfeld et al., 2017				
	Accelerating Energy Efficiency Improvement	**Sustainable Practices and Lifestyles (12.6/12.7/12.8)**				
		↑	[+1]	📖📖📖	☺☺☺	★★★
		Sustainable practices adopted by public and private bodies in their operations (e.g., for goods procurement, supply chain management and accounting) create an enabling environment in which renewable energy and energy efficiency measures may gain greater traction (McCollum et al., 2018).				
		Stefan and Paul, 2008; ECF, 2014; CDP, 2015; Khan et al., 2015; NCE, 2015; McCollum et al., 2018				

SDG 14 (Life Below Water)

Sector	Option	Interaction	Score	Evidence	Agreement	Confidence
Buildings	**Behavioural Response**		[0]			
		No direct interaction				
	Accelerating Energy Efficiency Improvement		[0]			
		No direct interaction				

SDG 15 (Life on Land)

Sector	Option	Interaction	Score	Evidence	Agreement	Confidence
Buildings	**Behavioural Response**		[0]			
		No direct interaction				
	Accelerating Energy Efficiency Improvement	**Reduced Deforestation (15.2)**				
		↑	[+2]	📖📖	☺☺☺	★★★
		Improved stoves has helped halt deforestation in rural India.				
		Bhojvaid et al., 2014				

Environment-Demand (continued)

		6 Clean Water and Sanitation					12 Responsible Consumption and Production					14 Life Below Water					15 Life on Land				
		Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence	Interaction	Score	Evidence	Agreement	Confidence
Buildings	**Improved Access and Fuel Switch to Modern Low-carbon Energy**	**Access to Improved Water and Sanitation (6.1/6.2), Water Efficiency and Pollution Prevention (6.3/6.4/6.6)**					**Sustainable Use and Management of Natural Resource (12.2)**										**Healthy Terrestrial Ecosystems (15.1/15.2/15.4/15.5/15.8)**				
		↑/↓	[+2,-1]	📖📖	☺☺	★★★	↑/↓	[+2,-1]	📖📖	☺☺	★★★		[0]				↑	[+2]	📖📖	☺☺☺	★★★
		A switch to low-carbon fuels in the residential sector can lead to a reduction in water demand and waste water if the existing higher-carbon fuel is associated with a higher water intensity than the lower-carbon fuel. However, in some situations the switch to a low-carbon fuel such as, for example, biofuel could increase water use compared to existing conditions if the biofuel comes from a water-intensive feedstock. Improved access to energy can support clean water and sanitation technologies. If energy access is supported with water-intensive energy sources, there could be trade-offs with water efficiency targets.					A switch to low-carbon fuels in the residential sector can lead to a reduction in water demand and waste water if the existing higher-carbon fuel is associated with a higher water intensity than the lower-carbon fuel. However, in some situations the switch to a low-carbon fuel such as, for example, biofuel could increase water use compared to existing conditions if the biofuel comes from a water-intensive feedstock. Improved access to energy can support clean water and sanitation technologies. If energy access is supported with water-intensive energy sources, there could be trade-offs with water efficiency targets.					No direct interaction					Ensuring that the world's poor have access to modern energy services would reinforce the objective of halting deforestation, since firewood taken from forests is a commonly used energy resource among the poor (McCollum et al., 2018).				
		Hejazi et al., 2015; Cibin et al., 2016; Fricko et al., 2016; Song et al., 2016; Rao and Pachauri, 2017					Hejazi et al., 2015; Cibin et al., 2016; Fricko et al., 2016; Song et al., 2016; Rao and Pachauri, 2017										Bazilian et al., 2011; Karekezi et al., 2012; Bailis et al., 2015; Winter et al., 2015; McCollum et al., 2018				
Transport	**Behavioural Response**	**Water Efficiency and Pollution Prevention (6.3/6.4/6.6)**					**Ensure Sustainable Consumption amd Production Patterns (12.3)**														
		↑	[+2]	📖📖	☺☺	★★	↑	[+2]	📖📖	☺☺	★★		[0]					[0]			
		Behavioural changes in the transport sector that lead to reduced transport demand can lead to reduced transport energy supply. As water is used to produce a number of important transport fuels, the reduction in transport demand is anticipated to reduce water consumption and waste water, resulting in more clean water for other sectors and the environment.					Urban carbon mitigation must consider the supply chain management of imported goods, the production efficiency within the city, the consumption patterns of urban consumers, and the responsibility of the ultimate consumers outside the city. Important for climate policy of monitoring the CO_2 clusters that dominate CO_2 emissions in global supply chains, because they offer insights on where climate policy can be effectively directed.					No direct interaction					No direct interaction				
		Vidic et al., 2013; Holland et al., 2015; Fricko et al., 2016; Tiedeman et al., 2016					Kagawa et al., 2015; Lin et al., 2015; Creutzig et al., 2016														
	Accelerating Energy Efficiency Improvement	**Water Efficiency and Pollution Prevention (6.3/6.4/6.6)**					**Sustainable Consumption (12.2/12.8)**														
		↑	[+2]	📖📖📖	☺☺☺	★★★	↑	[+2]	📖📖📖	☺☺☺	★★★		[0]					[0]			
		Similar to behavioural changes, efficiency measures in the transport sector that lead to reduced transport demand can lead to reduced transport energy supply. As water is used to produce a number of important transport fuels, the reduction in transport demand is anticipated to reduce water consumption and waste water, resulting in more clean water for other sectors and the environment.					Relational complex transport behaviour resulting in significant growth in energy-inefficient car choices, as well as differences in mobility patterns (distances driven, driving styles) and actual fuel consumption between different car segments all affect non-progress on transport decarbonization. Consumption choices and individual lifestyles are situated and tied to the form of the surrounding urbanization. Major behavioural changes and emissions reductions require understanding of this relational complexity, consideration of potential interactions with other policies, and the local context and implementation of both command-and-control as well as market-based measures.					No direct interaction					No direct interaction				
		Vidic et al., 2013; Holland et al., 2015; Fricko et al., 2016; Tiedeman et al., 2016					Stanley et al., 2011; Gallego et al., 2013; Heinonen et al., 2013; Aamaas and Peters, 2017; Azevedo and Leal, 2017; Gössling and Metzler, 2017														

Environment-Demand (continued)

		SDG 6 Interaction	Score	Evidence	Agreement	Confidence
Transport	Improved Access and Fuel Switch to Modern Low-carbon Energy	**Water Efficiency and Pollution Prevention (6.3/6.4/6.6)**				
		↑ / ↓	[+2,-1]	📖📖	☺☺	★★★
		A switch to low-carbon fuels in the transport sector can lead to a reduction in water demand and waste water if the existing higher-carbon fuel is associated with a higher water intensity than the lower-carbon fuel. However, in some situations the switch to a low-carbon fuel such as, for example, biofuel could increase water use compared to existing conditions if the biofuel comes from a water-intensive feedstock. Transport electrification could lead to trade-offs with water use if the electricity is provided with water intensive power generation.				
		Hejazi et al., 2015; Fricko et al., 2016; Song et al., 2016				

		SDG 12 Interaction	Score	Evidence	Agreement	Confidence
Transport	Improved Access and Fuel Switch to Modern Low-carbon Energy	**Ensure Sustainable Consumption and Production Patterns (12.3)**				
		↑	[+2]	📖📖📖	☺☺☺	★★★
		Due to persistent reliance on fossil fuels, it is posited that transport is more difficult to decarbonize than other sectors. This study partially confirms that transport is less reactive to a given carbon tax than the non-transport sectors: in the first half of the century, transport mitigation is delayed by 10–30 years compared to non-transport mitigation. The extent to which earlier mitigation is possible strongly depends on implemented technologies and model structures.				
		Figueroa et al., 2014; IPCC, 2014; Pietzcker et al., 2014; Creutzig et al., 2015				

		SDG 14 Interaction	Score	Evidence	Agreement	Confidence
Transport	Improved Access and Fuel Switch to Modern Low-carbon Energy		[0]			
		No direct interaction				

		SDG 15 Interaction	Score	Evidence	Agreement	Confidence
Transport	Improved Access and Fuel Switch to Modern Low-carbon Energy		[0]			
		No direct interaction				

5

Replacing Coal

SDG 6

Option	Target	Interaction	Score	Evidence	Agreement	Confidence	Description	References
Non-biomass Renewables - solar, wind hydro	**Water Efficiency and Pollution Prevention (6.3/6.4/6.6)/ Access to Improved Water and Sanitation (6.1/6.2)**	↑/↓	[+2,-2]	📖📖📖📖	☺☺☺☺	★★★★	Wind/solar renewable energy technologies are associated with very low water requirements compared to existing thermal power plant technologies. Widespread deployment is therefore anticipated to lead to improved water efficiency and avoided thermal pollution. However, managing wind and solar variability can increase water use at thermal power plants and can cause poor water quality downstream from hydropower plants. Access to distributed renewables can provide power to improve water access, but could also lead to increased groundwater pumping and stress if mismanaged. Developing dams to support reliable hydropower production can fragment rivers and alter natural flows reducing water and ecosystem quality. Developing dams to support reliable hydropower production can result in disputes for water in basins with up- and down-stream users. Storing water in reservoirs increases evaporation, which could offset water conservation targets and reduce availability of water downstream. However, hydropower plays an important role in energy access for water supply in developing regions, can support water security, and has the potential to reduce water demands if used without reservoir storage to displace other water intensive energy processes.	Bilton et al., 2011; Scott et al., 2011; Kumar et al., 2012; Ziv et al., 2012; Meldrum et al., 2013; Kern et al., 2014; Grill et al., 2015; Fricko et al., 2016; Grubert, 2016; De Stefano et al., 2017
Increased Use of Biomass	**Water Efficiency and Pollution Prevention (6.3/6.4/6.6)**	↑/↓	[+1,-2]	📖📖📖📖	☺☺	★★★★	Biomass expansion could lead to increased water stress when irrigated feedstocks and water-intensive processing steps are used. Bioenergy crops can alter flow over land and through soils as well as require fertilizer, and this can reduce water availability and quality. Planting bioenergy crops on marginal lands or in some situations to replace existing crops can lead to reductions in soil erosion and fertilizer inputs, improving water quality.	Hejazi et al., 2015; Bonsch et al., 2016; Cibin et al., 2016; Song et al., 2016; Gao and Bryan, 2017; Griffiths et al., 2017; Ha and Wu, 2017; Taniwaki et al., 2017; Woodbury et al., 2018

SDG 12

Option	Target	Interaction	Score	Evidence	Agreement	Confidence	Description	References
Non-biomass Renewables - solar, wind hydro	**Natural Resource Protection (12.2/12.3/12.4/12.5)**	↑	[+2]	📖📖📖	☺☺☺	★★★★	Renewable energy and energy efficiency slow the depletion of several types of natural resources, namely coal, oil, natural gas and uranium. In addition, the phasing-out of fossil fuel subsidies encourages less wasteful energy consumption; but if that is done, then the policies implemented must take care to minimize any counteracting adverse side-effects on the poor (e.g., fuel price rises). (Quote from McCollum et al., 2018)	Banerjee et al., 2012; Riahi et al., 2012; Schwanitz et al., 2014; Bhattacharyya et al., 2016; Cameron et al., 2016; McCollum et al., 2018
Increased Use of Biomass	**Natural Resource Protection (12.2/12.3/12.4/12.5)**	↑	[+2]	📖📖📖	☺☺☺	★★★★	Switching to renewable energy reduces the depletion of finite natural resources.	Banerjee et al., 2012; Riahi et al., 2012; Schwanitz et al., 2014; Bhattacharyya et al., 2016; Cameron et al., 2016; McCollum et al., 2018

SDG 14

Option	Target	Interaction	Score	Evidence	Agreement	Confidence	Description	References
Non-biomass Renewables - solar, wind hydro	**Marine Economies (14.7)/ Marine Protection (14.1/14.2/14.4/14.5)**	↑/↓	[2,-1]	📖📖	☺☺☺	★★★	Ocean-based energy from renewable sources (e.g., offshore wind farms, wave and tidal power) are potentially significant energy resource bases for island countries and countries situated along coastlines. Multi-use platforms combining renewable energy generation, aqua-culture, transport services and leisure activities can lay the groundwork for more diversified marine economies. Depending on the local context and prevailing regulations, ocean-based energy installations could either induce spatial competition with other marine activities, such as tourism, shipping, resources exploitation, and marine and coastal habitats and protected areas, or provide further grounds for protecting those exact habitats, therefore enabling marine protection. (Quote from McCollum et al., 2018) Hydropower disrupts the integrity and connectivity of aquatic habitats and impacts the productivity of inland waters and their fisheries.	Inger et al., 2009; Michler-Cieluch et al., 2009; Buck and Krause, 2012; WBGU, 2013; Cooke et al., 2016; Matthews and McCartney, 2018; McCollum et al., 2018
Increased Use of Biomass			[0]				No direct interaction	

SDG 15

Option	Target	Interaction	Score	Evidence	Agreement	Confidence	Description	References
Non-biomass Renewables - solar, wind hydro	**Healthy Terrestrial Ecosystems (15.1/15.2/15.4/15.5/15.8)**	↓	[-1]	📖📖📖	☺☺☺	★★★	Landscape and wildlife impact for wind; habitat impact for hydropower.	Alho, 2011; Garvin et al., 2011; Grodsky et al., 2011; Jain et al., 2011; Kumar et al., 2011; Kunz et al., 2011; Wiser et al., 2011; Dahl et al., 2012; de Lucas et al., 2012; Ziv et al., 2012; Lovich and Ennen, 2013; Smith et al., 2013; Matthews and McCartney, 2018
Increased Use of Biomass	**Healthy Terrestrial Ecosystems (15.1/15.2/15.4/15.5/15.8)**	↑/↓	[+1,-2]	📖	☺☺☺	★★	Protecting terrestrial ecosystems, sustainably managing forests, halting deforestation, preventing biodiversity loss and controlling invasive alien species could potentially clash with renewable energy expansion, if that would mean constraining large-scale utilization of bioenergy or hydropower. Good governance, cross-jurisdictional coordination and sound implementation practices are critical for minimizing trade-offs (McCollum et al., 2018).	Smith et al., 2010, 2014; Acheampong et al., 2017; McCollum et al., 2018

Environement-Supply (continued)

		6 (Interaction / Score / Evidence / Agreement / Confidence)	12 (Interaction / Score / Evidence / Agreement / Confidence)	14 (Interaction / Score / Evidence / Agreement / Confidence)	15 (Interaction / Score / Evidence / Agreement / Confidence)
Replacing Coal	**Nuclear/Advanced Nuclear**	**Water Efficiency and Pollution Prevention (6.3/6.4/6.6)** ↑/↓ [+2,-1] &&& JJJ ««« Nuclear power generation requires water for cooling which can lead to localized water stress and the resulting cooling effluents can cause thermal pollution in rivers and oceans. Webster et al., 2013; Holland et al., 2015; Fricko et al., 2016; Raptis et al., 2016	[0] No direct interaction	[0] No direct interaction	**Healthy Terrestrial Ecosystems (15.1/15.2/15.4/15.5/15.8)** ↓ [-1] && JJ «« Safety and waste concerns from uranium mining and milling. Bickerstaff et al., 2008; Sjoberg and Sjoberg, 2009; Ahearne, 2011; Corner et al., 2011; Visschers and Siegrist, 2012; IPCC, 2014
Replacing Coal	**CCS: Bioenergy**	**Water Efficiency and Pollution Prevention (6.3/6.4/6.6)** ↑/↓ [+1,-2] 🕮🕮 ☺ ★★ CCU/S requires access to water for cooling and processing which could contribute to localized water stress. However, CCS/U processes can potentially be configured for increased water efficiency compared to a system without carbon capture via process integration. The bioenergy component adds the additional trade-offs associated with bioenergy use. Large-scale bioenergy increases input demand, resulting in environmental degradation and water stress. Meldrum et al., 2013; Byers et al., 2016; Fricko et al., 2016; Brandl et al., 2017; Dooley and Kartha, 2018	**Natural Resource Protection (12.2/12.3/12.4/12.5)** ↑ [+1] 🕮🕮 ☺☺ ★★ Switching to renewable energy reduces the depletion of finite natural resources. On the other hand, the availability of underground storage is limited and therefore reduces the benefits of switching from finite resources to bioenergy. Banerjee et al., 2012; Riahi et al., 2012; Schwanitz et al., 2014; Bhattacharyya et al., 2016; Cameron et al., 2016; McCollum et al., 2018	[0] No direct interaction	**Healthy Terrestrial Ecosystems (15.1/15.2/15.4/15.5/15.8)** ↑/↓ [+1,-2] 🕮 ☺☺☺ ★★ Protecting terrestrial ecosystems, sustainably managing forests, halting deforestation, preventing biodiversity loss and controlling invasive alien species could potentially clash with renewable energy expansion, if that would mean constraining large-scale utilization of bioenergy or hydropower. Good governance, cross-jurisdictional coordination and sound implementation practices are critical for minimizing trade-offs (McCollum et al., 2018). Large-scale bioenergy increases input demand, resulting in environmental degradation and water stress. Smith et al., 2010, 2014; Acheampong et al., 2017; Dooley and Kartha, 2018, McCollum et al., 2018)
Advanced Coal	**CCS: Fossil**	**Water Efficiency and Pollution Prevention (6.3/6.4/6.6)** ↑/↓ [+1,-2] 🕮🕮🕮 ☺ ★★ CCU/S requires access to water for cooling and processing which could contribute to localized water stress. However, CCS/U processes can potentially be configured for increased water efficiency compared to a system without carbon capture via process integration. Coal mining to support clean coal CCS will negatively impact water resources due to the associated water demands, waste water and land-use requirements. Meldrum et al., 2013; Byers et al., 2016; Fricko et al., 2016; Brandl et al., 2017	[0] No direct interaction	[0] No direct interaction	[0] No direct interaction

Environement-Other

Sector	Response	SDG	Target	Interaction	Score	Evidence	Agreement	Confidence	Description	References
Agriculture and Livestock	Behavioural Response: Sustainable Healthy Diets and Reduced Food Waste	6	Water Efficiency and Pollution Prevention (6.3/6.4/6.6)	↑/↓	[+2,-1]	📖📖📖📖	☺☺☺☺	★★★★	Reduced food waste avoids direct water demand and waste water for crops and food processing, and avoids water used for energy supply by reducing agricultural, food processing and waste management energy inputs. Healthy diets will support water efficiency targets if the shift towards healthy foods results in food supply chains that are less water intensive than the supply chains supporting the historical dietary pattern.	Khan et al., 2009; Ingram, 2011; Kummu et al., 2012; Haileselassie et al., 2013; Bajželj et al., 2014; Tilman and Clark, 2014; Walker et al., 2014; Ran et al., 2016
Agriculture and Livestock	Behavioural Response: Sustainable Healthy Diets and Reduced Food Waste	12	Ensure Sustainable Consumption and Production Patterns, Sustainable Practices and Lifestyle (12.3/12.4/12.6/12.7/12.8)	↑	[+2]	📖📖📖📖	☺☺☺☺	★★★★	Reduce loss and waste in food systems, processing, distribution and by changing household habits. To reduce environmental impact of livestock both production and consumption trends in this sector should be traced. Livestock production needs to be intensified in a responsible way (i.e., be made more efficient in the way that it uses natural resources). Wasted food represents a waste of all the emissions generated during the course of producing and distributing that food. Mitigation measures include: eat no more than needed to maintain a healthy body weight; eat seasonal, robust, field-grown vegetables rather than protected, fragile foods prone to spoilage and requiring heating and lighting in their cultivation, refrigeration stage; consume fewer foods with low nutritional value e.g., alcohol, tea, coffee, chocolate and bottled water (these foods are not needed in our diet and need not be produced); shop on foot or over the Internet (reduced energy use). Reduction in food waste will not only pave the path for sustainable production but will also help in achieving sustainable consumption (Garnett, 2011). Reduce meat consumption to encourage more sustainable eating practices.	Stehfest et al., 2009; Steinfeld and Gerber, 2010; Garnett, 2011; Ingram, 2011; Beddington et al., 2012; Kummu et al., 2012; Bellarby et al., 2013; Dagevos and Voordouw, 2013; Smith, 2013; Bajželj et al., 2014; Hedenus et al., 2014; Tilman and Clark, 2014; West et al., 2014; Hiç et al., 2016; Lamb et al., 2016
Agriculture and Livestock	Behavioural Response: Sustainable Healthy Diets and Reduced Food Waste	14			[0]				No direct interaction	
Agriculture and Livestock	Behavioural Response: Sustainable Healthy Diets and Reduced Food Waste	15	Conservation of Biodiversity and Restoration of Land (15.1/15.5/15.9)	↑	[+1]	📖	☺	★	Reducing food waste has secondary benefits like protecting soil from degradation, and decreasing pressure for land conversion into agriculture and thereby protecting biodiversity. The agricultural area that becomes redundant through the dietary transitions can be used for other agricultural purposes such as energy crop production, or will revert to natural vegetation. A global food transition to less meat, or even a complete switch to plant-based protein food, could have a dramatic effect on land use. Up to 2,700 Mha of pasture and 100 Mha of crop land could be abandoned (Quoted from Stehfest et al., 2009)	Stehfest et al., 2009; Kummu et al., 2012
Agriculture and Livestock	Land-based Greenhouse Gas Reduction and Soil Carbon Sequestration	6	Water Efficiency and Pollution Prevention (6.3/6.4/6.6)	↑/↓	[+1,-1]	📖📖📖	☺☺	★★★	Soil carbon sequestration can alter the capacity of soils to store water, which impacts the hydrological cycle and could be positive or negative from a water perspective, dependent on existing conditions. CSA enrich linkages across sectors including management of water resources. Minimum tillage systems have been reported to reduce water erosion and thus sedimentation of water courses (Bustamante et al., 2014).	Behnassi et al., 2014; Bustamante et al., 2014; P. Smith et al., 2016b
Agriculture and Livestock	Land-based Greenhouse Gas Reduction and Soil Carbon Sequestration	12	Ensure Sustainable Production Patterns (12.3)	↑	[+1]	📖	☺	★	Millet or sorghum yield can double as compared with unimproved land by more than 1 tonne per hectare due to sustainable intensification. An integrated approach to safe applications of both conventional and modern agricultural biotechnologies will contribute to increased yield (Lakshmi et al., 2015).	Campbell et al., 2014; Lakshmi et al., 2015
Agriculture and Livestock	Land-based Greenhouse Gas Reduction and Soil Carbon Sequestration	14			[0]				No direct interaction	
Agriculture and Livestock	Land-based Greenhouse Gas Reduction and Soil Carbon Sequestration	15	Conservation of Biodiversity and Restoration of Land (15.1/15.5/15.9)	↑/↓	[+1,-1]	📖📖📖	☺☺☺	★★★	Agricultural intensification can promote conservation of biological diversity by reducing deforestation, and by rehabilitation and restoration of biodiverse communities on previously developed farm or pasture land. However, planting monocultures on biodiversity hot spots can have adverse side-effects, reducing biodiversity. Genetically modified crops reduce demand for cultivated land. Adaptation of integrated landscape approaches can provide various ecosystem services. CSA enrich linkages across sectors including management of land and bio-resources. Land sparing has the potential to be beneficial for biodiversity, including for many species of conservation concern, but benefits will depend strongly on the use of spared land. In addition, high yield farming involves trade-offs and is likely to be detrimental for wild species associated with farm land (Lamb et al., 2016).	Lybbert and Sumner, 2010; Behnassi et al., 2014; Harvey et al., 2014; IPCC, 2014; Lamb et al., 2016)

Environement-Other (continued)

Sector	Mitigation option	SDG 6 (Interaction / Score / Evidence / Agreement / Confidence)	SDG 12 (Interaction / Score / Evidence / Agreement / Confidence)	SDG 14 (Interaction / Score / Evidence / Agreement / Confidence)	SDG 15 (Interaction / Score / Evidence / Agreement / Confidence)
Agriculture and Livestock	**Greenhouse Gas Reduction from Improved Livestock Production and Manure Management Systems**	**Water Efficiency and Pollution Prevention (6.3/6.4/6.6)** ↑ / ↓ · [+2,-1] · 📖📖📖 · ☺☺☺ · ★★★ Livestock efficiency measures are expected to reduce water required for livestock systems as well as associated livestock waste water flows. However, efficiency measures that include agricultural intensification could increase water demands locally, leading to increased water stress if the intensification is mismanaged. In scenarios where zero human-edible concentrate feed is used for livestock, freshwater use reduces by 21%. Haileselassie et al., 2013; Schader et al., 2015; Kong et al., 2016; Ran et al., 2016	**Ensure Sustainable Production Patterns and Restructing Taxation (12.3/12c)** ↑ · [+1] · 📖📖 · ☺☺ · ★★ In the future, many developed countries will see a continuing trend in which livestock breeding focuses on other attributes in addition to production and productivity, such as product quality, increasing animal welfare, disease resistance (Thornton, 2010). Diet composition and quality are key determinants of the productivity and feed-use efficiency of farm animals (Herrero, et al., 2013). Mechanisms for effecting behavioural change in livestock systems need to be better understood by implementing combinations of incentives and taxes simultaneously in different parts of the world (Herrero and Thornton, 2013). Reducing the amount of human-edible crops that are fed to livestock represents a reversal of the current trend of steep increases in livestock production, and especially of monogastrics, so would require drastic changes in production and consumption (Schader et al., 2015). Thornton, 2010; Herrero and Thornton, 2013; Herrero et al., 2013; Schader et al., 2015	[0] No direct interaction	**Restoration of Land (15.1)** ↑ · [+1] · 📖 · ☺ · ★ Grasslands are valuable, but improved management is required as grass accounts for close to 50% of feed use in livestock systems . The scenario with 100% reduction of food-competing-feedstuffs resulted in a 335 Mha decrease in arable land area, which corresponds to a decrease of 22% in arable and 7% in the total agricultural area . Herrero et al., 2013; Schader et al., 2015
Forest	**Reduced Deforestation, REDD+**	**Water Efficiency and Pollution Prevention (6.3/6.4/6.6)** ↑ / ↓ · [+1,-1] · 📖📖 · ☺☺ · ★★ Forest management alters the hydrological cycle which could be positive or negative from a water perspective and is dependent on existing conditions. Conservation of ecosystem services indirectly could help countries maintain watershed integrity. Forests provide sustainable and regulated provision and help in water purification. Zomer et al., 2008; Kibria, 2015; Bonsch et al., 2016; Gao and Bryan, 2017; Griffiths et al., 2017; Katila et al., 2017	**Ensure Sustainable Consumption (12.3)** ↑ · [+1] · 📖 · ☺ · ★ Reduce the human pressure on forests, including actions to address drivers of deforestation. Bastos Lima et al., 2017	[0] No direct interaction	**Conservation of Biodiversity, Sustainability of Terrestrial Ecosystems (15.2/15.3/15.4/15.5/15.9)** ↑ · [+1] · 📖📖📖 · ☺☺☺ · ★★★ Policies and programmes for reducing deforestation and forest degradation for rehabilitation and restoration of degraded lands can promote conservation of biological diversity. Reduce the human pressure on forests, including actions to address drivers of deforestation. Efforts by the Government of Zambia to reduce emissions by REDD+ have contributed erosion control, ecotourism and pollination valued at 2.5% of the country's GDP. Miles and Kapos, 2008; IPCC, 2014; Bastos Lima et al., 2015; Turpie et al., 2015; Epstein and Theuer, 2017; Katila et al., 2017
Forest	**Afforestation and Reforestation**	**Enhance Water Quality (6.3)** ↑ / ↓ · [+2,-1] · 📖📖📖 · ☺☺☺ · ★★★ Similar to REDD+, forest management alters the hydrological cycle which could be positive or negative from a water perspective and is dependent on existing conditions. Forest landscape restoration can have a large impact on water cycles. Strategic placement of tree belts in lands affected by dryland salinity can remediate the affected lands by modifying landscape water balances. Watershed scale reforestation can result in the restoration of water quality. Fast-growing species can increase nutrient input and water inputs that can cause ecological damage and alter local hydrological patterns. Reforestation of mixed native species and in carefully chosen sites could increase biodiversity and restore waterways, reducing run-off and erosion (Dooley and Kartha, 2018). Zomer et al., 2008; Bustamante et al., 2014; Kibria, 2015; Lamb et al., 2016; Dooley and Kartha, 2018	[0] No direct interaction	**Marine Economies (14.7)/Marine Protection and Income Generation (14.1/14.2/14.4/14.5)** ↑ · [+2] · 📖 · ☺ · ★ Mangroves would help to enhance fisheries and tourism businesses. Kibria, 2015	**Conservation of Biodiversity and Restoration of Land (15.1/15.5/15.9)** ↑ · [+2] · 📖📖📖📖 · ☺☺☺☺ · ★★★★ Identified large amounts of land (749 Mha) globally as biophysically suitable and meeting the CDM eligibility criteria . Forest landscape restoration can conserve biodiversity and reduce land degradation. Mangroves reduce impacts of disasters (cyclones/storms/floods) acting as live seawalls and enhance forest resources/biodiversity. Forest goal can conserve/restore 3.9–8.8 m ha/year average, 77.2–176.9 m ha in total and 7.7–17.7 m ha /year in 2030 of forest area by 2030 (Wolosin, 2014). Forest and biodiversity conservation, protected area formation and forestry-based afforestation are practices that enhance resilience of forest ecosystems to climate change (IPCC, 2014). Strategic placement of tree belts in lands affected by dryland salinity can remediate the affected lands by modifying landscape water balances and protect livestock. It can restore biologically diverse communities on previously developed farmland . Large-scale restoration is likely to benefit ecosystem service provision, including recreation, biodiversity, conservation and flood mitigation. Reforestation of mixed native species and in carefully chosen sites could increase biodiversity, reducing run-off and erosion . Zomer et al., 2008; Bustamante et al., 2014; IPCC, 2014; Kibria, 2015; Lamb et al., 2016; Epstein and Theuer, 2017; Dooley and Kartha, 2018

Environement-Other (continued)

		SDG 6 (Interaction / Score / Evidence / Agreement / Confidence)	SDG 12 (Interaction / Score / Evidence / Agreement / Confidence)	SDG 14 (Interaction / Score / Evidence / Agreement / Confidence)	SDG 15 (Interaction / Score / Evidence / Agreement / Confidence)
Forest	**Behavioural Response (Responsible Sourcing)**	**Water Efficiency and Pollution Prevention (6.3/6.4/6.6)** ↑/↓ [+2,-1] 🕮 ☺☺ ★★ Responsible sourcing will have co-benefits for water efficiency and pollution prevention if the sourcing strategies incorporate water metrics. There is a risk that shifting supply sources could lead to increased water use in another part of the economy. At local levels, forest certification programmes and practicing sustainable forest management provide freshwater supplies. van Oel and Hoekstra, 2012; Launiainen et al., 2014; Hontelez, 2016	**Ensure Sustainable Production Patterns (12.3)** ↑ [+1] 🕮 ☺ ★ At local levels, forest certification programmes and practicing sustainable forest management provide the provision of raw materials for a 'low ecological footprint' economy. Hontelez, 2016	[0] No direct interaction	**Sustainability and Conservation (15.1/15.2/15.3)** ↑/↓ [+1,-1] 🕮 ☺ ★ At the macro level, forest certification has done little to stem the tide of forest degradation, conversion of forest land to agriculture, and illegal logging—all of which remain serious threats to Indonesian forests (Bartley, 2010). At local levels, forest certification programmes and practicing sustainable forest management help in biodiversity protection. Bartley, 2010; Hontelez, 2016
Oceans	**Ocean Iron Fertilization**	[0] No direct interaction	[0] No direct interaction	**Nutrient Pollution, Ocean Acidification, Fish Stocks, MPAs, SISD (14.1/14.3/14.4/14.5/14.7)** ↑/↓ [+1,-2] 🕮🕮🕮 ☺☺ ★ OIF could exacerbate or reduce nutrient pollution, increase the likelihood of mid-water deoxygenation, increase ocean acidification, might contribute to the rebuilding of fish stocks in producing plankton, therefore generating benefits for SISD, but might also be in conflict with designing MPAs. Gnanadesikan et al., 2003; Jin and Gruber, 2003; Denman, 2008; Lampitt et al., 2008; Smetacek and Naqvi, 2008; Güssow et al., 2010; Oschlies et al., 2010; Trick et al., 2010; Williamson et al., 2012	[0] No direct interaction
	Blue Carbon	**Integrated Water Resources Management (6.3/6.5)** ↑ [+2] 🕮 ☺ ★ Development of blue carbon resources (coastal and marine vegetated ecosystems) can lead to coordinated management of water in coastal areas. Vierros et al., 2015	[0] No direct interaction	**Ocean Acidification, Nutrient Pollution (14.3/14.1)** ↑/~ [+2,0] 🕮 ☺☺☺ ★★★ Mangroves could buffer acidification in their immediate vicinity; seaweeds have not been able to mitigate the effect on ocean foraminifera. Pettit et al., 2015; Sippo et al., 2016	**Conservation of Biodiversity and Restoration of Land (15.1/15.2/15.3/15.4/15.9)** ↑ [+3] 🕮 ☺☺☺☺ ★★★★ Average difference of 31 mm per year in elevation rates between areas with seagrass and unvegetated areas (case study areas: Scotland, Kenya, Tanzania and Saudi Arabia); mangroves fostering sediment accretion of about 5mm a year. Alongi, 2012; Potouroglou et al., 2017
	Enhanced Weathering	[0] No direct interaction	[0] No direct interaction	**Ocean Acidification, Nutrient Pollution (14.3/14.1)** ↑/↓ [+2,-1] 🕮🕮🕮 ☺☺☺ ★★★ Enhanced weathering (either by spreading lime or quicklime, in combination with CCS, over the ocean or olivine at beaches or the catchment area of rivers) opposes ocean acidification. "End-of-century ocean acidification is reversed under RCP4.5 and reduced by about two-thirds under RCP8.5; additionally, surface ocean aragonite saturation state, a key control on coral calcification rates, is maintained above 3.5 throughout the low latitudes, thereby helping maintain the viability of tropical coral reef ecosystems ." However, marine biology would also be affected, in particular if spreading olivine is used, which works like ocean (iron) fertilization. Köhler et al., 2010, 2013; Hartmann et al., 2013; Paquay and Zeebe, 2013; P. Smith et al., 2016a; Taylor et al., 2016	**Protect Inland Freshwater Systems (14.1)** ↓ [-2] 🕮 ☺ ★ Olivine can contain toxic metals such as nickel which could accumulate in the environment or disrupt the local ecosystem by changing the pH of the water (in case of spreading in the catchment area of rivers). Hartmann et al., 2013

SDG 7

Sector	Option	Target	Interaction	Score	Evidence	Agreement	Confidence	Explanation	References
Industry	Accelerating Energy Efficiency Improvement	**Energy Savings (7.1/7.3/7.a/7.b)**	↑	[+2]	🕮🕮🕮🕮	☺☺☺	★★★★	Energy efficiency leads to reduced energy demand and hence energy supply and energy security, reduces import. Positive rebound effect can raise demand but to a very less extent due to low rebound effect in industry sector in many countries and by appropriate mix of industries (China) can maintain energy savings gain. Supplying surplus energy to cities is also happening, proving maintenance culture, switching off idle equipment helps in saving energy (e.g Ghana).	Apeaning and Thollander, 2013; Chakravarty et al., 2013; IPCC, 2014; Karner et al., 2015; Zhang et al., 2015; Li et al., 2016; Fernando et al., 2017; Wesseling et al., 2017
Industry	Low-Carbon Fuel Switch	**Sustainable and Modern (7.2/7.a)**	↑	[+2]	🕮	☺	★	Industries are becoming suppliers of energy, waste heat, water and roof tops used for solar energy generation, and therefore helping to reduce primary energy demand. CHP in chemical industries can help in providing surplus power in the grid.	Karner et al., 2015; Griffin et al., 2018
Industry	Decarbonization/CCS/CCU	**Affordable and Sustainable Energy Sources**	↑ / ↓	[+2,-2]	🕮🕮	☺☺	★★	CCS for EPIs can be incremental, but need additional space and can need additional energy, sometimes compensating for higher efficiency. For example, recirculating blast R furnace and CCS for iron steel means high energy demand; electric melting in glass can mean higher electricity prices; in the paper industry, new separation and drying technologies are key to reducing the energy intensity, allowing for carbon neutral operation in the future; bio-refineries can reduce petro-refineries; DRI in iron and steel with H2 encourages innovation in hydrogen infrastructure; and the chemicals industry also encourage renewable electricity and hydrogen as bio-based polymers can increase biomass price.	Griffin et al., 2017; Wesseling et al., 2017

SDG 8

Sector	Option	Target	Interaction	Score	Evidence	Agreement	Confidence	Explanation	References
Industry	Accelerating Energy Efficiency Improvement	**Reduces Unemployment (8.2/8.3/8.4/8.5/8.6)**	↑	[+1]	🕮🕮	☺☺☺	★★★	Unemployment rate reduction from 25% to 12% in South Africa. Enhances firm productivity and technical and managerial capacity of the employees. New jobs for managing energy efficiency opens up opportunities in energy service delivery sector.	Altieri et al., 2016; Fernando et al., 2017; Johansson and Thollander, 2018
Industry	Low-Carbon Fuel Switch	**Economic Growth with Decent Employment (8.1/8.2/8.3/8.4)**	↑	[+2]	🕮🕮🕮🕮	☺☺☺☺	★★★★	The circular economy instead of linear global economy can achieve climate goals and can help in economic growth through industrialization, which saves on resources and the environment and supports small, medium and even large industries, which can lead to employment generation. So new regulations, incentives and a revised tax regime can help in achieving the goal.	Stahel, 2013, 2017; Liu et al., 2014; Leider et al., 2015; Supino et al., 2015; Zheng et al., 2016; Fan et al., 2017; Shi et al., 2017
Industry	Decarbonization/CCS/CCU	**Decouple Growth from Environmental Degradation (8.1/8.2/8.4)**	↑	[+2]	🕮🕮	☺☺☺	★★★	EPI s are important players for economic growth. Deep decarbonization of EPIs through radical innovation is consistent with well-below 2°C scenarios.	Denis-Ryan et al., 2016; Åhman et al., 2017; Wesseling et al., 2017

SDG 9

Sector	Option	Target	Interaction	Score	Evidence	Agreement	Confidence	Explanation	References
Industry	Accelerating Energy Efficiency Improvement	**Infrastructure Renewal (9.1/9.3/9.5/9.a)**	↑	[+1]	🕮🕮	☺☺	★★	Transitioning to a more renewables-based energy system that is highly energy efficient is well-aligned with the goal of upgrading energy infrastructure and making the energy industry more sustainable. At the same time, infrastructure upgrades in other parts of the economy, such as modernized telecommunications networks, can create the conditions for a successful expansion of renewable energy and energy efficiency measures (e.g., smart metering and demand-side management; McCollum et al., 2018).	Riahi et al., 2012; Apeaning and Thollander, 2013; Goldthau, 2014; Bhattacharyya et al., 2016; Meltzer, 2016; McCollum et al., 2018
Industry	Low-Carbon Fuel Switch	**Innovation and New Infrastructure (9.2/9.3/9.4/9.5/9.a)**	↑	[+2]	🕮🕮🕮🕮	☺☺☺☺	★★★★	A circular economy instead of linear global economy is helping new innovation, and infrastructure can achieve climate goals and can help in economic growth through industrialization which saves on resources and the environment and supports small, medium and even large industries, which can lead to employment generation. So new regulations, incentives and revised tax regime can help in achieving the goal.	Stahel, 2013, 2017; Liu et al., 2014; Leider et al., 2015; Supino et al., 2015; Zheng et al., 2016; Fan et al., 2017; Shi et al., 2017
Industry	Decarbonization/CCS/CCU	**Innovation and New Infrastructure (9.2/9.4/9.5)**	↑	[+2]	🕮	☺☺☺☺	★★★★	Deep decarbonization through radical technological change in EPI will lead to radical innovations, for example, in completely changing industries' innovation strategies, plants and equipment, skills, production techniques, design, etc. Radical CCS will need new infrastructure to transport CO_2.	Denis-Ryan et al., 2016; Åhman et al., 2017; Wesseling et al., 2017; Griffin et al., 2018

SDG 11

Sector	Option	Target	Interaction	Score	Evidence	Agreement	Confidence	Explanation	References
Industry	Accelerating Energy Efficiency Improvement	**Sustainable Cities (15.6/15.8/15.9)**	↑	[+2]	🕮	☺	★	Industries are becoming suppliers of energy, waste heat and water to neighbourial human settlements, and therefore there is a reduced primary energy demand, which also makes towns and cities grow sustainably.	Karner et al., 2015
Industry	Low-Carbon Fuel Switch	**Sustainable Cities (15.6/15.8/15.9)**	↑	[+2]	🕮	☺	★	Industries are becoming suppliers of energy, waste heat, water and roof tops used for solar energy generation, and supply to neighbourial human settlements, therefore reducing primary energy demand, which also makes towns and cities grow sustainably.	Karner et al., 2015
Industry	Decarbonization/CCS/CCU			[0]				No direct interaction	

Economic-Demand (continued)

Sector	Option	SDG target	Interaction	Score	Evidence	Agreement	Confidence	Explanation	References
Buildings	Behavioural Response	Saving Energy, Improvement in Energy Efficiency (7.3/7.a/7.b)	↑	[+2]	📖📖📖📖	☺☺☺☺	★★★	Lifestyle change measures and adoption behaviour affect residential energy use and implementation of efficient technologies as residential HVAC systems. Also, social influence can drive energy savings in users exposed to energy consumption feedback. Effect of autonomous motivation on energy savings behaviour is greater than that of other more established predictors, such as intentions, subjective norms, perceived behavioural control and past behaviour. Use of a hybrid engineering approach using social psychology and economic behaviour models are suggested for residential peak electricity demand response. However, some take-back in energy savings can happen due to rebound effects unless managed appropriately or accounted for welfare improvement. Adjusting thermostats helps in saving energy. Uptake of energy efficient appliances by households with an introduction to appliance standards, training, promotional material dissemination and the desire to save on energy bills are helping to change acquisition behaviour.	Chakravarty et al., 2013; Gyamfi et al., 2013; Hori et al., 2013; Huebner et al., 2013; Jain et al., 2013; Sweeney et al., 2013; Webb et al., 2013; Yue et al., 2013; Anda and Temmen, 2014; Allen et al., 2015; Noonan et al., 2015; de Koning et al., 2016; Isenhour and Feng, 2016; Santarius et al., 2016; Song et al., 2016; van Sluisveld et al., 2016; Sommerfeld et al., 2017; Zhao et al., 2017; Roy et al., 2018
		Progressively Improve Resource Efficiency (8.4), Employment Opportunities (8.2/8.3/8.5/8.6)	↑	[+2]	📖	☺	★	Behavioural change programmes help in sustaining energy savings through new infrastructure developments.	Anda and Temmen, 2014
		Innovation and New Infrastructure (9.2/9.4/9.5)	↑	[+2]	📖📖	☺☺	★★	Adoption of smart meters and smart grids following community-based social marketing help with infrastructure expansion. People are adopting solar rooftops, white roof/vertical garden/green roofs at much faster rates due to new innovations and regulations.	Anda and Temmen, 2014; Roy et al., 2018
		Sustainable Cities (15.6/15.8/15.9)	↑	[+2]	📖📖	☺☺	★★	Behavioural change programmes help in making cities more sustainable.	Anda and Temmen, 2014; Roy et al., 2018
	Accelerating Energy Efficiency Improvement	Increase in Energy Savings (7.3)	↑	[+2]	📖📖📖	☺☺☺	★★★★	There is high agreement among researchers based on a great deal of evidence across various countries that energy efficiency improvement reduces energy consumption and therefore leads to energy savings (e.g., efficient stoves save bioenergy). Countries with higher hours of use due to higher ambient temperatures or more carbon intensive electricity grids benefit more from available improvements in energy efficiency and use of refrigerant transition.	McLeod et al., 2013; Noris et al., 2013; Bhojvaid et al., 2014; Holopainen et al., 2014; Kwong et al., 2014; Yang et al., 2014; Cameron et al., 2015; Liddell and Guiney, 2015; Shah et al., 2015; Berrueta et al., 2017; Kim et al., 2017; Salvalai et al., 2017
		Employment Opportunities (8.2/8.3/8.5/8.6)/Strong Financial Institutions (8.10)	↑ / ↓	[+2,-1]	📖📖	☺	★★	Deploying renewables and energy efficient technologies, when combined with other targeted monetary and fiscal policies, can help spur innovation and reinforce local, regional and national industrial and employment objectives. Gross employment effects seem likely to be positive; however, uncertainty remains regarding the net employment effects due to several uncertainties surrounding macro-economic feedback loops playing out at the global level. Moreover, the distributional effects experienced by individual actors may vary significantly. Strategic measures may need to be taken to ensure that a large-scale switch to renewable energy minimizes any negative impacts on those currently engaged in the business of fossil fuels (e.g., government support could help businesses re-tool and workers re-train). To support clean energy and energy efficiency efforts, strengthened financial institutions in developing country communities are necessary for providing capital, credit and insurance to local entrepreneurs attempting to enact change (McCollum et al., 2018).	Babiker and Eckaus, 2007; Fankhauser and Tepic, 2007; Gohin, 2008; Frondel et al., 2010; Dinkelman, 2011; Guivarch et al., 2011; Jackson and Senker, 2011; Borenstein, 2012; Creutzig et al., 2013; Blyth et al., 2014; Clarke et al., 2014; Dechezleprêtre and Sato, 2014; Bertram et al., 2015; Johnson et al., 2015; IRENA, 2016; A. Smith et al., 2016; Berrueta et al., 2017; McCollum et al., 2018
		Innovation and New Infrastructure (9.2/9.4/9.5)	↑	[+2]	📖📖	☺☺	★★	Adoption of smart meters and smart grids following community-based social marketing help in infrastructure expansion. Statutory norms to enhance energy and resource efficiency in buildings is encouraging green building projects.	Anda and Temmen, 2014; Roy et al., 2018
		Urban Environmental Sustainability (11.3/11.6/11.b/11.c)	↑	[+2]	📖📖	☺☺☺	★★★★	Renewable energy technologies and energy efficient urban infrastructure solutions (e.g., public transit) can also promote urban environmental sustainability by improving air quality and reducing noise. Efficient transportation technologies powered by renewably based energy carriers will be a key building block of any sustainable transport system (McCollum et al., 2018). Green buildings help in sustainable construction.	Creutzig et al., 2012; Kahn Ribeiro et al., 2012; Riahi et al., 2012; Bongardt et al., 2013; Grubler and Fisk, 2013; Raji et al., 2015; Kim et al., 2017; McCollum et al., 2018

Economic-Demand (continued)

Sector	Option	SDG	Target	Interaction	Score	Evidence	Agreement	Confidence	Description	References
Buildings	Improved Access and Fuel Switch to Modern Low-carbon Energy	7	Meeting Energy Demand	↑	[+2]	🕮🕮🕮	☺☺☺	★★★	Renewable energies could potentially serve as the main source to meet energy demand in rapidly growing developing country cities. Ali et al. (2015) estimated the potential of solar, wind and biomass renewable energy options to meet part of the electricity demand in Karachi, Pakistan.	Li et al., 2013; Peng and Lu, 2013; Pietzcker, 2013; Pode, 2013; Yanine and Sauma, 2013; Zulu and Richardson, 2013; Connolly et al., 2014; Creutzig et al., 2014; Pietzcker et al., 2014; Ali et al., 2015; O'Mahony and Dufour, 2015; Abanda et al., 2016; Mittlefehldt, 2016; Biligii et al., 2017; Byravan et al., 2017; Islar et al., 2017; Ozturk et al., 2017
Buildings	Improved Access and Fuel Switch to Modern Low-carbon Energy	8	Sustainable Economic Growth and Employment	↑	[+2]	🕮🕮	☺☺☺	★★	Creutzig et al. (2014) assessed the potential for renewable energies in the European region. They found that a European energy transition with a high-level of renewable energy installations in the periphery could act as an economic stimulus, decrease trade deficits and possibly have positive employment effects. Provision of energy access can play a critical enabling role for new productive activities, livelihoods and employment. Reliable access to modern energy services can have an important influence on productivity and earnings (McCollum et al., 2018).	Grogan and Sadanand, 2013; Pueyo et al., 2013; Rao et al., 2013; Chakravorty et al., 2014; Creutzig et al., 2014; Ali et al., 2015; Bernard and Torero, 2015; Byravan et al., 2017; McCollum et al., 2018
Buildings	Improved Access and Fuel Switch to Modern Low-carbon Energy	9	Innovation and New Infrastructure (9.2/9.4/9.5)	↑	[+2]	🕮🕮	☺☺	★★	Adoption of smart meters and smart grids following community-based social marketing help in infrastructure expansion. Statutory norms to enhance energy and resource efficiency in buildings is encouraging green building projects. Introduction of incentives and norms for solar rooftops/white/green roofs in cities are helping to accelerate innovation and the expansion of infrastructure.	Roy et al., 2018; Anda and Temmen, 2014
Buildings	Improved Access and Fuel Switch to Modern Low-carbon Energy	11	Housing (11.1)	↑	[+3]	🕮🕮🕮	☺☺☺	★★★★	Ensuring access to basic housing services implies that households have access to modern energy forms. (Quote from McCollum et al., 2018) Solar roof tops in Macau make cities sustainable. Introduction of incentives and norms for solar/white/green rooftops in cities are helping to accelerate the expansion of the infrastructure.	Bhattacharyya et al., 2016; Song et al., 2016; UN, 2016; McCollum et al., 2018; Roy et al., 2018
Transport	Behavioural Response	7	Energy Savings (7.3/7.a/7.b)	↑	[+2]	🕮🕮	☺☺	★★	Behavioural responses will reduce the volume of transport needs and, by extension, energy demand.	Figueroa and Ribeiro, 2013; Ahmad and Puppim de Oliveira, 2016
Transport	Behavioural Response	8	Promote Sustained, Inclusive Economic Growth (8.3)	↓	[-2]	🕮🕮🕮	☺☺☺	★★★	Policy contradictions (e.g., standards, efficient technologies leading to increased electricity prices leading the poor to switch away from clean(er) fuels) and unintended outcomes (e.g., redistribution of income generated by carbon taxes) results in contradictions of the primary aims of (productive) job creation and poverty alleviation, and in trade-offs between mitigation, adaptation and development policies. Detailed assessments of mitigation policies consequences requires developing methods and reliable evidence to enable policymakers to more systematically identify how different social groups may be affected by the different available policy options.	Lucas and Pangbourne, 2014; Suckall et al., 2014; Klausbruckner et al., 2016
Transport	Behavioural Response	9	Build Resilient Infrastructure (9.1)	↑	[+2]	🕮🕮	☺☺	★★	As people prefer more mass transportation – train lines, tram lines, BRTs, gondola lift systems, bicycle-sharing systems and hybrid buses – and telecommuting, the need for new infrastructure increases.	Dulac, 2013; Aamaas and Peters, 2017; Martínez-Jaramillo et al., 2017; Xylia and Silveira, 2017
Transport	Behavioural Response	11	Make Cities and Human Settlements Inclusive, Safe, Resilient	↑	[+2]	🕮🕮	☺☺	★★	Climate change threatens to worsen poverty, therefore pro-poor mitigation policies are needed to reduce this threat; for example, investing more and better in infrastructure by leveraging private resources and using designs that account for future climate change and the related uncertainty.	Ahmad and Puppim de Oliveira, 2016; Hallegatte et al., 2016a
Transport	Accelerating Energy Efficiency Improvement	7	Energy Savings (7.3/7.a/7.b)	↑	[+2]	🕮	☺	★	Accelerating efficiency in tourism transport reduces energy demand (China).	Shukxin et al., 2016
Transport	Accelerating Energy Efficiency Improvement	8	Promote Sustained, Inclusive Economic Growth (8.3)	↑/↓	[+2,-2]	🕮🕮	☺☺	★★	Significant opportunities to slow travel growth and improve efficiency exist and, similarly, alternatives to petroleum exist but have different characteristics in terms of availability, cost, distribution, infrastructure, storage and public acceptability. Production of new technologies, fuels and infrastructure can favour economic growth; however, efficient financing of increased capital spending and infrastructure is critical.	Gouldson et al., 2015; Karkatsoulis et al., 2016
Transport	Accelerating Energy Efficiency Improvement	9	Build Resilient Infrastructure (9.1)	↑	[+2]	🕮🕮	☺☺	★★	Combining promotion of mass transportation – train lines, tram lines, BRTs, gondola lift systems, bicycle-sharing systems and hybrid buses – and telecommuting reduces traffic and significantly contributes to meeting climate targets. A comprehensive package of complementary mitigation options is necessary for deep and sustained emissions reductions. In Sweden, a public bus fleet is aiming more towards decarbonization than efficiency.	Dulac, 2013; Aamaas and Peters, 2017; Martínez-Jaramillo et al., 2017; Xylia and Silveira, 2017
Transport	Accelerating Energy Efficiency Improvement	11	Make Cities Sustainable (11.2/11.3)	↑	[+2]	🕮	☺	★	The two most important elements of making cities sustainable are efficient buildings and transport (e.g., Macau).	Song et al., 2016
Transport	Improved Access and Fuel Switch to Modern Low-carbon Energy	7	Increase Share of Renewable (7.2)	↑	[+2]	🕮🕮	☺☺	★★	Biofuel increases share of the renewables but can perform poorly if too many countries increase their use of biofuel, whereas electrification performs best when many other countries implement this technology. The strategies are not mutually exclusive and simultaneous implementation of some provides synergies for national energy security. Therefore, it is important to consider the results of material and contextual factors that co-evolve. Electric vehicles using electricity from renewables or low carbon sources combined with e-mobility options such as trolley buses, metros, trams and electro buses, as well as promote walking and biking, especially for short distances, need consideration.	Ajanovic, 2015; Månsson, 2016; Alahakoon, 2017; Wolfram et al., 2017
Transport	Improved Access and Fuel Switch to Modern Low-carbon Energy	8	Promote Sustained, Inclusive Economic Growth (8.3)	↑/↓	[+2,-2]	🕮🕮	☺☺	★★	The decarbonization of the freight sector tends to occur in the second part of the century, and the sector decarbonizes by a lower extent than the rest of the economy. Decarbonizing road freight on a global scale remains a challenge even when notable progress in biofuels and electric vehicles has been accounted for.	IPCC, 2014; Creutzig et al., 2015; Carrara and Longden, 2017
Transport	Improved Access and Fuel Switch to Modern Low-carbon Energy	9	Help Building Inclusive Infrastructure (9.1/9.a)	↑	[+2]	🕮🕮🕮	☺☺☺	★★★	Lack of appropriate infrastructure leads to limited access to jobs for the urban poor (Africa, Latin America, India).	Figueroa et al., 2013; Gouldson et al., 2015; Vasconcellos and Mendonça, 2016; Lall et al., 2017
Transport	Improved Access and Fuel Switch to Modern Low-carbon Energy	11	Make Cities and Human Settlements Inclusive, Safe, Resilient	↑	[+2]	🕮🕮	☺☺	★★	In rapidly growing cities, the carbon savings from investments at scale, in cost-effective low-carbon measures, could be quickly overwhelmed – in as little as 7 years – by the impacts of sustained population and economic growth, highlighting the need to build capacities that enable the exploitation not only of the economically attractive options in the short term but also of those deeper and more structural changes that are likely to be needed in the longer term. With hybrid electric vehicles and plug-in electric vehicles, there is the emergence of new concepts in transportation, such as electric highways.	Figueroa et al., 2013; Gouldson et al., 2015; Vasconcellos and Mendonça, 2016; Alahakoon, 2017

		SDG 7	Interaction	Score	Evidence	Agreement	Confidence	Description	References
Replacing Coal	Non-biomass Renewables - solar, wind, hydro	Sustainable and Modern Energy (7.2/7.a)	↑	[+3]	🕮🕮🕮	☺☺☺	★★★★	Decarbonization of the energy system through an upscaling of renewables will greatly facilitate access to clean, affordable and reliable energy. Hydropower plays an increasingly important role for the global electricity supply. This mitigation option is in line with the targets of SDG7 under the caveat of a transition to modern biomass.	Rogelj et al., 2013; Cherian, 2015; Jingura and Kamusoko, 2016
Replacing Coal	Increased Use of Biomass	Sustainable and Modern Energy (7.2/7.a)	↑	[+3]	🕮🕮🕮	☺☺☺	★★★	Increased use of modern biomass will facilitate access to clean, affordable and reliable energy. This mitigation option is in line with the targets of SDG7.	Rogelj et al., 2013; Cherian, 2015; Jingura and Kamusoko, 2016
Replacing Coal	Nuclear/Advanced Nuclear	Sustainable and Modern Energy (7.2/7.a)	↑	[1]	🕮🕮	☺	★★	Increased use of nuclear power can provide stable baseload power supply and reduce price volatility.	IPCC, 2014
Replacing Coal	CCS: Bioenergy	Sustainable and Modern Energy (7.2/7.a)	↑	[+2]	🕮🕮🕮	☺☺☺	★★★	Increased use of modern biomass will facilitate access to clean, affordable and reliable energy.	IPCC, 2014
Advanced Coal	CCS: Fossil	Ensure energy access and promote investment in new technologies (7.1/7.b)	↑	[+2]	🕮🕮🕮	☺☺☺	★★★	Advanced and cleaner fossil fuel technology is in line with the targets of SDG7.	IPCC, 2014

		SDG 8	Interaction	Score	Evidence	Agreement	Confidence	Description	References
Replacing Coal	Non-biomass Renewables - solar, wind, hydro	Innovation and Growth (8.1/8.2/8.4)	~	[0]	🕮🕮	☺☺	★★	Decarbonization of the energy system through an upscaling of renewables and energy efficiency is consistent with sustained economic growth and resource decoupling. Long-term scenarios point towards slight consumption losses caused by a rapid and pervasive expansion of such energy solutions. Whether sustainable growth, as an overarching concept, is attainable or not is more disputed in the literature. Existing literature is also undecided as to whether or not access to modern energy services causes economic growth (McCollum et al., 2018).	Jackson and Senker, 2011; Bonan et al., 2014; Clarke et al., 2014; NCE, 2014; OECD, 2017; York and McGee, 2017; McCollum et al., 2018
Replacing Coal	Increased Use of Biomass	Innovation and Growth (8.1/8.2/8.4)	↑	[+1]	🕮	☺	★	Decarbonization of the energy system through an upscaling of renewables will greatly facilitate access to clean, affordable and reliable energy.	Jingura and Kamusoko, 2016
Replacing Coal	Nuclear/Advanced Nuclear	Innovation and Growth (8.1/8.2/8.4)	↑	[1]	🕮🕮	☺	★★	Local employment impact and reduced price volatility.	IPCC, 2014
Replacing Coal	CCS: Bioenergy	Innovation and Growth (8.1/8.2/8.4)	↑	[+1]	🕮	☺	★	See positive impacts of bioenergy use.	
Advanced Coal	CCS: Fossil	Innovation and Growth (8.1/8.2/8.4)	↓	[-1]	🕮🕮🕮	☺☺☺	★★★	Lock-in of human and physical capital in the fossil resources industry.	IPCC, 2005, 2014; Benson and Cole, 2008; Fankhaeser et al., 2008; Vergragt et al., 2011; Markusson et al., 2012; Shackley and Thompson, 2012; Bertram et al., 2015; Johnson et al., 2015

		SDG 9	Interaction	Score	Evidence	Agreement	Confidence	Description	References
Replacing Coal	Non-biomass Renewables - solar, wind, hydro	Inclusive and Sustainable Industrialization (9.2/9.4)	~ / ↓	[0,-1]	🕮🕮	☺☺☺	★★	A rapid upscaling of renewable energies could necessitate the early retirement of fossil energy infrastructure (e.g., power plants, refineries, pipelines) on a large scale. The implications of this could in some cases be negative, unless targeted policies can help alleviate the burden on industry (McCollum et al., 2018).	Fankhaeser et al., 2008; McCollum et al., 2008; Guivarch et al., 2011; Bertram et al., 2015; Johnson et al., 2015
Replacing Coal	Increased Use of Biomass	Innovation and New Infrastructure (9.2/9.4/9.5)	↑	[+1]	🕮🕮	☺☺☺	★★	Access to modern and sustainable energy will be critical to sustain economic growth.	Jingura and Kamusoko, 2016; Shahbaz et al., 2016
Replacing Coal	Nuclear/Advanced Nuclear	Innovation and New Infrastructure (9.2/9.4/9.5)	↓	[-1]	🕮🕮	☺☺☺	★★★	Legacy cost of waste and abandoned reactors.	Marra and Palmer, 2011; Greenberg et al., 2013; Schwenk-Ferrero, 2013; Skipperud et al., 2013; Tyler et al., 2013; IPCC, 2014
Replacing Coal	CCS: Bioenergy	Innovation and New Infrastructure (9.2/9.4/9.5)	↑	[+1]	🕮	☺	★	See positive impacts of bioenergy use and CCS/CCU in industrial demand.	
Advanced Coal	CCS: Fossil	Innovation and New Infrastructure (9.2/9.4/9.5)	↑	[+1]	🕮	☺	★	See positive impacts of CCS/CCU in industrial demand.	

		SDG 11	Interaction	Score	Evidence	Agreement	Confidence	Description	References
Replacing Coal	Non-biomass Renewables - solar, wind, hydro	Disaster Preparedness and Prevention (11.5)	↑	[+2]	🕮🕮🕮	☺☺	★★★	Deployment of renewable energy and improvements in energy efficiency globally will aid climate change mitigation efforts, and this, in turn, can help to reduce the exposure of people to certain types of disasters and extreme events (McCollum et al., 2018).	Tully, 2006; Riahi et al., 2012; Daut et al., 2013; IPCC, 2014; Hallegatte et al., 2016b; McCollum et al., 2018
Replacing Coal	Increased Use of Biomass			[0]				No direct interaction	
Replacing Coal	Nuclear/Advanced Nuclear			[0]				No direct interaction	
Replacing Coal	CCS: Bioenergy			[0]				No direct interaction	
Advanced Coal	CCS: Fossil			[0]				No direct interaction	

Agriculture and Livestock

SDG 7

Response	Target	Interaction	Score	Evidence	Agreement	Confidence	Description	References
Behavioural Response: Sustainable Healthy Diets and Reduced Food Waste	Energy Efficiency, Universal Access (7.1/7.3)	↑	[+1]	🕮	☺	★	Reducing global food supply chain losses have several important secondary benefits like conserving energy.	Kummu et al., 2012
Land-based Greenhouse Gas Reduction and Soil Carbon Sequestration	Sustainable and Modern Energy (7.b)	↑	[+1]	🕮🕮🕮	☺☺☺	★★★	Conventional agricultural biotechnology methods such as energy efficient farming can help in sequestration of soil carbon. Modern biotechnologies such as green energy and N-efficient GM crops can also help in C-sequestration. Biotech crops allow farmers to use less – and environmentally friendly – energy and practice soil carbon sequestration. Biofuels, both from traditional and GMO crops, such as sugar cane, oilseed, rapeseed and jatropha, can be produced. Green energy programmes through plantations of perennial nonedible oilseed producing plants and production of biodiesel for direct use in the energy sector or blending biofuels with fossil fuels in certain proportions can thereby minimize fossil fuel use. (Quoted from Lakshmi et al., 2015) GM crops reduce demand for fossil fuel-based inputs.	Johnson et al., 2007; Sarin et al., 2007; Treasury, 2009; Jain and Sharma, 2010; Lybbert and Sumner, 2010; Mtui, 2011; Lakshmi et al., 2015
Greenhouse Gas Reduction from Improved Livestock Production and Manure	Energy Efficiency (7.3)	↑	[+1]	&	J	«	Scenarios where zero human-edible concentrate feed is used for livestock, non-renewable energy use is reduced by 36%.	Schader et al., 2015

SDG 8

Response	Target	Interaction	Score	Evidence	Agreement	Confidence	Description	References
Behavioural Response: Sustainable Healthy Diets and Reduced Food Waste	Sustained and Inclusive Economic Growth (8.2)	↑	[+1]	🕮🕮🕮	☺☺☺	★★★	23–24% of total cropland and fertilizers are used to produce losses. So reduction in food losses will help to diversify these valuable resources into other productive activities.	Kummu et al., 2012; Hiç et al., 2016
Land-based Greenhouse Gas Reduction and Soil Carbon Sequestration	Sustainable Growth (8.2)	↑/↓	[+2,-1]	🕮🕮	☺☺	★★	Many developing countries including Gulf States will benefit from CSA given the central role of agriculture in their economic and social development. (Quoted from Behnassi et al. 2014). Low commodity prices have reduced the incentive to invest in yield growth and have led to declining farm labour and farm capital investment. (Quoted from Lamb et al., 2016)	Behnassi et al., 2014; Lamb et al., 2016
Greenhouse Gas Reduction from Improved Livestock Production and Manure	Sustainable Economic Growth (8.4)	↑	[+1]	&	J	«	Exploiting the increasingly decoupled interactions between crops and livestock could be beneficial for promoting structural changes in the livestock sector and is a prerequisite for the sustainable growth of the sector. (Quoted from Herrero et al., 2013)	Herrero and Thornton, 2013; Herrero et al., 2013

SDG 9

Response	Target	Interaction	Score	Evidence	Agreement	Confidence	Description	References
Behavioural Response: Sustainable Healthy Diets and Reduced Food Waste	Infrastructure Building and Promotion of Inclusive Industrialization (9.1/9.2)	↑	[+1]	🕮🕮🕮	☺☺☺	★★★	By targeting infrastructure, processing and distribution losses, wastage in food systems can be minimized. 23–24% of total cropland and fertilizers are used to produce losses. So reduction in food losses will help to diversify these valuable resources into other productive activities.	Ingram, 2011; Beddington et al., 2012; Kummu et al., 2012; Hiç et al., 2016; Lamb et al., 2016
Land-based Greenhouse Gas Reduction and Soil Carbon Sequestration	Infrastructure Building, Promotion of Inclusive Industrialization and Innovation (9.1/9.2/9.5/9.b)	↑/↓	[+2,-2]	🕮🕮🕮	☺☺☺	★★★	Reduced research support and delayed industrialization will have an adverse effect on food security and nourishment of children. Organic farming technologies utilizing bio-based fertilizers (composted human and animal manure) are some of the conventional biotechnological options for reducing artificial fertilizer use (Lakshmi et al., 2015). CSA requires huge financial investment and institutional innovation. CSA is committed to new ways of engaging in participatory research and partnerships with producers (Steenwerth et al., 2014). Technologies used on-farm and during food processing to increase productivity which also helps in adaptation and/or mitigation are new, so convincing potential customers is difficult. Also, low-awareness of CSA, inaccessible language, high costs, lack of verified impact of technologies, hard to reach and train farmers, low consumer demand and unequal distribution of costs/benefits across supply chains are barriers to CSA technology adoption (Long et al., 2016). Low commodity prices have reduced the incentive to invest in yield growth and have led to declining investment in research and development (Lamb et al., 2016).	Evenson, 1999; Behnassi et al., 2014; Steenwerth et al., 2014; Lakshmi et al., 2015; Lamb et al., 2016; Long et al., 2016
Greenhouse Gas Reduction from Improved Livestock Production and Manure	Technological Upgradation and Innovation (9.2)	↑	[+2]	🕮🕮🕮	☺☺☺	★★★	Complete genome maps for poultry and cattle now exist, and these open up the way to possible advances in evolutionary biology, animal breeding and animal models for human diseases. Genomic selection should be able to at least double the rate of genetic gain in the dairy industry. (Quoted from Thornton, 2010) Nanotechnology, biogas technology and separation technologies are disruptive technologies that enhance biogas production from anaerobic digesters or to reduce odours.	Sansoucy, 1995; Burton, 2007; Thornton, 2010

SDG 11

Response	Target	Interaction	Score	Evidence	Agreement	Confidence	Description	References
Behavioural Response: Sustainable Healthy Diets and Reduced Food Waste			[0]				No interaction	
Land-based Greenhouse Gas Reduction and Soil Carbon Sequestration			[0]				no direct interaction	
Greenhouse Gas Reduction from Improved Livestock Production and Manure			[0]				No direct interaction	

Economic-Other (continued)

		SDG 7 (Interaction / Score / Evidence / Agreement / Confidence)	SDG 8 (Interaction / Score / Evidence / Agreement / Confidence)	SDG 9 (Interaction / Score / Evidence / Agreement / Confidence)	SDG 11 (Interaction / Score / Evidence / Agreement / Confidence)
Forest	**Reduced Deforestation, REDD+**	**Energy Efficiency (7.3)** ↑/↓ [+1,-1] 🕮 ☺ ★ Consider the entire sinks and reservoirs of GHG while developing the nationally appropriate mitigation actions. For countries with a significant contribution of forest degradation (and GHG emissions) from wood fuels, this should be considered. (Quoted from Bastos Lima et al., 2017). Biomass for energy is recognized as often being inefficient, and is often harvested in an unsustainable manner, but is a renewable energy source. Bastos Lima et al., 2017; Katila et al., 2017	**Sustainable Economic Growth (8.4)** ↑ [+1] 🕮 ☺ ★ Efforts by the Government of Zambia to reduce emissions by REDD+ have contributed to erosion control, ecotourism and pollination valued at 2.5% of the country's GDP. Partnerships between local forest managers, community enterprises and private sector companies can support local economies and livelihoods, and boost regional and national economic growth. Turpie et al., 2015; Epstein and Theuer, 2017; Katila et al., 2017	**Infrastructure, Promotion of Inclusive Industrialization (9.1/9.2/9.5)** ↑/↓ [+1,-1] 🕮 ☺ ★ Expanding road networks are recognized as one of the main drivers of deforesting and forest degradation, diminishing forest benefits to communities, On the other hand, roads can enhance market access, thereby boosting local benefits (SDG 1) from the commercialization of forest products. (Quoted from Katila et al., 2017). Efforts by the Government of Zambia to reduce emissions by REDD+ have contributed to erosion control, ecotourism and pollination valued at 2.5% of the country's GDP. Turpie et al., 2015; Epstein and Theuer, 2017; Katila et al., 2017	[0] No direct interaction
	Afforestation and Reforestation	**Energy Conservation (7.3/7.b)** ↑ [+1] 🕮 ☺ ★ The US Forest Service estimates that an average NYC street tree (urban afforestation) produces 209 USD in annual benefits, which is primarily driven by aesthetic (90 USD per tree) and energy savings (from shade) benefits (47.63 USD per tree). Jones and McDermott, 2018	**Decent Job Creation and Sustainable Economic Growth (8.3/8.4)** ↑ [+2] 🕮🕮 ☺☺ ★★ Many tree plantations worldwide have higher growth rates which can provide higher rates of returns for investors. Agroforestry initiatives that offer significant opportunities for projects to provide benefits to smallholder farmers can also help address land degradation through community-based efforts in more marginal areas. Mangroves reduce impacts of disasters (cyclones/storms/floods) and enhance water quality, fisheries, tourism businesses and livelihoods. Zomer et al., 2008; Kibria, 2015	[0] No direct interaction	**Improving Air Quality, Green and Public Spaces (11.6/11.7/11.a/11.b)** ↑ [+2] 🕮🕮🕮🕮 ☺☺☺☺ ★★★★ Many urban tree plantations worldwide are created with a focus on multiple benefits, like air quality improvement, cultural preference for green nature, healthy community interaction as well as temperature control and biodiversity enhancement goals. Chen and Qi, 2018; Fu et al., 2018; Kowarik, 2018; McKinney and Ingo, 2018; McPherson et al., 2018; Pei et al., 2018
	Behavioural Response (Responsible Sourcing)	**Universal Access (7.3)** ↑ [+1] 🕮 ☺ ★ The trade of wood pellets from clean wood waste should be facilitated with less administrative import barriers by the EU, in order to have this new option seriously accounted for as a future resource for energy. (Quoted from Sikkema et al., 2014) Recommends further harmonization of legal harvesting, sustainable sourcing and cascaded use requirements for woody biomass for energy with the current requirements of voluntary SFM certification schemes. Sikkema et al., 2014	**Decent Job Creation and Sustainable Economic Growth (8.3/8.4)** ↑ [+2] 🕮 ☺ ★ Some standards seek primarily to coordinate global trade, many purport to promote ecological sustainability and social justice or to institutionalize CSR, for example, labour standards developed in the wake of sweatshops and child labour scandals. Environmental standards for pollution control, etc. Indonesian factories may seek advantages through non-price competition—perhaps by highlighting decent working conditions or the existence of a union—or to see trade associations or government promoting the country as a responsible sourcing location. Bartley, 2010	**Technological Upgradation and Innovation, Promotion of Inclusive Industrialization (9.1/9.2/9.5)** ↑ [+2] 🕮🕮 ☺☺ ★ Capacity for processing certified timber is often underutilized, due to the limited supply available. As a result, manufacturing firms that are seeking to tap into green markets often turn to other sources of timber. (Quoted from Bartley, 2010) Responsible sourcing, when integrated into business practices, can enable retailers to better manage brand value and reputation by avoiding negative public relations, as well as maintaining and enhancing brand integrity (Huang et al., 2013). Bartley, 2010; Huang et al., 2013	**Improving Air Quality, Green and Public Spaces, Peri-urban Spaces (11.6/11.7/11.a/11.b)** ↑ [+2] 🕮🕮🕮🕮 ☺☺☺☺ ★★★★ Many urban tree plantations worldwide are created with a focus on multiple benefits, like air quality improvement, cultural preference for green nature, healthy community interaction as well as temperature control and biodiversity enhancement goals. People's preference for urban forest gardens are encouraging new urban green spaces, and tree selection helps in building resilience to disaster. Chen and Qi, 2018; Fu et al., 2018; Kowarik, 2018; McKinney and Ingo, 2018; McPherson et al., 2018; Pei et al., 2018
Oceans	**Ocean Iron Fertilization**	[0] No direct interaction	[0] No direct interaction	[0] No direct interaction	[0] No direct interaction
	Blue Carbon	[0] No direct interaction	[0] No direct interaction	[0] No direct interaction	[0] No direct interaction
	Enhanced Weathering	[0] No direct interaction	[0] No direct interaction	[0] No direct interaction	[0] No direct interaction

References

Note that this reference list does not account for the references in Table 5.2, for which a separate reference list is provided.

Abel, G.J., B. Barakat, S. KC, and W. Lutz, 2016: Meeting the Sustainable Development Goals leads to lower world population growth. *Proceedings of the National Academy of Sciences*, **113(50)**, 14294–14299, doi:10.1073/pnas.1611386113.

Absar, S.M. and B.L. Preston, 2015: Extending the Shared Socioeconomic Pathways for sub-national impacts, adaptation, and vulnerability studies. *Global Environmental Change*, **33**, 83–96, doi:10.1016/j.gloenvcha.2015.04.004.

Adam, H.N., 2015: Mainstreaming adaptation in India – the Mahatma Gandhi National Rural Employment Guarantee Act and climate change. *Climate and Development*, **7(2)**, 142–152, doi:10.1080/17565529.2014.934772.

Adger, W.N. et al., 2014: Human security. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 755–791.

Aggarwal, A., 2014: How sustainable are forestry clean development mechanism projects? A review of the selected projects from India. *Mitigation and Adaptation Strategies for Global Change*, **19(1)**, 73–91, doi:10.1007/s11027-012-9427-x.

Agoramoorthy, G. and M.J. Hsu, 2016: Small dams revive dry rivers and mitigate local climate change in India's drylands. *International Journal of Climate Change Strategies and Management*, **8(2)**, 271–285, doi:10.1108/ijccsm-12-2014-0141.

Agyeman, J., D. Schlosberg, L. Craven, and C. Matthews, 2016: Trends and directions in environmental justice: from inequity to everyday life, community, and just sustainabilities. *Annual Review of Environment and Resources*, **41**, 321–340, doi:10.1146/annurev-environ-110615-090052.

Aha, B. and J.Z. Ayitey, 2017: Biofuels and the hazards of land grabbing: tenure (in)security and indigenous farmers' investment decisions in Ghana. *Land Use Policy*, **60**, 48–59, doi:10.1016/j.landusepol.2016.10.012.

Ahmed, N., W.W.L. Cheung, S. Thompson, and M. Glaser, 2017a: Solutions to blue carbon emissions: Shrimp cultivation, mangrove deforestation and climate change in coastal Bangladesh. *Marine Policy*, **82**, 68–75, doi:10.1016/j.marpol.2017.05.007.

Ahmed, N., S.W. Bunting, M. Glaser, M.S. Flaherty, and J.S. Diana, 2017b: Can greening of aquaculture sequester blue carbon? *Ambio*, **46(4)**, 468–477, doi:10.1007/s13280-016-0849-7.

Aipira, C., A. Kidd, and K. Morioka, 2017: Climate Change Adaptation in Pacific Countries: Fostering Resilience Through Gender Equality. In: *Climate Change Adaptation in Pacific Countries: Fostering Resilience and Improving the Quality of Life* [Leal Filho, W. (ed.)]. Springer International Publishing AG, Cham, Switzerland, pp. 225–239, doi:10.1007/978-3-319-50094-2_13.

Ajanovic, A., 2015: The future of electric vehicles: prospects and impediments. *Wiley Interdisciplinary Reviews: Energy and Environment*, **4(6)**, 521–536, doi:10.1002/wene.160.

Al Ansari, M.S., 2013: Climate change policies and the potential for energy efficiency in the Gulf Cooperation Council (GCC) Economy. *Environment and Natural Resources Research*, **3(4)**, 106–117, doi:10.5539/enrr.v3n4p106.

Albert, S. et al., 2017: Heading for the hills: climate-driven community relocations in the Solomon Islands and Alaska provide insight for a 1.5°C future. *Regional Environmental Change*, 1–12, doi:10.1007/s10113-017-1256-8.

Ali, A. and O. Erenstein, 2017: Assessing farmer use of climate change adaptation practices and impacts on food security and poverty in Pakistan. *Climate Risk Management*, **16**, 183–194, doi:10.1016/j.crm.2016.12.001.

Al-Maamary, H.M.S., H.A. Kazem, and M.T. Chaichan, 2016: Changing the Energy Profile of the GCC States: A Review. *International Journal of Applied Engineering Research*, **11(3)**, 1980–1988, www.ripublication.com/volume/ijaerv11n3.htm.

Al-Maamary, H.M.S., H.A. Kazem, and M.T. Chaichan, 2017: The impact of oil price fluctuations on common renewable energies in GCC countries. *Renewable and Sustainable Energy Reviews*, **75**, 989–1007, doi:10.1016/j.rser.2016.11.079.

Alshehry, A.S. and M. Belloumi, 2015: Energy consumption, carbon dioxide emissions and economic growth: the case of Saudi Arabia. *Renewable and Sustainable Energy Reviews*, **41**, 237–247, doi:10.1016/j.rser.2014.08.004.

Alsheyab, M.A.T., 2017: Qatar's effort for the deployment of Carbon Capture and Storage. *Global Nest Journal*, **19(3)**, 453–457, https://journal.gnest.org/sites/default/files/submissions/gnest_02269/gnest_02269_published.pdf.

Altieri, K.E. et al., 2016: Achieving development and mitigation objectives through a decarbonization development pathway in South Africa. *Climate Policy*, **16(sup1)**, S78–S91, doi:10.1080/14693062.2016.1150250.

Amann, M. et al., 2011: Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications. *Environmental Modelling & Software*, **26(12)**, 1489–1501, doi:10.1016/j.envsoft.2011.07.012.

Anand, R., 2004: *International environmental justice: A North-South Dimension*. Routledge, London, UK, 161 pp.

Andonova, L.B., T.N. Hale, and C.B. Roger, 2017: National policy and transnational governance of climate change: substitutes or complements? *International Studies Quarterly*, **61(2)**, 253–268, doi:10.1093/isq/sqx014.

Ansuategi, A. et al., 2015: *The impact of climate change on the achievement of the post-2015 sustainable development goals*. Metroeconomica, HR Wallingford and CDKN, 84 pp.

Antwi-Agyei, P., A.J. Dougill, and L.C. Stringer, 2015: Impacts of land tenure arrangements on the adaptive capacity of marginalized groups: The case of Ghana's Ejura Sekyedumase and Bongo districts. *Land Use Policy*, **49**, 203–212, doi:10.1016/j.landusepol.2015.08.007.

Antwi-Agyei, P., A. Dougill, and L. Stringer, 2017a: Assessing Coherence between Sector Policies and Climate Compatible Development: Opportunities for Triple Wins. *Sustainability*, **9(11)**, 2130, doi:10.3390/su9112130.

Antwi-Agyei, P., A.J. Dougill, L.C. Stringer, and S.N.A. Codjoe, 2018: Adaptation opportunities and maladaptive outcomes in climate vulnerability hotspots of northern Ghana. *Climate Risk Management*, **19**, 83–93, doi:10.1016/j.crm.2017.11.003.

Antwi-Agyei, P. et al., 2017b: Perceived stressors of climate vulnerability across scales in the Savannah zone of Ghana: a participatory approach. *Regional Environmental Change*, **17(1)**, 213–227, doi:10.1007/s10113-016-0993-4.

Apgar, M.J., W. Allen, K. Moore, and J. Ataria, 2015: Understanding adaptation and transformation through indigenous practice: the case of the Guna of Panama. *Ecology and Society*, **20(1)**, 45, doi:10.5751/es-07314-200145.

Arakelyan, I., D. Moran, and A. Wreford, 2017: Climate smart agriculture: a critical review. In: *Making Climate Compatible Development Happen* [Nunan, F. (ed.)]. Routledge, Abingdon, UK and New York, NY, USA, pp. 66–86.

Arbuthnott, K., S. Hajat, C. Heaviside, and S. Vardoulakis, 2016: Changes in population susceptibility to heat and cold over time: assessing adaptation to climate change. *Environmental Health*, **15(S1)**, S33, doi:10.1186/s12940-016-0102-7.

Archer, D. et al., 2014: Moving towards inclusive urban adaptation: approaches to integrating community-based adaptation to climate change at city and national scale. *Climate and Development*, **6(4)**, 345–356, doi:10.1080/17565529.2014.918868.

Armitage, D.R., 2015: Social-ecological change in Canada's Arctic: coping, adapting, learning for an uncertain future. In: *Climate Change and the Coast: Building Resilient Communities* [Glavovic, B., M. Kelly, R. Kay, and A. Travers (eds.)]. CRC Press, Boca Raton, FL, USA, pp. 103–124.

Arnell, N.W. and S.N. Gosling, 2016: The impacts of climate change on river flood risk at the global scale. *Climatic Change*, **134(3)**, 387–401, doi:10.1007/s10584-014-1084-5.

Arnell, N.W. et al., 2015: *The global impacts of climate change under pathways that reach 2°, 3° and 4°C above pre-industrial levels*. Report from AVOID2 project to the Committee on Climate Change, 34 pp.

Arriagada, R.A., E.O. Sills, P.J. Ferraro, and S.K. Pattanayak, 2015: Do payments pay off? Evidence from participation in Costa Rica's PES program. *PLOS ONE*, **10(7)**, 1–17, doi:10.1371/journal.pone.0131544.

Arthurson, K. and S. Baum, 2015: Making space for social inclusion in conceptualising climate change vulnerability. *Local Environment*, **20(1)**, 1–17, doi:10.1080/13549839.2013.818951.

Arts, K., 2017: Inclusive sustainable development: a human rights perspective. *Current Opinion in Environmental Sustainability*, **24**, 58–62, doi:10.1016/j.cosust.2017.02.001.

Atalay, Y., F. Biermann, and A. Kalfagianni, 2016: Adoption of renewable energy technologies in oil-rich countries: explaining policy variation in the Gulf Cooperation Council states. *Renewable Energy*, **85**, 206–214, doi:10.1016/j.renene.2015.06.045.

Ayers, J.M., S. Huq, H. Wright, A.M. Faisal, and S.T. Hussain, 2014: Mainstreaming climate change adaptation into development in Bangladesh. *Climate and Development*, **6(4)**, 293–305, doi:10.1002/wcc.226.

Babiker, M.H., 2016: Options for climate change policy in MENA countries after Paris. Policy Perspective No. 18, The Economic Research Forum (ERF), Giza, Egypt, 7 pp.

Bado, B.V., P. Savadogo, and M.L.S. Manzo, 2016: *Restoration of Degraded Lands in West Africa Sahel: Review of experiences in Burkina Faso and Niger*. CGIAR, 16 pp.

Bai, X. et al., 2016: Plausible and desirable futures in the Anthropocene: A new research agenda. *Global Environmental Change*, **39**, 351–362, doi:10.1016/j.gloenvcha.2015.09.017.

Bai, X. et al., 2018: Six research priorities for cities and climate change. *Nature*, **555**, 23–25, doi:10.1038/d41586-018-02409-z.

Bajželj, B. et al., 2014: Importance of food-demand management for climate mitigation. *Nature Climate Change*, **4(10)**, 924–929, doi:10.1038/nclimate2353.

Baldacchino, G., 2017: Seizing history: development and non-climate change in Small Island Developing States. *International Journal of Climate Change Strategies and Management*, 10(2), 217–228, doi:10.1108/ijccsm-02-2017-0037.

Banda, M.L. and S. Fulton, 2017: Litigating Climate Change in National Courts: Recent Trends and Developments in Global Climate Law. *Environmental Law Reporter*, **47(10121)**, 10121–10134, www.eli.org/sites/default/files/elr/featuredarticles/47.10121.pdf.

Barnes, P., 2015: The political economy of localization in the transition movement. *Community Development Journal*, **50(2)**, 312–326, doi:10.1093/cdj/bsu042.

Barnett, J. and E. Walters, 2016: Rethinking the Vulnerability of Small Island States: Climate Change and Development in the Pacific Islands. In: *The Palgrave Handbook of International Development* [Grugel, J. and D. Hammett (eds.)]. Palgrave, London, UK, pp. 731–748, doi:10.1057/978-1-137-42724-3_40.

Barnett, J., P. Tschakert, L. Head, and W.N. Adger, 2016: A science of loss. *Nature Climate Change*, **6**, 976–978, doi:10.1038/nclimate3140.

Barnett, J. et al., 2014: A local coastal adaptation pathway. *Nature Climate Change*, **4(12)**, 1103–1108, doi:10.1038/nclimate2383.

Barrett, S., 2013: Local level climate justice? Adaptation finance and vulnerability reduction. *Global Environmental Change*, **23(6)**, 1819–1829, doi:10.1016/j.gloenvcha.2013.07.015.

Barrington-Leigh, C., 2016: Sustainability and Well-Being: A Happy Synergy. *Development*, **59**, 292–298, doi:10.1057/s41301-017-0113-x.

Bartos, M.D. and M. Chester, 2014: The Conservation Nexus: Valuing Interdependent Water and Energy Savings in Arizona. *Environmental Science & Technology*, **48(4)**, 2139–2149, doi:10.1021/es4033343.

Bathiany, S., V. Dakos, M. Scheffer, and T.M. Lenton, 2018: Climate models predict increasing temperature variability in poor countries. *Science Advances*, **4(5)**, eaar5809, doi:10.1126/sciadv.aar5809.

Bauer, N. et al., 2016: Global fossil energy markets and climate change mitigation – an analysis with REMIND. *Climatic Change*, **136(1)**, 69–82, doi:10.1007/s10584-013-0901-6.

Bayram, H. and A.B. Öztürk, 2014: Global climate change, desertification, and its consequences in Turkey and the Middle East. In: *Global Climate Change and Public Health* [Pinkerton, K.E. and W.N. Rom (eds.)]. Springer, New York, NY, USA, pp. 293–305, doi:10.1007/978-1-4614-8417-2_17.

Bebbington, J. and C. Larrinaga, 2014: Accounting and sustainable development: an exploration. *Accounting, Organizations and Society*, **39(6)**, 395–413, doi:10.1016/j.aos.2014.01.003.

Beilin, R. and C. Wilkinson, 2015: Introduction: Governing for urban resilience. *Urban Studies*, **52(7)**, 1205–1217, doi:10.1177/0042098015574955.

Bell, K., 2015: Can the capitalist economic system deliver environmental justice? *Environmental Research Letters*, **10(12)**, 125017, doi:10.1088/1748-9326/10/12/125017.

Berger, M., S. Pfister, V. Bach, and M. Finkbeiner, 2015: Saving the planet's climate or water resources? The trade-off between carbon and water footprints of European biofuels. *Sustainability*, **7(6)**, 6665–6683, doi:10.3390/su7066665.

Berner, J. et al., 2016: Adaptation in Arctic circumpolar communities: food and water security in a changing climate. *International Journal of Circumpolar Health*, **75(1)**, 33820, doi:10.3402/ijch.v75.33820.

Berrueta, V.M., M. Serrano-Medrano, C. Garcia-Bustamante, M. Astier, and O.R. Masera, 2017: Promoting sustainable local development of rural communities and mitigating climate change: the case of Mexico's Patsari improved cookstove project. *Climatic Change*, **140(1)**, 63–77, doi:10.1007/s10584-015-1523-y.

Bertram, C. et al., 2018: Targeted policies can compensate most of the increased sustainability risks in 1.5°C mitigation scenarios. *Environmental Research Letters*, **13(6)**, 064038, doi:10.1088/1748-9326/aac3ec.

Betts, R.A. et al., 2018: Changes in climate extremes, fresh water availability and vulnerability to food insecurity projected at 1.5°C and 2°C global warming with a higher-resolution global climate model. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376(2119)**, 20160452, doi:10.1098/rsta.2016.0452.

Betzold, C. and F. Weiler, 2017: Allocation of aid for adaptation to climate change: do vulnerable countries receive more support? *International Environmental Agreements: Politics, Law and Economics*, **17**, 17–36, doi:10.1007/s10784-016-9343-8.

Bexell, M. and K. Jönsson, 2017: Responsibility and the United Nations' Sustainable Development Goals. *Forum for Development Studies*, **44(1)**, 13–29, doi:10.1080/08039410.2016.1252424.

Bickersteth, S. et al., 2017: *Mainstreaming climate compatible development: Insights from CDKN's first seven years*. Climate and Development Knowledge Network (CDKN), London, 199 pp.

Biermann, F. and I. Boas, 2017: Towards a global governance system to protect climate migrants: taking stock. In: *Research Handbook on Climate Change, Migration and the Law* [Mayer, B. and F. Crepeau (eds.)]. Edward Elgar Publishing, Cheltenham, UK and Northampton, MA, USA, pp. 405–419, doi:10.4337/9781785366598.00026.

Biermann, M., K. Hillmer-Pegram, C.N. Knapp, and R.E. Hum, 2016: Approaching a critical turn? A content analysis of the politics of resilience in key bodies of resilience literature. *Resilience*, **4(2)**, 59–78, doi:10.1080/21693293.2015.1094170.

Binam, J.N., F. Place, A.A. Djalal, and A. Kalinganire, 2017: Effects of local institutions on the adoption of agroforestry innovations: evidence of farmer managed natural regeneration and its implications for rural livelihoods in the Sahel. *Agricultural and Food Economics*, **5(1)**, 2, doi:10.1186/s40100-017-0072-2.

Blanco, V., C. Brown, S. Holzhauer, G. Vulturius, and M.D.A. Rounsevell, 2017: The importance of socio-ecological system dynamics in understanding adaptation to global change in the forestry sector. *Journal of Environmental Management*, **196**, 36–47, doi:10.1016/j.jenvman.2017.02.066.

Blondeel, M. and T. van de Graaf, 2018: Toward a global coal mining moratorium? A comparative analysis of coal mining policies in the USA, China, India and Australia. *Climatic Change*, 1–13, doi:10.1007/s10584-017-2135-5.

Blyth, W., R. McCarthy, and R. Gross, 2015: Financing the UK power sector: is the money available? *Energy Policy*, **87**, 607–622, doi:10.1016/j.enpol.2015.08.028.

Boke, C., 2015: Resilience's problem of the present: reconciling social justice and future-oriented resilience planning in the Transition Town movement. *Resilience*, **3(3)**, 207–220, doi:10.1080/21693293.2015.1072313.

Bonsch, M. et al., 2016: Trade-offs between land and water requirements for large-scale bioenergy production. *GCB Bioenergy*, **8(1)**, 11–24, doi:10.1111/gcbb.12226.

Boonstra, W.J., E. Björkvik, L.J. Haider, and V. Masterson, 2016: Human responses to social-ecological traps. *Sustainability Science*, **11(6)**, 877–889, doi:10.1007/s11625-016-0397-x.

Bosomworth, K., P. Leith, A. Harwood, and P.J. Wallis, 2017: What's the problem in adaptation pathways planning? The potential of a diagnostic problem-structuring approach. *Environmental Science & Policy*, **76**, 23–28, doi:10.1016/j.envsci.2017.06.007.

Bowyer, P., M. Schaller, S. Bender, and D. Jacob, 2015: Adaptation as ClimateRisk Management: Methods and Approaches. In: *Handbook of Climate Change Adaptation* [Filho, L. (ed.)]. Springer, Berlin and Heidelberg, Germany, pp. 71–92, doi:10.1007/978-3-642-38670-1_28.

Boyd, E., R.A. James, R.G. Jones, H.R. Young, and F.E.L. Otto, 2017: A typology of loss and damage perspectives. *Nature Climate Change*, **7(10)**, 723–729, doi:10.1038/nclimate3389.

5

Boyle, J. et al., 2013: *Exploring Trends in Low-Carbon, Climate-Resilient Development*. International Institute for Sustainable Development (IISD), 37 pp.

Boysen, L.R., W. Lucht, and D. Gerten, 2017: Trade-offs for food production, nature conservation and climate limit the terrestrial carbon dioxide removal potential. *Global Change Biology*, **23(10)**, 4303–4317, doi:10.1111/gcb.13745.

Brink, E. et al., 2016: Cascades of green: A review of ecosystem-based adaptation in urban areas. *Global Environmental Change*, **36**, 111–123, doi:10.1016/j.gloenvcha.2015.11.003.

Brockington, D. and S. Ponte, 2015: The Green Economy in the global South: experiences, redistributions and resistance. *Third World Quarterly*, **36(12)**, 2197–2206, doi:10.1080/01436597.2015.1086639.

Brohé, A., 2014: Whither the CDM? Investment outcomes and future prospects. *Environment, Development and Sustainability*, **16(2)**, 305–322, doi:10.1007/s10668-013-9478-5.

Brown, D. and G. McGranahan, 2016: The urban informal economy, local inclusion and achieving a global green transformation. *Habitat International*, **53**, 97–105, doi:10.1016/j.habitatint.2015.11.002.

Brown, E., J. Cloke, D. Gent, P.H. Johnson, and C. Hill, 2014: Green growth or ecological commodification: debating the green economy in the global south. *Geografiska Annaler, Series B: Human Geography*, **96(3)**, 245–259, doi:10.1111/geob.12049.

Bryan, E., Q. Bernier, M. Espinal, and C. Ringler, 2017: Making climate change adaptation programmes in sub-Saharan Africa more gender responsive: insights from implementing organizations on the barriers and opportunities. *Climate and Development*, 1–15, doi:10.1080/17565529.2017.1301870.

Buch-Hansen, H., 2018: The Prerequisites for a Degrowth Paradigm Shift: Insights from Critical Political Economy. *Ecological Economics*, **146**, 157–163, doi:10.1016/j.ecolecon.2017.10.021.

Bulkeley, H., G.A.S. Edwards, and S. Fuller, 2014: Contesting climate justice in the city: examining politics and practice in urban climate change experiments. *Global Environmental Change*, **25(1)**, 31–40, doi:10.1016/j.gloenvcha.2014.01.009.

Bulkeley, H., J.A. Carmin, V. Castán Broto, G.A.S. Edwards, and S. Fuller, 2013: Climate justice and global cities: mapping the emerging discourses. *Global Environmental Change*, **23(5)**, 914–925, doi:10.1016/j.gloenvcha.2013.05.010.

Buntaine, M.T. and L. Prather, 2018: Preferences for Domestic Action Over International Transfers in Global Climate Policy. *Journal of Experimental Political Science*, 1–15, doi:10.1017/xps.2017.34.

Burke, M., S.M. Hsiang, and E. Miguel, 2015: Global non-linear effect of temperature on economic production. *Nature*, **527(7577)**, 235–239, doi:10.1038/nature15725.

Burns, W. and S. Nicholson, 2017: Bioenergy and carbon capture with storage (BECCS): the prospects and challenges of an emerging climate policy response. *Journal of Environmental Studies and Sciences*, **7(4)**, 527–534, doi:10.1007/s13412-017-0445-6.

Bustamante, M. et al., 2014: Co-benefits, trade-offs, barriers and policies for greenhouse gas mitigation in the agriculture, forestry and other land use (AFOLU) sector. *Global Change Biology*, **20(10)**, 3270–3290, doi:10.1111/gcb.12591.

Butler, C., K.A. Parkhill, and N.F. Pidgeon, 2016: Energy consumption and everyday life: choice, values and agency through a practice theoretical lens. *Journal of Consumer Culture*, **16(3)**, 887–907, doi:10.1177/1469540514553691.

Butler, J.R.A. et al., 2016: Scenario planning to leap-frog the Sustainable Development Goals: an adaptation pathways approach. *Climate Risk Management*, **12**, 83–99, doi:10.1016/j.crm.2015.11.003.

Butt, N. et al., 2016: Challenges in assessing the vulnerability of species to climate change to inform conservation actions. *Biological Conservation*, **199**, 10–15, doi:10.1016/j.biocon.2016.04.020.

Byers, E.A., J.W. Hall, and J.M. Amezaga, 2014: Electricity generation and cooling water use: UK pathways to 2050. *Global Environmental Change*, **25**, 16–30, doi:10.1016/j.gloenvcha.2014.01.005.

Byers, E.A. et al., 2018: Global exposure and vulnerability to multi-sector development and climate change hotspots. *Environmental Research Letters*, **13(5)**, 055012, doi:10.1088/1748-9326/aabf45.

Byrne, J. et al., 2016: Could urban greening mitigate suburban thermal inequity?: the role of residents' dispositions and household practices. *Environmental Research Letters*, **11(9)**, 095014, doi:10.1088/1748-9326/11/9/095014.

Byrnes, W.M., 2014: Climate justice, Hurricane Katrina, and African American environmentalism. *Journal of African American Studies*, **18(3)**, 305–314, doi:10.1007/s12111-013-9270-5.

Cabezon, E., L. Hunter, P. Tumbarello, K. Washimi, and Yiqun Wu, 2016: Strengthening Macro-Fiscal Resilience to Natural Disasters and Climate Change in the Small States of the Pacific. In: *Resilience and Growth in the Small States of the Pacific* [Khor, H.E., R.P. Kronenberg, and P. Tumbarello (eds.)]. International Monetary Fund (IMF), Washington DC, USA, pp. 71–94.

Caldecott, B., O. Sartor, and T. Spencer, 2017: *Lessons from previous 'coal transitions': High-level summary for decision-makers*. IDDRI and Climate Strategies, 24 pp.

Callen, T., R. Cherif, F. Hasanov, A. Hegazy, and P. Khandelwal, 2014: Economic Diversification in the GCC: Past, Present, and Future. IMF Staff Discussion Note SDN/14 /12, International Monetary Fund (IMF), 32 pp.

Calliari, E., 2016: Loss and damage: a critical discourse analysis of Parties' positions in climate change negotiations. *Journal of Risk Research*, **9877**, 1–23, doi:10.1080/13669877.2016.1240706.

Calvet-Mir, L., E. Corbera, A. Martin, J. Fisher, and N. Gross-Camp, 2015: Payments for ecosystem services in the tropics: a closer look at effectiveness and equity. *Current Opinion in Environmental Sustainability*, **14**, 150–162, doi:10.1016/j.cosust.2015.06.001.

Calvin, K. et al., 2017: The SSP4: A world of deepening inequality. *Global Environmental Change*, **42**, 284–296, doi:10.1016/j.gloenvcha.2016.06.010.

Cameron, C. et al., 2016: Policy trade-offs between climate mitigation and clean cook-stove access in South Asia. *Nature Energy*, **1**, 1–5, doi:10.1038/nenergy.2015.10.

Cameron, R.W.F., J. Taylor, and M. Emmett, 2015: A Hedera green facade – energy performance and saving under different maritime-temperate, winter weather conditions. *Building and Environment*, **92**, 111–121, doi:10.1016/j.buildenv.2015.04.011.

Campbell, B.M. et al., 2016: Reducing risks to food security from climate change. *Global Food Security*, **11**, 34–43, doi:10.1016/j.gfs.2016.06.002.

Câmpeanu, C.N. and I. Fazey, 2014: Adaptation and pathways of change and response: a case study from Eastern Europe. *Global Environmental Change*, **28**, 351–367, doi:10.1016/j.gloenvcha.2014.04.010.

Campiglio, E., 2016: Beyond carbon pricing: The role of banking and monetary policy in financing the transition to a low-carbon economy. *Ecological Economics*, **121**, 220–230, doi:10.1016/j.ecolecon.2015.03.020.

Carr, E.R. and M.C. Thompson, 2014: Gender and climate change adaptation in agrarian settings. *Geography Compass*, **8(3)**, 182–197, doi:10.1111/gec3.12121.

Carr, E.R. and K.N. Owusu-Daaku, 2015: The shifting epistemologies of vulnerability in climate services for development: The case of Mali's agrometeorological advisory programme. *Area*, 7–17, doi:10.1111/area.12179.

Carr, E.R. and S.N. Onzere, 2018: Really effective (for 15% of the men): Lessons in understanding and addressing user needs in climate services from Mali. *Climate Risk Management*, **22**, 82–95, doi:10.1016/j.crm.2017.03.002.

Carter, T.R. et al., 2016: Characterising vulnerability of the elderly to climate change in the Nordic region. *Regional Environmental Change*, **16(1)**, 43–58, doi:10.1007/s10113-014-0688-7.

Castán Broto, V., 2017: Urban Governance and the Politics of Climate change. *World Development*, **93**, 1–15, doi:10.1016/j.worlddev.2016.12.031.

Castro, P., 2016: Common but differentiated responsibilities beyond the nation state: how is differential treatment addressed in transnational Climate governance initiatives? *Transnational Environmental Law*, **5(02)**, 379–400, doi:10.1017/s2047102516000224.

Cavanagh, C. and T.A. Benjaminsen, 2014: Virtual nature, violent accumulation: The 'spectacular failure' of carbon offsetting at a Ugandan National Park. *Geoforum*, **56**, 55–65, doi:10.1016/j.geoforum.2014.06.013.

Cervigni, R. and M. Morris (eds.), 2016: *Confronting Drought in Africa's Drylands: Opportunities for Enhancing Resilience*. World Bank, Washington DC, USA, 299 pp.

Chakrabarti, S. and E.J. Shin, 2017: Automobile dependence and physical inactivity: insights from the California Household Travel Survey. *Journal of Transport and Health*, **6**, 262–271, doi:10.1016/j.jth.2017.05.002.

Chakravarty, D. and M. Tavoni, 2013: Energy poverty alleviation and climate change mitigation: Is there a trade off? *Energy Economics*, **40**, S67–S73, doi:10.1016/j.eneco.2013.09.022.

Chakravarty, D. and J. Roy, 2016: The Global South: New Estimates and Insights from Urban India. In: *Rethinking Climate and Energy Policies: New Perspectives on the Rebound Phenomenon* [Santarius, T., H.J. Walnum, and A. Carlo (eds.)]. Springer, Cham, Switzerland, pp. 55–72, doi:10.1007/978-3-319-38807-6_4.

Chakravarty, D., S. Dasgupta, and J. Roy, 2013: Rebound effect: how much to worry? *Current Opinion in Environmental Sustainability*, **5(2)**, 216–228, doi:10.1016/j.cosust.2013.03.001.

5

Chan, K.M.A., E. Anderson, M. Chapman, K. Jespersen, and P. Olmsted, 2017: Payments for ecosystem services: rife with problems and potential-for transformation towards sustainability. *Ecological Economics*, **140**, 110–122, doi:10.1016/j.ecolecon.2017.04.029.

Chancel, L. and T. Picketty, 2015: *Carbon and inequality: from Kyoto to Paris. Trends in the global inequality of carbon emissions (1998–2013) & prospects for an equitable adaptation fund*. Paris School of Economics, Paris, France, 50 pp.

Chapin, F.S., C.N. Knapp, T.J. Brinkman, R. Bronen, and P. Cochran, 2016: Community-empowered adaptation for self-reliance. *Current Opinion in Environmental Sustainability*, **19**, 67–75, doi:10.1016/j.cosust.2015.12.008.

Chaturvedi, V. and P.R. Shukla, 2014: Role of energy efficiency in climate change mitigation policy for India: assessment of co-benefits and opportunities within an integrated assessment modeling framework. *Climatic Change*, **123(3)**, 597–609, doi:10.1007/s10584-013-0898-x.

Chelleri, L., G. Minucci, and E. Skrimizea, 2016: Does community resilience decrease social-ecological vulnerability? Adaptation pathways trade-off in the Bolivian Altiplano. *Regional Environmental Change*, **16(8)**, 2229–2241, doi:10.1007/s10113-016-1046-8.

Chen, X., X. Liu, and D. Hu, 2015: Assessment of sustainable development: A case study of Wuhan as a pilot city in China. *Ecological Indicators*, **50**, 206–214, doi:10.1016/j.ecolind.2014.11.002.

Cheung, W.W.L., G. Reygondeau, and T.L. Frölicher, 2016: Large benefits to marine fisheries of meeting the 1.5°C global warming target. *Science*, **354(6319)**, 1591–1594, doi:10.1126/science.aag2331.

Chief, K., A. Meadow, and K. Whyte, 2016: Engaging southwestern tribes in sustainable water resources topics and management. *Water*, **8(8)**, 1–21, doi:10.3390/w8080350.

Chong, J., 2014: Ecosystem-based approaches to climate change adaptation: progress and challenges. *International Environmental Agreements: Politics, Law and Economics*, **14(4)**, 391–405, doi:10.1007/s10784-014-9242-9.

Chu, E., I. Anguelovski, and D. Roberts, 2017: Climate adaptation as strategic urbanism: assessing opportunities and uncertainties for equity and inclusive development in cities. *Cities*, **60**, 378–387, doi:10.1016/j.cities.2016.10.016.

Chung Tiam Fook, T., 2017: Transformational processes for community-focused adaptation and social change: a synthesis. *Climate and Development*, **9(1),** 5–21, doi:10.1080/17565529.2015.1086294.

Clarke, L.E. et al., 2014: Assessing transformation pathways. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 413–510.

Clements, R., 2009: *The Economic Cost of Climate Change in Africa*. Pan African Climate Justice Alliance (PACJA), 52 pp.

Cobbinah, P.B. and G.K. Anane, 2016: Climate change adaptation in rural Ghana: indigenous perceptions and strategies. *Climate and Development*, **8(2)**, 169–178, doi:10.1080/17565529.2015.1034228.

Coe, R., F. Sinclair, and E. Barrios, 2014: Scaling up agroforestry requires research 'in' rather than 'for' development. *Current Opinion in Environmental Sustainability*, **6(1)**, 73–77, doi:10.1016/j.cosust.2013.10.013.

Coe, R., J. Njoloma, and F. Sinclair, 2017: To control or not to control: how do we learn more about how agronomic innovations perform on farms? *Experimental Agriculture*, 1–7, doi:10.1017/s0014479717000102.

Cohen, M.G. (ed.), 2017: *Climate change and gender in rich countries: work, public policy and action*. Routledge, Abingdon, UK and New York, NY, USA, 322 pp.

Cole, M.J., R.M. Bailey, and M.G. New, 2017: Spatial variability in sustainable development trajectories in South Africa: provincial level safe and just operating spaces. *Sustainability Science*, **12(5)**, 829–848, doi:10.1007/s11625-016-0418-9.

Colenbrander, S., D. Dodman, and D. Mitlin, 2017: Using climate finance to advance climate justice: the politics and practice of channelling resources to the local level. *Climate Policy*, 1–14, doi:10.1080/14693062.2017.1388212.

Colenbrander, S. et al., 2016: Can low-carbon urban development be pro-poor? The case of Kolkata, India. *Environment and Urbanization*, **29(1)**, 139–158, doi:10.1177/0956247816677775.

Colloff, M.J. et al., 2017: An integrative research framework for enabling transformative adaptation. *Environmental Science & Policy*, **68**, 87–96, doi:10.1016/j.envsci.2016.11.007.

Conservation International, 2016: *Ecosystem Based Adaptation: Essential for Achieving the Sustainable Development Goals*. Conservation International, Arlington, VA, USA, 4 pp.

Conway, D. et al., 2015: Climate and southern Africa's water-energy-food nexus. *Nature Climate Change*, **5(9)**, 837–846, doi:10.1038/nclimate2735.

Corbera, E., C. Hunsberger, and C. Vaddhanaphuti, 2017: Climate change policies, land grabbing and conflict: perspectives from Southeast Asia. *Canadian Journal of Development Studies*, **38(3)**, 297–304, doi:10.1080/02255189.2017.1343413.

Cretney, R.M., A.C. Thomas, and S. Bond, 2016: Maintaining grassroots activism: Transition Towns in Aotearoa New Zealand. *New Zealand Geographer*, **72(2)**, 81–91, doi:10.1111/nzg.12114.

Creutzig, F. et al., 2015: Bioenergy and climate change mitigation: an assessment. *GCB Bioenergy*, **7(5)**, 916–944, doi:10.1111/gcbb.12205.

Croce, D., C. Kaminker, and F. Stewart, 2011: he Role of Pension Funds in Financing Green Growth Initiatives. OECD Working Papers on Finance, Insurance and Private Pensions No. 10, Organisation for Economic Co-operation and Development (OECD) Publishing, Paris, France, doi:10.1787/5kg58j1lwdjd-en.

Crosland, T., A. Meyer, and M. Wewerinke-singh, 2016: The Paris Agreement Implementation Blueprint: a practical guide to bridging the gap between actions and goal and closing the accountability deficit (Part 1). *Environmental liability*, **25(2)**, 114–125, https://ssrn.com/abstract=2952215.

CSO Equity Review, 2015: *Fair Shares: A Civil Society Equity Review of INDCs*. CSO Equity Review Coalition, Manila, London, Cape Town, Washington, et al. 36 pp.

Cugurullo, F., 2013: How to build a sandcastle: an analysis of the genesis and development of Masdar City. *Journal of Urban Technology*, **20(1)**, 23–37, doi:10.1080/10630732.2012.735105.

Cundill, G. et al., 2014: *Social learning for adaptation: a descriptive handbook for practitioners and action researchers*. IRDC, Rhodes University, Ruliv, 118 pp.

Cutter, S.L., 2016: Resilience to What? Resilience for Whom? *Geographical Journal*, **182(2)**, 110–113, doi:10.1111/geoj.12174.

Cvitanovic, C. et al., 2016: Linking adaptation science to action to build food secure Pacific Island communities. *Climate Risk Management*, **11**, 53–62, doi:10.1016/j.crm.2016.01.003.

Daigneault, A., P. Brown, and D. Gawith, 2016: Dredging versus hedging: Comparing hard infrastructure to ecosystem-based adaptation to flooding. *Ecological Economics*, **122**, 25–35, doi:10.1016/j.ecolecon.2015.11.023.

Dasgupta, P., 2016: *Climate Sensitive Adaptation in Health: Imperatives for India in a Developing Economy Context*. Springer India, 194 pp.

Dasgupta, P., K. Ebi, and I. Sachdeva, 2016: Health sector preparedness for adaptation planning in India. *Climatic Change*, **138(3–4)**, 551–566, doi:10.1007/s10584-016-1745-7.

Dasgupta, S., M. Huq, M.G. Mustafa, M.I. Sobhan, and D. Wheeler, 2017: The impact of aquatic salinization on fish habitats and poor communities in a changing climate: evidence from southwest coastal Bangladesh. *Ecological Economics*, **139**, 128–139, doi:10.1016/j.ecolecon.2017.04.009.

Datta, N., 2015: Evaluating impacts of watershed development program on agricultural productivity, income, and livelihood in bhalki watershed of Bardhaman District, West Bengal. *World Development*, **66**, 443–456, doi:10.1016/j.worlddev.2014.08.024.

Davies, K., 2015: Kastom, climate change and intergenerational democracy: experiences from Vanuatu. In: *Climate change in the Asia-Pacific region* [Leal Filho, W. (ed.)]. Springer, Cham, Switzerland, pp. 49–66, doi:10.1007/978-3-319-14938-7_4.

Davies, T.E., N. Pettorelli, W. Cresswill, and I.R. Fazey, 2014: Who are the poor? Measuring wealth inequality to aid understanding of socioeconomic contexts for conservation: a case-study from the Solomon Islands. *Environmental Conservation*, **41(04)**, 357–366, doi:10.1017/s0376892914000058.

de Coninck, H.C. and D. Puig, 2015: Assessing climate change mitigation technology interventions by international institutions. *Climatic Change*, **131(3)**, 417–433, doi:10.1007/s10584-015-1344-z.

de Coninck, H.C. and A. Sagar, 2015: Making sense of policy for climate technology development and transfer. *Climate Policy*, **15(1)**, 1–11, doi:10.1080/14693062.2014.953909.

de Coninck, H.C. and A. Sagar, 2017: Technology development and transfer (Article 10). In: *The Paris Agreement on Climate Change* [Klein, D., M.P. Carazo, M. Doelle, J. Bulmer, and A. Higham (eds.)]. Oxford University Press, Oxford, UK, pp. 258–276.

De Stefano, L., J.D. Petersen-Perlman, E.A. Sproles, J. Eynard, and A.T. Wolf, 2017: Assessment of transboundary river basins for potential hydro-political tensions. *Global Environmental Change*, **45**, 35–46, doi:10.1016/j.gloenvcha.2017.04.008.

Dearing, J.A. et al., 2014: Safe and just operating spaces for regional social-ecological systems. *Global Environmental Change*, **28(1)**, 227–238, doi:10.1016/j.gloenvcha.2014.06.012.

Death, C., 2014: The Green Economy in South Africa: Global Discourses and Local Politics. *Politikon*, **41(1)**, 1–22, doi:10.1080/02589346.2014.885668.

Death, C., 2015: Four discourses of the green economy in the global South. *Third World Quarterly*, **36(12)**, 2207–2224, doi:10.1080/01436597.2015.1068110.

Death, C., 2016: Green states in Africa: beyond the usual suspects. *Environmental Politics*, **25:1**, 116–135, doi:10.1080/09644016.2015.1074380.

DeCaro, D.A., C. Anthony, T. Arnold, E.F. Boamah, and A.S. Garmestani, 2017: Understanding and applying principles of social cognition and decision making in adaptive environmental governance. *Ecology and Society*, **22(1)**, 33, doi:10.5751/es-09154-220133.

DeClerck, F.A.J. et al., 2016: Agricultural ecosystems and their services: the vanguard of sustainability? *Current Opinion in Environmental Sustainability*, **23**, 92–99, doi:10.1016/j.cosust.2016.11.016.

Delponte, I., I. Pittaluga, and C. Schenone, 2017: Monitoring and evaluation of Sustainable Energy Action Plan: practice and perspective. *Energy Policy*, **100**, 9–17, doi:10.1016/j.enpol.2016.10.003.

Dennig, F., M.B. Budolfson, M. Fleurbaey, A. Siebert, and R.H. Socolow, 2015: Inequality, climate impacts on the future poor, and carbon prices. *Proceedings of the National Academy of Sciences*, **112(52)**, 15827–15832, doi:10.1073/pnas.1513967112.

Denton, F. et al., 2014: Climate-resilient pathways: adaptation, mitigation, and sustainable development. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1101–1131.

Derbez, M. et al., 2014: Indoor air quality and comfort in seven newly built, energy-efficient houses in France. *Building and Environment*, **72**, 173–187, doi:10.1016/j.buildenv.2013.10.017.

Di Gregorio, M. et al., 2017: Climate policy integration in the land use sector: Mitigation, adaptation and sustainable development linkages. *Environmental Science & Policy*, **67**, 35–43, doi:10.1016/j.envsci.2016.11.004.

Dilling, L., M.E. Daly, W.R. Travis, O. Wilhelmi, and R.A. Klein, 2015: The dynamics of vulnerability: why adapting to climate variability will not always prepare us for climate change. *Wiley Interdisciplinary Reviews: Climate Change*, **6(4)**, 413–425, doi:10.1002/wcc.341.

Ding, H. et al., 2016: *Climate Benefits, Tenure Costs: The Economic Case For Securing Indigenous Land Rights in the Amazon*. World Resources Institute, Washington DC, USA, 98 pp.

Dinku, T. et al., 2014: Bridging critical gaps in climate services and applications in Africa. *Earth Perspectives*, **1(1)**, 15, doi:10.1186/2194-6434-1-15.

Dodman, D., H. Leck, M. Rusca, and S. Colenbrander, 2017: African urbanisation and urbanism: implications for risk accumulation and reduction. *International Journal of Disaster Risk Reduction*, **26**, 7–15, doi:10.1016/j.ijdrr.2017.06.029.

Doswald, N. et al., 2014: Effectiveness of ecosystem-based approaches for adaptation: review of the evidence-base. *Climate and Development*, **6(2)**, 185–201, doi:10.1080/17565529.2013.867247.

Douxchamps, S. et al., 2016: Linking agricultural adaptation strategies, food security and vulnerability: evidence from West Africa. *Regional Environmental Change*, **16(5)**, 1305–1317, doi:10.1007/s10113-015-0838-6.

Dovie, D.B.K., M. Dzodzomenyo, and O.A. Ogunseitan, 2017: Sensitivity of health sector indicators' response to climate change in Ghana. *Science of the Total Environment*, **574**, 837–846, doi:10.1016/j.scitotenv.2016.09.066.

Dow, K. et al., 2013: Limits to adaptation. *Nature Climate Change*, **3(4)**, 305–307, doi:10.1038/nclimate1847.

Dual Citizen LLC, 2016: *The Global Green Economy Index – GGEI 2016: Measuring National Performance in the Green Economy*. Dual Citizen LLC, Washington DC, USA and New York, NY, USA, 58 pp.

Duarte, C.M., J. Wu, X. Xiao, A. Bruhn, and D. Krause-Jensen, 2017: Can Seaweed Farming Play a Role in Climate Change Mitigation and Adaptation? *Frontiers in Marine Science*, **4**, 100, doi:10.3389/fmars.2017.00100.

Duguma, L.A., P.A. Minang, and M. Van Noordwijk, 2014: Climate change mitigation and adaptation in the land use sector: from complementarity to synergy. *Environmental Management*, **54(3)**, 420–432, doi:10.1007/s00267-014-0331-x.

Dumont, E.S., S. Bonhomme, T.F. Pagella, and F.L. Sinclair, 2017: Structured stakeholder engagement leads to development of more diverse and inclusive agroforestry options. *Experimental Agriculture*, 1–23, doi:10.1017/s0014479716000788.

Eakin, H.C., M.C. Lemos, and D.R. Nelson, 2014: Differentiating capacities as a means to sustainable climate change adaptation. *Global Environmental Change*, **27(27)**, 1–8, doi:10.1016/j.gloenvcha.2014.04.013.

Ebi, K.L. and M. Otmani del Barrio, 2017: Lessons Learned on Health Adaptation to Climate Variability and Change: Experiences Across Low- and Middle-Income Countries. *Environmental Health Perspectives*, **125(6)**, 065001, doi:10.1289/ehp405.

Ebi, K.L. et al., 2014: A new scenario framework for climate change research: background, process, and future directions. *Climatic Change*, **122(3)**, 363–372, doi:10.1007/s10584-013-0912-3.

Echegaray, F., 2016: Consumers' reactions to product obsolescence in emerging markets: the case of Brazil. *Journal of Cleaner Production*, **134**, 191–203, doi:10.1016/j.jclepro.2015.08.119.

Ehresman, T.G. and C. Okereke, 2015: Environmental justice and conceptions of the green economy. *International Environmental Agreements: Politics, Law and Economics*, **15(1)**, 13–27, doi:10.1007/s10784-014-9265-2.

Ekwurzel, B. et al., 2017: The rise in global atmospheric CO_2, surface temperature, and sea level from emissions traced to major carbon producers. *Climatic Change*, 1–12, doi:10.1007/s10584-017-1978-0.

Enqvist, J., M. Tengö, and W.J. Boonstra, 2016: Against the current: rewiring rigidity trap dynamics in urban water governance through civic engagement. *Sustainability Science*, **11(6)**, 919–933, doi:10.1007/s11625-016-0377-1.

Ensor, J., 2016: Adaptation and resilience in Vanuatu: Interpreting community perceptions of vulnerability, knowledge and power for community-based adaptation programming. Report by SEI for Oxfam Australia, Carlton, 32 pp.

Ensor, J. and B. Harvey, 2015: Social learning and climate change adaptation: evidence for international development practice. *Wiley Interdisciplinary Reviews: Climate Change*, **6(5)**, 509–522, doi:10.1002/wcc.348.

Entzinger, H. and P. Scholten, 2016: *Adapting to Climate Change through Migration. A case study of the Vietnamese Mekong River Delta*. International Organization for Migration (IOM), Geneva, Switzerland, 62 pp.

Epule, T.E., J.D. Ford, S. Lwasa, and L. Lepage, 2017: Climate change adaptation in the Sahel. *Environmental Science & Policy*, **75**, 121–137, doi:10.1016/j.envsci.2017.05.018.

Eriksen, S., L.O. Naess, R. Haug, L. Lenaerts, and A. Bhonagiri, 2017: Courting catastrophe? Can humanitarian actions contribute to climate change adaptation? *IDS Bulletin*, **48(4)**, doi:10.19088/1968-2017.149.

Eriksson, H. et al., 2017: The role of fish and fisheries in recovering from natural hazards: lessons learned from Vanuatu. *Environmental Science & Policy*, **76**, 50–58, doi:10.1016/j.envsci.2017.06.012.

Estrella, M., F.G. Renaud, K. Sudmeier-Rieux, and U. Nehren, 2016: Defining New Pathways for Ecosystem-Based Disaster Risk Reduction and Adaptation in the Post-2015 Sustainable Development Agenda. In: *Ecosystem-Based Disaster Risk Reduction and Adaptation in Practice* [Renaud, F.G., K. Sudmeier-Rieux, M. Estrella, and U. Nehren (eds.)]. Springer, Cham, Switzerland, pp. 553–591, doi:10.1007/978-3-319-43633-3.

Evans, G. and L. Phelan, 2016: Transition to a post-carbon society: linking environmental justice and just transition discourses. *Energy Policy*, **99**, 329–339, doi:10.1016/j.enpol.2016.05.003.

Evans, J.P., R.B. Smith, and R.J. Oglesby, 2004: Middle East climate simulation and dominant precipitation processes. *International Journal of Climatology*, **24(13)**, 1671–1694, doi:10.1002/joc.1084.

Falcone, P.M., P. Morone, and E. Sica, 2018: Greening of the financial system and fuelling a sustainability transition: a discursive approach to assess landscape pressures on the Italian financial system. *Technological Forecasting and Social Change*, **127**, 23–37, doi:10.1016/j.techfore.2017.05.020.

Fan, Y., Q. Qiao, L. Fang, and Y. Yao, 2017: Energy analysis on industrial symbiosis of an industrial park: a case study of Hefei economic and technological development area. *Journal of Cleaner Production*, **141**, 791–798, doi:10.1016/j.jclepro.2016.09.159.

Fankhauser, S. and T.K.J. McDermott, 2014: Understanding the adaptation deficit: Why are poor countries more vulnerable to climate events than rich countries? *Global Environmental Change*, **27**, 9–18, doi:10.1016/j.gloenvcha.2014.04.014.

Fankhauser, S. and N. Stern, 2016: Climate change, development, poverty and economics. Grantham Research Institute on Climate Change and the Environment Working Paper No. 253, Grantham Research Institute, London, UK, 25 pp.

FAO, 2015: *Adaptation to climate risk and food security: Evidence from smallholder farmers in Ethiopia*. Food and Agriculture Organization (FAO), Rome, Italy, 50 pp.

FAO and NZAGRC, 2017a: *Low emissions development of the beef cattle sector in Uruguay – reducing enteric methane for food security and livelihoods*. Food and

5

Agriculture Organization of the United Nations and New Zealand Agricultural Greenhouse Gas Research Centre (NZAGRC), Rome, Italy, 34 pp.
FAO and NZAGRC, 2017b: *Supporting low emissions development in the Ethiopian dairy cattle sector – reducing enteric methane for food security and livelihoods*. Food and Agriculture Organization of the United Nations and New Zealand Agricultural Greenhouse Gas Research Centre (NZAGRC), Rome, Italy, 34 pp.
Fatima, R., A.J. Wadud, and S. Coelho, 2014: *Human Rights, Climate Change, Environmental Degradation and Migration: A New Paradigm*. International Organization for Migration and Migration Policy Institute, Bangkok, Thailand and Washington DC, USA, 12 pp.
Fay, M. et al., 2015: *Decarbonizing Development: Three Steps to a Zero-Carbon Future*. World Bank, Washington DC, USA, 185 pp, doi:10.1596/978-1-4648-0479-3.
Fazey, I. et al., 2016: Past and future adaptation pathways. *Climate and Development*, **8(1)**, 26–44, doi:10.1080/17565529.2014.989192.
Fazey, I. et al., 2018: Community resilience for a 1.5°C world. *Current Opinion in Environmental Sustainability*, **31**, 30–40, doi:10.1016/j.cosust.2017.12.006.
Feola, G. and R. Nunes, 2014: Success and failure of grassroots innovations for addressing climate change: The case of the Transition Movement. *Global Environmental Change*, **24**, 232–250, doi:10.1016/j.gloenvcha.2013.11.011.
Ferguson, P., 2015: The green economy agenda: business as usual or transformational discourse? *Environmental Politics*, **24(1)**, 17–37, doi:10.1080/09644016.2014.919748.
Fernandes-Jesus, M., A. Carvalho, L. Fernandes, and S. Bento, 2017: Community engagement in the Transition movement: views and practices in Portuguese initiatives. *Local Environment*, **22(12)**, 1546–1562, doi:10.1080/13549839.2017.1379477.
Few, R., A. Martin, and N. Gross-Camp, 2017: Trade-offs in linking adaptation and mitigation in the forests of the Congo Basin. *Regional Environmental Change*, **17(3)**, 851–863, doi:10.1007/s10113-016-1080-6.
Ficklin, L., L.C. Stringer, A.J. Dougill, and S.M. Sallu, 2018: Climate compatible development reconsidered: calling for a critical perspective. *Climate and Development*, **10(3)**, 193–196, doi:10.1080/17565529.2017.1372260.
Field, C.B. et al., 2014: Technical Summary. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 35–94.
Filho, L. and J. Nalau (eds.), 2018: *Limits to climate change adaptation*. Springer International Publishing, Cham, Switzerland, 410 pp., doi:10.1007/978-3-319-64599-5.
Fincher, R., J. Barnett, S. Graham, and A. Hurlimann, 2014: Time stories: making sense of futures in anticipation of sea-level rise. *Geoforum*, **56**, 201–210, doi:10.1016/j.geoforum.2014.07.010.
Fleurbaey, M. et al., 2014: Sustainable development and equity. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 283–350.
Ford, J.D. et al., 2016: Community-based adaptation research in the Canadian Arctic. *Wiley Interdisciplinary Reviews: Climate Change*, **7(2)**, 175–191, doi:10.1002/wcc.376.
Francis, R., P. Weston, and J. Birch, 2015: *The social, environmental and economics benefits of Farmer Managed Natural Regeneration (FMNR)*. World Vision Australia, Melbourne, Australia, 44 pp.
Frank, S. et al., 2017: Reducing greenhouse gas emissions in agriculture without compromising food security? *Environmental Research Letters*, **12(10)**, 105004, doi:10.1088/1748-9326/aa8c83.
Fricko, O. et al., 2016: Energy sector water use implications of a 2°C degree climate policy. *Environmental Research Letters*, **11(3)**, 034011, doi:10.1088/1748-9326/11/3/034011.
Frumhoff, P.C., R. Heede, and N. Oreskes, 2015: The climate responsibilities of industrial carbon producers. *Climatic Change*, **132(2)**, 157–171, doi:10.1007/s10584-015-1472-5.
Fuchs, D. et al., 2016: Power: the missing element in sustainable consumption and absolute reductions research and action. *Journal of Cleaner Production*, **132**, 298–307, doi:10.1016/j.jclepro.2015.02.006.
Fuglestvedt, J.S. and S. Kallbekken, 2016: Climate responsibility: fair shares? *Nature Climate Change*, **6(1)**, 19–20, doi:10.1038/nclimate2791.
Fuhr, H., T. Hickmann, and K. Kern, 2018: The role of cities in multi-level climate governance: local climate policies and the 1.5°C target. *Current Opinion in Environmental Sustainability*, **30**, 1–6, doi:10.1016/j.cosust.2017.10.006.
Fujimori, S., N. Hanasaki, and T. Masui, 2017a: Projections of industrial water withdrawal under shared socioeconomic pathways and climate mitigation scenarios. *Sustainability Science*, **12**, 275–292, doi:10.1007/s11625-016-0392-2.
Fujimori, S. et al., 2017b: SSP3: AIM implementation of Shared Socioeconomic Pathways. *Global Environmental Change*, **42**, 268–283, doi:10.1016/j.gloenvcha.2016.06.009.
Fukuda-Parr, S., A.E. Yamin, and J. Greenstein, 2014: The power of numbers: a critical review of Millennium Development Goal targets for human development and human rights. *Journal of Human Development and Capabilities*, **15(2–3)**, 105–117, doi:10.1080/19452829.2013.864622.
Fuller, R. and J. Lain, 2017: *Building Resilience: A meta-analysis of Oxfam's resilience*. Oxfam Effectiveness Reviews, Oxfam, 35 pp.
Gajjar, S.P., C. Singh, and T. Deshpande, 2018: Tracing back to move ahead: a review of development pathways that constrain adaptation futures. *Climate and Development*, 1–15, doi:10.1080/17565529.2018.1442793.
Galgóczi, B., 2014: The Long and Winding Road from Black to Green: Decades of Structural Change in the Ruhr Region. *International Journal of Labour Research*, **6(2)**, 217–240, www.ilo.org/wcmsp5/groups/public/---ed_dialogue/---actrav/documents/publication/wcms_375223.pdf.
Garg, A., P. Mohan, S. Shukla, B. Kankal, and S.S. Vishwanathan, 2017: *High impact opportunities for energy efficiency in India*. UNEP DTU Partnerhsip, Copenhagen, Denmark, 49 pp.
Gebrehaweria, G., A. Dereje Assefa, G. Girmay, M. Giordano, and L. Simon, 2016: An assessment of integrated watershed management in Ethiopia. IWMI Working Paper 170, International Water Management Institute (IWMI), Colombo, Sri Lanka, 28 pp., doi:10.5337/2016.214.
Georgeson, L., M. Maslin, and M. Poessinouw, 2017a: Global disparity in the supply of commercial weather and climate information services. *Science Advances*, **3**, e1602632, doi:10.1126/sciadv.1602632.
Georgeson, L., M. Maslin, and M. Poessinouw, 2017b: The global green economy: a review of concepts, definitions, measurement methodologies and their interactions. *Geo: Geography and Environment*, **4(1)**, e00036, doi:10.1002/geo2.36.
Gero, A. et al., 2013: *Understanding the Pacific's adaptive capacity to emergencies in the context of climate change: Country Report – Vanuatu*. Report prepared for NCCARF by the Institute for Sustainable Futures, and WHO Collaborating Centre, University of Technology, Sydney, Australia, 36 pp.
Gillard, R., A. Gouldson, J. Paavola, and J. Van Alstine, 2016: Transformational responses to climate change: beyond a systems perspective of social change in mitigation and adaptation. *Wiley Interdisciplinary Reviews: Climate Change*, **7(2)**, 251–265, doi:10.1002/wcc.384.
Gillingham, K., D. Rapson, and G. Wagner, 2016: The rebound effect and energy efficiency policy. *Review of Environmental Economics and Policy*, **10(1)**, 68–88, doi:10.1093/reep/rev017.
Giwa, A., A. Alabi, A. Yusuf, and T. Olukan, 2017: A comprehensive review on biomass and solar energy for sustainable energy generation in Nigeria. *Renewable and Sustainable Energy Reviews*, **69,** 620–641, doi:10.1016/j.rser.2016.11.160.
Glazebrook, G. and P. Newman, 2018: The City of the Future. *Urban Planning*, **3(2)**, 1–20, doi:10.17645/up.v3i2.1247.
Godfrey-Wood, R. and L.O. Naess, 2016: Adapting to Climate Change: Transforming Development? *IDS Bulletin*, **47(2)**, 49–62, doi:10.19088/1968-2016.131.
Gomez-Echeverri, L., 2018: Climate and development: enhancing impact through stronger linkages in the implementation of the Paris Agreement and the Sustainable Development Goals (SDGs). *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376(2119)**, 20160444, doi:10.1098/rsta.2016.0444.
Gorddard, R., M.J. Colloff, R.M. Wise, D. Ware, and M. Dunlop, 2016: Values, rules and knowledge: Adaptation as change in the decision context. *Environmental Science & Policy*, **57**, 60–69, doi:10.1016/j.envsci.2015.12.004.
Gore, C., 2015: Climate Change Adaptation and African Cities: Understanding the Impact of Government and Governance on Future Action. In: *The Urban Climate Challenge: Rethinking the Role of Cities in the Global Climate Regime* [Johnson, C., N. Toly, and H. Schroeder (eds.)]. Routledge, New York, NY, USA and London, UK, pp. 205–226.
Government of Kiribati, 2016: *Kiribati development plan 2016–19*. Government of Kiribati, 75 pp.

Granderson, A.A., 2017: Value conflicts and the politics of risk: challenges in assessing climate change impacts and risk priorities in rural Vanuatu. *Climate and Development*, 1–14, doi:10.1080/17565529.2017.1318743.

Grantham, R.W. and M.A. Rudd, 2017: Household susceptibility to hydrological change in the Lower Mekong Basin. *Natural Resources Forum*, **41(1)**, 3–17, doi:10.1111/1477-8947.12113.

Gray, E., N. Henninger, C. Reij, R. Winterbottom, and P. Agostini, 2016: *Integrated landscape approaches for Africa's drylands*. World Bank, Washington DC, USA, 184 pp., doi:10.1596/978-1-4648-0826-5.

Green, F., 2018: Anti-fossil fuel norms. *Climatic Change*, 1–14, doi:10.1007/s10584-017-2134-6.

Griffiths, S., 2017a: A review and assessment of energy policy in the Middle East and North Africa region. *Energy Policy*, **102**, 249–269, doi:10.1016/j.enpol.2016.12.023.

Griffiths, S., 2017b: Renewable energy policy trends and recommendations for GCC countries. *Energy Transitions*, **1(1)**, 3, doi:10.1007/s41825-017-0003-6.

Grill, G. et al., 2015: An index-based framework for assessing patterns and trends in river fragmentation and flow regulation by global dams at multiple scales. *Environmental Research Letters*, **10(1)**, 015001, doi:10.1088/1748-9326/10/1/015001.

Grist, N. et al., 2017: Framing innovations for climate resilience for farmers in Sahel. *Resilience Intel*, **9**, 20, www.odi.org/sites/odi.org.uk/files/resource-documents/11647.pdf.

Grossmann, M. and E. Creamer, 2017: Assessing diversity and inclusivity within the Transition Movement: an urban case study. *Environmental Politics*, **26(1)**, 161–182, doi:10.1080/09644016.2016.1232522.

Grubert, E.A., A.S. Stillwell, and M.E. Webber, 2014: Where does solar-aided seawater desalination make sense? A method for identifying sustainable sites. *Desalination*, **339**, 10–17, doi:10.1016/j.desal.2014.02.004.

Grubler, A. et al., 2018: A low energy demand scenario for meeting the 1.5°C target and sustainable development goals without negative emission technologies. *Nature Energy*, **3(6)**, 515–527, doi:10.1038/s41560-018-0172-6.

Gupta, J. and K. Arts, 2017: Achieving the 1.5°C objective: just implementation through a right to (sustainable) development approach. *International Environmental Agreements: Politics, Law and Economics*, doi:10.1007/s10784-017-9376-7.

Gupta, J. and N. Pouw, 2017: Towards a trans-disciplinary conceptualization of inclusive development. *Current Opinion in Environmental Sustainability*, **24**, 96–103, doi:10.1016/j.cosust.2017.03.004.

Gustafson, S. et al., 2017: Merging science into community adaptation planning processes: a cross-site comparison of four distinct areas of the Lower Mekong Basin. *Climatic Change*, 1–16, doi:10.1007/s10584-016-1887-7.

Gwimbi, P., 2017: Mainstreaming national adaptation programmes of action into national development plans in Lesotho: lessons and needs. *International Journal of Climate Change Strategies and Management*, **9(3)**, 299–315, doi:10.1108/ijccsm-11-2015-0164.

Hackmann, B., 2016: Regime learning in global environmental governance. *Environmental Values*, **25(6)**, 663–686, doi:10.3197/096327116x14736981715625.

Haider, L.J., W.J. Boonstra, G.D. Peterson, and M. Schlüter, 2018: Traps and Sustainable Development in Rural Areas: A Review. *World Development*, **101(2013)**, 311–321, doi:10.1016/j.worlddev.2017.05.038.

Hajer, M. et al., 2015: Beyond cockpit-ism: Four insights to enhance the transformative potential of the sustainable development goals. *Sustainability*, **7(2)**, doi:10.3390/su7021651.

Hale, T., 2016: "All Hands on Deck": The Paris Agreement and Nonstate Climate Action. *Global Environmental Politics*, **16(3)**, 12–22, doi:10.1162/glep_a_00362.

Hallegatte, S. and J. Rozenberg, 2017: Climate change through a poverty lens. *Nature Climate Change*, **7(4)**, 250–256, doi:10.1038/nclimate3253.

Hallegatte, S. et al., 2014: Climate Change and Poverty – An Analytical Framework. WPS7126, World Bank Group, Washington DC, USA, 47 pp.

Hallegatte, S. et al., 2016: *Shock Waves: Managing the Impacts of Climate Change on Poverty*. The World Bank, Washington, DC, USA, 227 pp., doi:10.1596/978-1-4648-0673-5.

Halonen, M. et al., 2017: *Mobilizing climate finance flows: Nordic approaches and opportunities*. TemaNord 2017:519, Nordic Council of Ministers, 151 pp., doi:10.6027/TN2017-519.

Hammill, B.A. and H. Price-Kelly, 2017: *Using NDCs, NAPs and the SDGs to Advance Climate-Resilient Development*. NDC Expert perspectives, NDC Partnership, Washington DC, USA and Bonn, Germany, 10 pp.

Handmer, J. and H. Iveson, 2017: Cyclone Pam in Vanuatu: Learning from the low death toll. *Australian jouranl of Emergency Management*, **22(2)**, 60–65, https://ajem.infoservices.com.au/items/ajem-32-02-22.

Hanna, R. and P. Oliva, 2016: Implications of Climate Change for Children in Developing Countries. *The Future of Children*, **26(1)**, 115–132, doi:10.1353/foc.2016.0006.

Hansen, G. and D. Stone, 2016: Assessing the observed impact of anthropogenic climate change. *Nature Climate Change*, **6(5)**, 532–537, doi:10.1038/nclimate2896.

Harris, L.M., E.K. Chu, and G. Ziervogel, 2017: Negotiated resilience. *Resilience*, **3293**, 1–19, doi:10.1080/21693293.2017.1353196.

Hartzell-Nichols, L., 2017: *A Climate of Risk: Precautionary Principles, Catastrophes, and Climate Change*. Routledge, New York, NY, USA, 168 pp.

Hasegawa, T. et al., 2014: Climate change impact and adaptation assessment on food consumption utilizing a new scenario framework. *Environmental Science & Technology*, **48(1)**, 438–445, doi:10.1021/es4034149.

Hasegawa, T. et al., 2015: Consequence of climate mitigation on the risk of hunger. *Environmental Science & Technology*, **49(12)**, 7245–7253, doi:10.1021/es5051748.

Hashemi, S., A. Bagheri, and N. Marshall, 2017: Toward sustainable adaptation to future climate change: insights from vulnerability and resilience approaches analyzing agrarian system of Iran. *Environment, Development and Sustainability*, **19(1)**, 1–25, doi:10.1007/s10668-015-9721-3.

Hatfield-Dodds, S. et al., 2015: Australia is 'free to choose' economic growth and falling environmental pressures. *Nature*, **527(7576)**, 49–53, doi:10.1038/nature16065.

Havlík, P. et al., 2014: Climate change mitigation through livestock system transitions. *Proceedings of the National Academy of Sciences*, **111(10)**, 3709–14, doi:10.1073/pnas.1308044111.

Hayashi, A., F. Akimoto, F. Sano, and T. Tomoda, 2015: Evaluation of global energy crop production potential up to 2100 under socioeconomic development and climate change scenarios. *Journal of the Japan Institute of Energy*, **94(6)**, 548–554, doi:10.3775/jie.94.548.

Hayashi, A., F. Sano, Y. Nakagami, and K. Akimoto, 2018: Changes in terrestrial water stress and contributions of major factors under temperature rise constraint scenarios. *Mitigation and Adaptation Strategies for Global Change*, 1–27, doi:10.1007/s11027-018-9780-5.

Häyhä, T., P.L. Lucas, D.P. van Vuuren, S.E. Cornell, and H. Hoff, 2016: From Planetary Boundaries to national fair shares of the global safe operating space – How can the scales be bridged? *Global Environmental Change*, **40**, 60–72, doi:10.1016/j.gloenvcha.2016.06.008.

Hayward, B., 2017: *Sea change: climate politics and New Zealand*. Bridget Williams Books, Wellington, NZ, 120 pp.

He, J., Y. Huang, and F. Tarp, 2014: Has the clean development mechanism assisted sustainable development? *Natural Resources Forum*, **38(4)**, 248–260, doi:10.1111/1477-8947.12055.

Healy, N. and J. Barry, 2017: Politicizing energy justice and energy system transitions: Fossil fuel divestment and a "just transition". *Energy Policy*, **108**, 451–459, doi:10.1016/j.enpol.2017.06.014.

Heard, B.P., B.W. Brook, T.M.L. Wigley, and C.J.A. Bradshaw, 2017: Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems. *Renewable and Sustainable Energy Reviews*, **76**, 1122–1133, doi:10.1016/j.rser.2017.03.114.

Heede, R., 2014: Tracing anthropogenic carbon dioxide and methane emissions to fossil fuel and cement producers, 1854–2010. *Climatic Change*, **122(1–2)**, 229–241, doi:10.1007/s10584-013-0986-y.

Helliwell, J., R. Layard, and J. Sachs (eds.), 2018: *World Happiness Report*. Sustainable Development Solutions Network, New York, NY, USA, 167 pp.

Hemstock, S.L. et al., 2017: A Case for Formal Education in the Technical, Vocational Education and Training (TVET) Sector for Climate Change Adaptation and Disaster Risk Reduction in the Pacific Islands Region. In: *Climate Change Adaptation in Pacific Countries: Fostering Resilience and Improving the Quality of Life* [Filho, W. (ed.)]. Springer Nature, Cham, Switzerland, pp. 309–324, doi:10.1007/978-3-319-50094-2_19.

Hess, J.J. and K.L. Ebi, 2016: Iterative management of heat early warning systems in a changing climate. *Annals of the New York Academy of Sciences*, **1382(1)**, 21–30, doi:10.1111/nyas.13258.

Heyward, C. and D. Roser (eds.), 2016: *Climate justice in a non-ideal world*. Oxford University Press, Oxford UK, 352 pp.

Hiç, C., P. Pradhan, D. Rybski, and J.P. Kropp, 2016: Food Surplus and Its Climate Burdens. *Environmental Science & Technology*, **50(8)**, 4269–4277, doi:10.1021/acs.est.5b05088.

Hildingsson, R. and B. Johansson, 2015: Governing low-carbon energy transitions in sustainable ways: potential synergies and conflicts between climate and environmental policy objectives. *Energy Policy*, **88**, 245–252, doi:10.1016/j.enpol.2015.10.029.

HLCCP, 2017: *Report of the High-Level Commission on Carbon Prices*. High-Level Commission on Carbon Prices (HLCCP). World Bank, Washington DC, USA, 61 pp.

Holden, E., K. Linnerud, and D. Banister, 2017: The imperatives of sustainable development. *Sustainable Development*, **25(3)**, 213–226, doi:10.1002/sd.1647.

Holz, C., S. Kartha, and T. Athanasiou, 2018: Fairly sharing 1.5: national fair shares of a 1.5°C-compliant global mitigation effort. *International Environmental Agreements: Politics, Law and Economics*, **18(1)**, 117–134, doi:10.1007/s10784-017-9371-z.

Horstmann, B. and J. Hein, 2017: *Aligning climate change mitigation and sustainable development under the UNFCCC: A critical assessment of the Clean Development Mechanism, the Green Climate Fund and REDD+*. German Development Institute, Bonn, 154 pp.

Howarth, C. and I. Monasterolo, 2017: Opportunities for knowledge co-production across the energy-food-water nexus: making interdisciplinary approaches work for better climate decision making. *Environmental Science & Policy*, **75**, 103–110, doi:10.1016/j.envsci.2017.05.019.

Howarth, N., M. Galeotti, A. Lanza, and K. Dubey, 2017: Economic development and energy consumption in the GCC: an international sectoral analysis. *Energy Transitions*, **1(2)**, 6, doi:10.1007/s41825-017-0006-3.

Howell, R. and S. Allen, 2017: People and Planet: values, motivations and formative influences of individuals acting to mitigate climate change. *Environmental Values*, **26(2)**, 131–155, doi:10.3197/096327117x14847335385436.

Hubacek, K., G. Baiocchi, K. Feng, and A. Patwardhan, 2017: Poverty eradication in a carbon constrained world. *Nature Communications*, **8(1)**, 1–8, doi:10.1038/s41467-017-00919-4.

Huggel, C., I. Wallimann-Helmer, D. Stone, and W. Cramer, 2016: Reconciling justice and attribution research to advance climate policy. *Nature Climate Change*, **6(10)**, 901–908, doi:10.1038/nclimate3104.

Hughes, S., E.K. Chu, and S.G. Mason (eds.), 2018: *Climate Change in Cities: Innovations in Multi-Level Governance*. Springer International Publishing, Cham, Switzerland, 378 pp.

Hunsberger, C., S. Bolwig, E. Corbera, and F. Creutzig, 2014: Livelihood impacts of biofuel crop production: implications for governance. *Geoforum*, **54**, 248–260, doi:10.1016/j.geoforum.2013.09.022.

Huq, N., A. Bruns, L. Ribbe, and S. Huq, 2017: Mainstreaming ecosystem services based climate change adaptation (EbA) in bangladesh: status, challenges and opportunities. *Sustainability*, **9(6)**, 926, doi:10.3390/su9060926.

Hwang, J., K. Joh, and A. Woo, 2017: Social inequalities in child pedestrian traffic injuries: Differences in neighborhood built environments near schools in Austin, TX, USA. *Journal of Transport and Health*, **6**, 40–49, doi:10.1016/j.jth.2017.05.003.

Griggs, D.J., M. Nilsson, A. Stevance, and D. McCollum (eds.), 2017: *A Guide to SDG interactions: from Science to Implementation*. International Council for Science (ICSU), Paris, France, 239 pp., doi:10.24948/2017.01.

IEA, 2015: *India Energy Outlook*. International Energy Agency (IEA), Paris, France, 187 pp.

IEA, 2016: *Energy and Air Pollution: World Energy Outlook Special Report*. International Energy Agency (IEA), Paris, France, 266 pp.

IEA, 2017: *Energy Access Outlook 2017: From Poverty to Prosperity*. International Energy Agency (IEA), Paris, France, 144 pp., doi:10.1787/9789264285569-en.

IEA and World Bank, 2017: *Sustainable Energy for All 2017 – Progress towards Sustainable Energy*. International Energy Agency (IEA) and International Bank for Reconstruction and Development / The World Bank, Washington DC, USA, 208 pp., doi:10.1596/ 978-1-4648-1084-8.

INC, 1991: *Vanuatu: Draft annex relating to Article 23 (Insurance) for inclusion in the revised single text on elements relating to mechanisms (A/AC.237/WG.II/Misc.13) submitted by the Co-Chairmen of Working Group II*. A/AC.237/WG.II/CRP.8, Intergovernmental Negotiating Committee for a Framework Convention on Climate Change: Working Group II.

IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC, 2014a: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1454 pp.

IPCC, 2014b: Summary for Policymakers. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1–30.

IRENA, 2016: *Renewable Energy Market Analysis: The GCC Region*. International Renewable Energy Agency (IRENA), Abu Dhabi, United Arab Emirates, 96 pp.

Ishida, H. et al., 2014: Global-scale projection and its sensitivity analysis of the health burden attributable to childhood undernutrition under the latest scenario framework for climate change research. *Environmental Research Letters*, **9(6)**, 064014, doi:10.1088/1748-9326/9/6/064014.

Islam, M.R. and M. Shamsuddoha, 2017: Socioeconomic consequences of climate induced human displacement and migration in Bangladesh. *International Sociology*, **32(3)**, 277–298, doi:10.1177/0268580917693173.

Jägermeyr, J., A. Pastor, H. Biemans, and D. Gerten, 2017: Reconciling irrigated food production with environmental flows for Sustainable Development Goals implementation. *Nature Communications*, **8**, 1–9, doi:10.1038/ncomms15900.

Jaglin, S., 2014: Regulating service delivery in southern cities: rethinking urban heterogeneity. In: *The Routledge Handbook on Cities of the Global South* [Parnell, S. and S. Oldfield (eds.)]. pp. 434–447, doi:10.4324/9780203387832.ch37.

Jakob, M. and J. C. Steckel, 2016: Implications of climate change mitigation for sustainable development. *Environmental Research Letters*, **11(10)**, 104010, doi:10.1088/1748-9326/11/10/104010.

Janetos, A.C., E. Malone, E. Mastrangelo, K. Hardee, and A. de Bremond, 2012: Linking climate change and development goals: framing, integrating, and measuring. *Climate and Development*, **4(2)**, 141–156, doi:10.1080/17565529.2012.726195.

Jha, C.K., V. Gupta, U. Chattopadhyay, and B. Amarayil Sreeraman, 2017: Migration as adaptation strategy to cope with climate change: A study of farmers' migration in rural India. *International Journal of Climate Change Strategies and Management*, 10(1), 121–141, doi:10.1108/ijccsm-03-2017-0059.

Jiang, L. and B.C. O'Neill, 2017: Global urbanization projections for the Shared Socioeconomic Pathways. *Global Environmental Change*, **42**, 193–199, doi:10.1016/j.gloenvcha.2015.03.008.

Johansson, E.L., M. Fader, J.W. Seaquist, and K.A. Nicholas, 2016: Green and blue water demand from large-scale land acquisitions in Africa. *Proceedings of the National Academy of Sciences*, **113(41)**, 11471–11476, doi:10.1073/pnas.1524741113.

Johnson, C.A., 2017: Resilient cities? The global politics of urban climate adaptation. In: *The Power of Cities in Global Climate Politics* [Johnson, C.A. (ed.)]. Palgrave Macmillan, London, UK, pp. 91–146, doi:10.1057/978-1-137-59469-3_4.

Johnson, N. et al., 2015: Stranded on a low-carbon planet: implications of climate policy for the phase-out of coal-based power plants. *Technological Forecasting and Social Change*, **90(Part A)**, 89–102, doi:10.1016/j.techfore.2014.02.028.

Jones, L. and T. Tanner, 2017: 'Subjective resilience': using perceptions to quantify household resilience to climate extremes and disasters. *Regional Environmental Change*, **17(1)**, 229–243, doi:10.1007/s10113-016-0995-2.

Jordaan, S.M. et al., 2017: The role of energy technology innovation in reducing greenhouse gas emissions: a case study of Canada. *Renewable and Sustainable Energy Reviews*, **78**, 1397–1409, doi:10.1016/j.rser.2017.05.162.

Kagawa, S. et al., 2015: CO_2 emission clusters within global supply chain networks: Implications for climate change mitigation. *Global Environmental Change*, **35**, 486–496, doi:10.1016/j.gloenvcha.2015.04.003.

Kaijser, A. and A. Kronsell, 2014: Climate change through the lens of intersectionality. *Environmental Politics*, **23(3)**, 417–433, doi:10.1080/09644016.2013.835203.

Kalafatis, S., 2017: Identifying the Potential for Climate Compatible Development Efforts and the Missing Links. *Sustainability*, **9(9)**, 1642, doi:10.3390/su9091642.

Karlsson, L., A. Nightingale, L.O. Naess, and J. Thompson, 2017: 'Triple wins' or 'triple faults'? Analysing policy discourse on climate-smart agriculture (CSA).

5

Working Paper no.197, CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Copenhagen, Denmark, 43 pp.

Karner, K., M. Theissing, and T. Kienberger, 2015: Energy efficiency for industries through synergies with urban areas. *Journal of Cleaner Production*, **2020**, 1–11, doi:10.1016/j.jclepro.2016.02.010.

Kartha, S. et al., 2018: Inequitable mitigation: cascading biases against poorer countries. *Nature Climate Change*, **8**, 348–349, doi:10.1038/s41558-018-0152-7.

Kassie, M., H. Teklewold, M. Jaleta, P. Marenya, and O. Erenstein, 2015: Understanding the adoption of a portfolio of sustainable intensification practices in eastern and southern Africa. *Land Use Policy*, **42**, 400–411, doi:10.1016/j.landusepol.2014.08.016.

Keairns, D.L., R.C. Darton, and A. Irabien, 2016: The energy-water-food nexus. *Annual Review of Chemical and Biomolecular Engineering*, **7(1)**, 239–262, doi:10.1146/annurev-chembioeng-080615-033539.

Kelman, I., 2017: Linking disaster risk reduction, climate change, and the sustainable development goals. *Disaster Prevention and Management: An International Journal*, **26(3)**, 254–258, doi:10.1108/dpm-02-2017-0043.

Kenis, A., 2016: Ecological citizenship and democracy: Communitarian versus agonistic perspectives. *Environmental Politics*, **4016**, 1–22, doi:10.1080/09644016.2016.1203524.

Kenis, A. and E. Mathijs, 2014: (De)politicising the local: The case of the Transition Towns movement in Flanders (Belgium). *Journal of Rural Studies*, **34**, 172–183, doi:10.1016/j.jrurstud.2014.01.013.

Keohane, R.O. and D.G. Victor, 2016: Cooperation and discord in global climate policy. *Nature Climate Change*, **6(6)**, 570–575, doi:10.1038/nclimate2937.

Khanna, N., D. Fridley, and L. Hong, 2014: China's pilot low-carbon city initiative: A comparative assessment of national goals and local plans. *Sustainable Cities and Society*, **12**, 110–121, doi:10.1016/j.scs.2014.03.005.

Khosla, R., A. Sagar, and A. Mathur, 2017: Deploying Low-carbon Technologies in Developing Countries: A view from India's buildings sector. *Environmental Policy and Governance*, **27(2)**, 149–162, doi:10.1002/eet.1750.

Khreis, H., A.D. May, and M.J. Nieuwenhuijsen, 2017: Health impacts of urban transport policy measures: a guidance note for practice. *Journal of Transport & Health*, **6**, 209–227, doi:10.1016/j.jth.2017.06.003.

Kim, S.-Y. and E. Thurbon, 2015: Developmental Environmentalism: Explaining South Korea's Ambitious Pursuit of Green Growth. *Politics & Society*, **43(2)**, 213–240, doi:10.1177/0032329215571287.

Kim, Y. et al., 2017: A perspective on climate-resilient development and national adaptation planning based on USAID's experience. *Climate and Development*, **9(2)**, 141–151, doi:10.1080/17565529.2015.1124037.

King, A.D., D.J. Karoly, and B.J. Henley, 2017: Australian climate extremes at 1.5°C and 2°C of global warming. *Nature Climate Change*, **7**, 412–416, doi:10.1038/nclimate3296.

Kirby, P. and T. O'Mahony, 2018: Development Models: Lessons from International Development. In: *The Political Economy of the Low-Carbon Transition: Pathways Beyond Techno-Optimism*. Springer International Publishing, Cham, Switzerland, pp. 89–114, doi:10.1007/978-3-319-62554-6_4.

Klausbruckner, C., H. Annegarn, L.R.F. Henneman, and P. Rafaj, 2016: A policy review of synergies and trade-offs in South African climate change mitigation and air pollution control strategies. *Environmental Science & Policy*, **57**, 70–78, doi:10.1016/j.envsci.2015.12.001.

Klein, R.J.T. et al., 2014: Adaptation opportunities, constraints, and limits. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 899–943.

Klimont, Z. et al., 2017: Bridging the gap – the role of short-lived climate pollutants. In: *The Emissions Gap Report 2017: A UN Environmental Synthesis Report*. United Nations Environment Programme (UNEP), Nairobi, Kenya, pp. 48–57.

Klinsky, S. and A. Golub, 2016: Justice and Sustainability. In: *Sustainability Science: An introduction* [Heinrichs, H., P. Martens, G. Michelsen, and A. Wiek (eds.)]. Springer Netherlands, Dordrecht, Netherlands, pp. 161–173, doi:10.1007/978-94-017-7242-6.

Klinsky, S. and H. Winkler, 2018: Building equity in: strategies for integrating equity into modelling for a 1.5°C world. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376(2119)**, 20160461, doi:10.1098/rsta.2016.0461.

Klinsky, S., D. Waskow, E. Northrop, and W. Bevins, 2017a: Operationalizing equity and supporting ambition: identifying a more robust approach to 'respective capabilities'. *Climate and Development*, **9(4)**, 1–11, doi:10.1080/17565529.2016.1146121.

Klinsky, S. et al., 2017b: Why equity is fundamental in climate change policy research. *Global Environmental Change*, **44**, 170–173, doi:10.1016/j.gloenvcha.2016.08.002.

Kongsager, R. and E. Corbera, 2015: Linking mitigation and adaptation in carbon forestry projects: Evidence from Belize. *World Development*, **76**, 132–146, doi:10.1016/j.worlddev.2015.07.003.

Kongsager, R., B. Locatelli, and F. Chazarin, 2016: Addressing climate change mitigation and adaptation together: a global assessment of agriculture and forestry projects. *Environmental Management*, **57(2)**, 271–282, doi:10.1007/s00267-015-0605-y.

Kreibich, N., L. Hermwille, C. Warnecke, and C. Arens, 2017: An update on the Clean Development Mechanism in Africa in times of market crisis. *Climate and Development*, **9(2)**, 178–190, doi:10.1080/17565529.2016.1145102.

Kumar, N.S. et al., 2014: *Climatic Risks and Strategizing Agricultural Adaptation in Climatically Challenged Regions*. TB-ICN: 136/2014, Indian Agriculture Research Institute, New Delhi, India, 106 pp.

Kuramochi, T. et al., 2018: Ten key short-term sectoral benchmarks to limit warming to 1.5°C. *Climate Policy*, **18(3)**, 287–305, doi:10.1080/14693062.2017.1397495.

Kuruppu, N. and R. Willie, 2015: Barriers to reducing climate enhanced disaster risks in least developed country-small islands through anticipatory adaptation. *Weather and Climate Extremes*, **7**, 72–83, doi:10.1016/j.wace.2014.06.001.

Kusumaningtyas, S.D.A. and E. Aldrian, 2016: Impact of the June 2013 Riau province Sumatera smoke haze event on regional air pollution. *Environmental Research Letters*, **11(7)**, 075007, doi:10.1088/1748-9326/11/7/075007.

La Rovere, E.L., 2017: Low-carbon development pathways in Brazil and 'Climate Clubs'. *Wiley Interdisciplinary Reviews: Climate Change*, **8(1)**, 1–7, doi:10.1002/wcc.439.

Labordena, M., A. Patt, M. Bazilian, M. Howells, and J. Lilliestam, 2017: Impact of political and economical barriers for concentrating solar power in Sub-Saharan Africa. *Energy Policy*, **102**, 52–72, doi:10.1016/j.enpol.2016.12.008.

Labriet, M., C. Fiebig, and M. Labrousse, 2015: *Working towards a Smart Energy Path: Experience from Benin, Mali and Togo*. Inside Stories on climate compatible development, Climate and Development Knowlegdge Network (CDKN), 6 pp.

Lade, S.J., L.J. Haider, G. Engström, and M. Schlüter, 2017: Resilience offers escape from trapped thinking on poverty alleviation. *Science Advances*, **3(5)**, e1603043, doi:10.1126/sciadv.1603043.

Lahn, B., 2018: In the light of equity and science: scientific expertise and climate justice after Paris. *International Environmental Agreements: Politics, Law and Economics*, **18(1)**, 29–43, doi:10.1007/s10784-017-9375-8.

Lamb, A. et al., 2016: The potential for land sparing to offset greenhouse gas emissions from agriculture. *Nature Climate Change*, **6**, 488–492, doi:10.1038/nclimate2910.

Langford, M., A. Sumner, and A.E. Yamin (eds.), 2013: *The Millennium Development Goals and Human Rights: Past, Present and Future*. Cambridge University Press, New York, NY, USA, 571 pp.

Lasage, R. et al., 2015: A Stepwise, participatory approach to design and implement community based adaptation to drought in the Peruvian Andes. *Sustainability*, **7(2)**, 1742–1773, doi:10.3390/su7021742.

Lawrence, J. and M. Haasnoot, 2017: What it took to catalyse uptake of dynamic adaptive pathways planning to address climate change uncertainty. *Environmental Science & Policy*, **68**, 47–57, doi:10.1016/j.envsci.2016.12.003.

Lechtenboehmer, S. and K. Knoop, 2017: *Realising long-term transitions towards low carbon societies. Impulses from the 8th Annual Meeting of the International Research Network for Low Carbon Societies*. Wuppertal Spezial no. 53, Wuppertal Institut für Klima, Umwelt, Energie, Wuppertal, Germany, 100 pp.

Lefale, P., P. Faiva, and A. C, 2017: *Living with Change (LivC): An Integrated National Strategy for Enhancing the Resilience of Tokelau to Climate Change and Related Hazards, 2017–2030*. Government of Tokelau, Apia, Soamoa, 16 pp.

Leichenko, R. and J.A. Silva, 2014: Climate change and poverty: vulnerability, impacts, and alleviation strategies. *Wiley Interdisciplinary Reviews: Climate Change*, **5(4)**, 539–556, doi:10.1002/wcc.287.

Lemoine, D. and S. Kapnick, 2016: A top-down approach to projecting market impacts of climate change. *Nature Climate Change*, **6(1)**, 51–55, doi:10.1038/nclimate2759.

Lemos, C.M., Y. Lo, D.R. Nelson, H. Eakin, and A.M. Bedran-Martins, 2016: Linking development to climate adaptation: Leveraging generic and specific capacities to reduce vulnerability to drought in NE Brazil. *Global Environmental Change*, **39**, 170–179, doi:10.1016/j.gloenvcha.2016.05.001.

Ley, D., 2017: Sustainable Development, Climate Change, and Renewable Energy in Rural Central America. In: *Evaluating Climate Change Action for Sustainable Development* [Uitto, J.I., J. Puri, and R.D. van den Berg (eds.)]. Springer International Publishing, Cham, Switzerland, pp. 187–212, doi:10.1007/978-3-319-43702-6.

Li, T. et al., 2016: Aging will amplify the heat-related mortality risk under a changing climate: projection for the elderly in Beijing, China. *Scientific Reports*, **6(1)**, 28161, doi:10.1038/srep28161.

Liddell, C. and C. Guiney, 2015: Living in a cold and damp home: Frameworks for understanding impacts on mental well-being. *Public Health*, **129(3)**, 191–199, doi:10.1016/j.puhe.2014.11.007.

Lilliestam, J. and A. Patt, 2015: Barriers, risks and policies for renewables in the Gulf states. *Energies*, **8(8)**, 8263–8285, doi:10.3390/en8088263.

Lin, B.B. et al., 2017: Adaptation Pathways in Coastal Case Studies: Lessons Learned and Future Directions. *Coastal Management*, **45(5)**, 384–405, doi:10.1080/08920753.2017.1349564.

Lin, J., Y. Hu, S. Cui, J. Kang, and A. Ramaswami, 2015: Tracking urban carbon footprints from production and consumption perspectives. *Environmental Research Letters*, **10(5)**, 054001, doi:10.1088/1748-9326/10/5/054001.

Lipper, L. et al., 2014: Climate-smart agriculture for food security. *Nature Climate Change*, **4(12)**, 1068–1072, doi:10.1038/nclimate2437.

Lorek, S. and J.H. Spangenberg, 2014: Sustainable consumption within a sustainable economy – Beyond green growth and green economies. *Journal of Cleaner Production*, **63**, 33–44, doi:10.1016/j.jclepro.2013.08.045.

Lotze-Campen, H. et al., 2014: Impacts of increased bioenergy demand on global food markets: an AgMIP economic model intercomparison. *Agricultural Economics*, **45(1)**, 103–116, doi:10.1111/agec.12092.

Lucas, K. and K. Pangbourne, 2014: Assessing the equity of carbon mitigation policies for transport in Scotland. *Case Studies on Transport Policy*, **2(2)**, 70–80, doi:10.1016/j.cstp.2014.05.003.

Lucon, O. et al., 2014: Buildings. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, S. I. Baum, P. Brunner, B. Eickemeier, J. Kriemann, S. Savolainen, C. Schlömer, V. Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 671–738.

Luomi, M., 2014: Mainstreaming climate policy in the Gulf Cooperation Council States. OIES Paper: MEP 7, The Oxford Institute for Energy Studies, Oxford, UK, 73 pp.

Lwasa, S., K. Buyana, P. Kasaija, and J. Mutyaba, 2018: Scenarios for adaptation and mitigation in urban Africa under 1.5°C global warming. *Current Opinion in Environmental Sustainability*, **30**, 52–58, doi:10.1016/j.cosust.2018.02.012.

Lyon, C., 2018: Complexity ethics and UNFCCC practices for 1.5°C climate change. *Current Opinion in Environmental Sustainability*, **31**, 48–55, doi:10.1016/j.cosust.2017.12.008.

Mace, M.J., 2016: Mitigation commitments under the Paris Agreement and the way forward. *Climate Law*, **6(1–2)**, 21–39, doi:10.1163/18786561-00601002.

Macintyre, T., H. Lotz-Sisitka, A. Wals, C. Vogel, and V. Tassone, 2018: Towards transformative social learning on the path to 1.5°C degrees. *Current Opinion in Environmental Sustainability*, **31**, 80–87, doi:10.1016/j.cosust.2017.12.003.

Maclellan, N., 2015: *Yumi stap redi long klaemet jenis: Lessons from the Vanuatu NGO Climate Change Adaptation Program*. Oxfam Australia, 48 pp.

Maidment, C.D., C.R. Jones, T.L. Webb, E.A. Hathway, and J.M. Gilbertson, 2014: The impact of household energy efficiency measures on health: A meta-analysis. *Energy Policy*, **65**, 583–593, doi:10.1016/j.enpol.2013.10.054.

Maor, M., J. Tosun, and A. Jordan, 2017: Proportionate and disproportionate policy responses to climate change: core concepts and empirical applications. *Journal of Environmental Policy and Planning*, 1–13, doi:10.1080/1523908x.2017.1281730.

Mapfumo, P. et al., 2017: Pathways to transformational change in the face of climate impacts: an analytical framework. *Climate and Development*, **9(5)**, 439–451, doi:10.1080/17565529.2015.1040365.

Marjanac, S. and L. Patton, 2018: Extreme weather event attribution science and climate change litigation: an essential step in the causal chain? *Journal of Energy & Natural Resources Law*, 1–34, doi:10.1080/02646811.2018.1451020.

Markandya, A. et al., 2018: Health co-benefits from air pollution and mitigation costs of the Paris Agreement: a modelling study. *The Lancet Planetary Health*, **2(3)**, e126–e133, doi:10.1016/s2542-5196(18)30029-9.

Marsh, J., 2015: Mixed motivations and complex causality in the Mekong. *Forced Migration Review*, 68–69, www.fmreview.org/climatechange-disasters/marsh.

Martinez-Baron, D., G. Orjuela, G. Renzoni, A.M. Loboguerrero Rodríguez, and S.D. Prager, 2018: Small-scale farmers in a 1.5°C future: the importance of local social dynamics as an enabling factor for implementation and scaling of climate-smart agriculture. *Current Opinion in Environmental Sustainability*, **31**, 112–119, doi:10.1016/j.cosust.2018.02.013.

Mathur, V.N., S. Afionis, J. Paavola, A.J. Dougill, and L.C. Stringer, 2014: Experiences of host communities with carbon market projects: towards multi-level climate justice. *Climate Policy*, **14(1)**, 42–62, doi:10.1080/14693062.2013.861728.

Maupin, A., 2017: The SDG13 to combat climate change: an opportunity for Africa to become a trailblazer? *African Geographical Review*, **36(2)**, 131–145, doi:10.1080/19376812.2016.1171156.

Mayer, B., 2016: The relevance of the no-harm principle to climate change law and politics. *Asia Pacific Journal of Environmental Law*, **19(1)**, 79–104, doi:10.4337/apjel.2016.01.04.

Mbow, C., C. Neely, and P. Dobie, 2015: How can an integrated landscape approach contribute to the implementation of the Sustainable Development Goals (SDGs) and advance climate-smart objectives? In: *Climate-Smart Landscapes: Multifunctionality in Practice* [Minang, P.A., M. van Noordwijk, C. Mbow, J. de Leeuw, and D. Catacutan (eds.)]. World Agroforestry Centre (ICRAF), Nairobi, Kenya, pp. 103–117.

McCollum, D.L. et al., 2018a: Connecting the Sustainable Development Goals by their energy inter-linkages. *Environmental Research Letters,* **13(3),** 033006, doi:10.1088/1748-9326/aaafe3.

McCollum, D.L. et al., 2018b: Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. *Nature Energy*, **3(7)**, 589–599, doi:10.1038/s41560-018-0179-z.

McCubbin, S., B. Smit, and T. Pearce, 2015: Where does climate fit? Vulnerability to climate change in the context of multiple stressors in Funafuti, Tuvalu. *Global Environmental Change*, **30**, 43–55, doi:10.1016/j.gloenvcha.2014.10.007.

McGlade, C. and P. Ekins, 2015: The geographical distribution of fossil fuels unused when limiting global warming to 2°C. *Nature*, **517(7533)**, 187–190, doi:10.1038/nature14016.

McGranahan, G., D. Schensul, and G. Singh, 2016: Inclusive urbanization: can the 2030 Agenda be delivered without it? *Environment and Urbanization*, **28(1)**, 13–34, doi:10.1177/0956247815627522.

McKay, B., S. Sauer, B. Richardson, and R. Herre, 2016: The political economy of sugarcane flexing: initial insights from Brazil, Southern Africa and Cambodia. *The Journal of Peasant Studies*, **43(1)**, 195–223, doi:10.1080/03066150.2014.992016.

McNamara, K.E., 2015: Cross-border migration with dignity in Kiribati. *Forced Migration Review*, **49**, 62, www.fmreview.org/climatechange-disasters/mcnamara.

McNamara, K.E. and S.S. Prasad, 2014: Coping with extreme weather: Communities in Fiji and Vanuatu share their experiences and knowledge. *Climatic Change*, **123(2)**, 121–132, doi:10.1007/s10584-013-1047-2.

Mechler, R. and T. Schinko, 2016: Identifying the policy space for climate loss and damage. *Science*, **354(6310)**, 290–292, doi:10.1126/science.aag2514.

Mechler, R., L.M. Bouwer, T. Schinko, S. Surminski, and J. Linnerooth-Bayer (eds.), 2019: *Loss and Damage from Climate Change: Concepts, Methods and Policy Options*. Springer International Publishing, 561 pp, doi:10.1007/978-3-319-72026-5.

Meerow, S. and J.P. Newell, 2016: Urban resilience for whom, what, when, where, and why? *Urban Geography*, 1–21, doi:10.1080/02723638.2016.1206395.

Mehmood, A., 2016: Of resilient places: planning for urban resilience. *European Planning Studies*, **24(2)**, 407–419, doi:10.1080/09654313.2015.1082980.

Meinshausen, M. et al., 2015: National post-2020 greenhouse gas targets and diversity-aware leadership. *Nature Climate Change*, **5(12)**, 1098–1106, doi:10.1038/nclimate2826.

Melica, G. et al., 2018: Multilevel governance of sustainable energy policies: The role of regions and provinces to support the participation of small local authorities in the Covenant of Mayors. *Sustainable Cities and Society*, **39**, 729–739, doi:10.1016/j.scs.2018.01.013.

Michaelowa, A., M. Allen, and F. Sha, 2018: Policy instruments for limiting global temperature rise to 1.5°C – can humanity rise to the challenge? *Climate Policy*, **18(3)**, 275–286, doi:10.1080/14693062.2018.1426977.

Millar, R.J. et al., 2017: Emission budgets and pathways consistent with limiting warming to 1.5°C. *Nature Geoscience*, 1–8, doi:10.1038/ngeo3031.

Millard-Ball, A., 2013: The limits to planning: causal impacts of city climate action plans. *Journal of Planning Education and Research*, **33(1)**, 5–19, doi:10.1177/0739456x12449742.

Mishra, V., S. Mukherjee, R. Kumar, and D. Stone, 2017: Heat wave exposure in India in current, 1.5°C, and 2.0°C worlds. *Environmental Research Letters*, **12**, 124012, doi:10.1088/1748-9326/aa9388.

Mitchell, D. et al., 2016: Attributing human mortality during extreme heat waves to anthropogenic climate change. *Environmental Research Letters*, **11(7)**, 074006, doi:10.1088/1748-9326/11/7/074006.

MoCC, 2016: *Corporate Plan 2016–2018*. Ministry of Climate Chanage and Adaptation (MoCC), Government of Vanuatu, Vanuatu, 98 pp.

Moellendorf, D., 2015: Climate change justice. *Philosophy Compass*, **10**, 173–186, doi:10.3197/096327111x12997574391887.

Morita, K. and K. Matsumoto, 2015: Enhancing Biodiversity Co-benefits of Adaptation to Climate Change. In: *Handbook of Climate Change Adaptation* [Filho, W.L. (ed.)]. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 953–972, doi:10.1007/978-3-642-38670-1_21.

Mouratiadou, I. et al., 2018: Water demand for electricity in deep decarbonisation scenarios: a multi-model assessment. *Climatic Change*, **147(1)**, 91–106, doi:10.1007/s10584-017-2117-7.

MRFCJ, 2015a: *Women's Participation – An Enabler of Climate Justice*. Mary Robinson Foundation Climate Justice (MRFCJ), Dublin, Ireland, 24 pp.

MRFCJ, 2015b: *Zero Carbon, Zero Poverty The Climate Justice Way: Achieving an equitable phase-out of carbon emissions by 2050 while protecting human rights*. Mary Robinson Foundation Climate Justice (MRFCJ), Dublin, Ireland, 70 pp.

Muratori, M., K. Calvin, M. Wise, P. Kyle, and J. Edmonds, 2016: Global economic consequences of deploying bioenergy with carbon capture and storage (BECCS). *Environmental Research Letters*, **11(9)**, 1–9, doi:10.1088/1748-9326/11/9/095004.

Murphy, D.J., L. Yung, C. Wyborn, and D.R. Williams, 2017: Rethinking climate change adaptation and place through a situated pathways framework: a case study from the Big Hole Valley, USA. *Landscape and Urban Planning*, **167**, 441–450, doi:10.1016/j.landurbplan.2017.07.016.

Murphy, K., G.A. Kirkman, S. Seres, and E. Haites, 2015: Technology transfer in the CDM: an updated analysis. *Climate Policy*, **15(1)**, 127–145, doi:10.1080/14693062.2013.812719.

Murtinho, F., 2016: What facilitates adaptation? An analysis of community-based adaptation to environmental change in the Andes. *International Journal of the Commons*, **10(1)**, 119–141, doi:10.18352/ijc.585.

Muttarak, R. and W. Lutz, 2014: Is education a key to reducing vulnerability to natural disasters and hence unavoidable climate change? *Ecology and Society*, **19(1)**, 42, doi:10.5751/es-06476-190142.

Myers, S.S. et al., 2017: Climate Change and Global Food Systems: Potential Impacts on Food Security and Undernutrition. *Annual Review of Public Health*, 1–19, doi:10.1146/annurev-publhealth-031816-044356.

Naess, L.O. et al., 2015: Climate policy meets national development contexts: insights from Kenya and Mozambique. *Global Environmental Change*, **35**, 534–544, doi:10.1016/j.gloenvcha.2015.08.015.

Nagoda, S., 2015: New discourses but same old development approaches? Climate change adaptation policies, chronic food insecurity and development interventions in northwestern Nepal. *Global Environmental Change*, **35**, 570–579, doi:10.1016/j.gloenvcha.2015.08.014.

Nalau, J., J. Handmer, and M. Dalesa, 2017: The role and capacity of government in a climate crisis: Cyclone Pam in Vanuatu. In: *Climate Change Adaptation in Pacific Countries: Fostering Resilience and Improving the Quality of Life* [Leal Filho, W. (ed.)]. Springer International Publishing, Cham, Switzerland, pp. 151–161, doi:10.1007/978-3-319-50094-2_9.

Nalau, J. et al., 2016: The practice of integrating adaptation and disaster risk reduction in the south-west Pacific. *Climate and Development*, **8(4)**, 365–375, doi:10.1080/17565529.2015.1064809.

NASEM, 2016: *Attribution of Extreme Weather Events in the Context of Climate Change*. National Academies of Sciences, Engineering, and Medicine (NASEM). The National Academies Press, Washington DC, USA, 186 pp., doi:10.17226/21852.

Nelson, D.R., M.C. Lemos, H. Eakin, and Y.-J. Lo, 2016: The limits of poverty reduction in support of climate change adaptation. *Environmental Research Letters*, **11(9)**, 094011, doi:10.1088/1748-9326/11/9/094011.

Newell, P. et al., 2014: The Political Economy of Low Carbon Energy in Kenya. IDS Working Papers Vol 2014 No 445, Institute of Development Studies (IDS), Brighton, UK, 38 pp., doi:10.1111/j.2040-0209.2014.00445.x.

Newman, P., T. Beatley, and H. Boyer, 2017: *Resilient Cities: Overcoming Fossil Fuel Dependence (2nd edition)*. Island Press, Washington DC, USA, 264 pp.

Nguyen, M.T., S. Vink, M. Ziemski, and D.J. Barrett, 2014: Water and energy synergy and trade-off potentials in mine water management. *Journal of Cleaner Production*, **84(1)**, 629–638, doi:10.1016/j.jclepro.2014.01.063.

Nhamo, G., 2016: New Global Sustainable Development Agenda: A Focus on Africa. *Sustainable Development*, **25**, 227–241, doi:10.1002/sd.1648.

Niang, I. et al., 2014: Africa. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1199–1265.

Nicholls, R.J. et al., 2018: Stabilization of global temperature at 1.5°C and 2.0°C: implications for coastal areas. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376(2119)**, 20160448, doi:10.1098/rsta.2016.0448.

Nicolosi, E. and G. Feola, 2016: Transition in place: Dynamics, possibilities, and constraints. *Geoforum*, **76**, 153–163, doi:10.1016/j.geoforum.2016.09.017.

Nilsson, M., D. Griggs, and M. Visback, 2016: Map the interactions between Sustainable Development Goals. *Nature*, **534(7607)**, 320–322, doi:10.1038/534320a.

Nkomwa, E.C., M.K. Joshua, C. Ngongondo, M. Monjerezi, and F. Chipungu, 2014: Assessing indigenous knowledge systems and climate change adaptation strategies in agriculture: a case study of Chagaka Village, Chikhwawa, Southern Malawi. *Physics and Chemistry of the Earth, Parts A/B/C*, **67–69**, 164–172, doi:10.1016/j.pce.2013.10.002.

Noble, I. et al., 2014: Adaptation needs and options. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 659–708.

Normann, H.E., 2015: The role of politics in sustainable transitions: The rise and decline of offshore wind in Norway. *Environmental Innovation and Societal Transitions*, **15(2015)**, 180–193, doi:10.1016/j.eist.2014.11.002.

North, P. and N. Longhurst, 2013: Grassroots localisation? The scalar potential of and limits of the 'transition' approach to climate change and resource constraint. *Urban Studies*, **50(7)**, 1423–1438, doi:10.1177/0042098013480966.

Nunan, F. (ed.), 2017: *Making Climate Compatible Development Happen*. Routledge, Abingdon, UK and New York, NY, USA, 262 pp.

Nunn, P.D., W. Aalbersberg, S. Lata, and M. Gwilliam, 2014: Beyond the core: Community governance for climate-change adaptation in peripheral parts of Pacific Island Countries. *Regional Environmental Change*, **14(1)**, 221–235, doi:10.1007/s10113-013-0486-7.

Nyantakyi-Frimpong, H. and R. Bezner-Kerr, 2015: The relative importance of climate change in the context of multiple stressors in semi-arid Ghana. *Global Environmental Change*, **32**, 40–56, doi:10.1016/j.gloenvcha.2015.03.003.

O'Brien, K.L., 2016: Climate change and social transformations: is it time for a quantum leap? *Wiley Interdisciplinary Reviews: Climate Change*, **7(5)**, 618–626, doi:10.1002/wcc.413.

O'Brien, K.L., 2017: Climate Change Adaptation and Social Transformation. In: *International Encyclopedia of Geography: People, the Earth, Environment and Technology*. John Wiley & Sons, Ltd, Oxford, UK, pp. 1–8, doi:10.1002/9781118786352.wbieg0987.

O'Brien, K.L., 2018: Is the 1.5°C target possible? Exploring the three spheres of transformation. *Current Opinion in Environmental Sustainability*, **31**, 153–160, doi:10.1016/j.cosust.2018.04.010.

O'Brien, K.L., S. Eriksen, T.H. Inderberg, and L. Sygna, 2015: Climate change and development: adaptation through transformation. In: *Climate Change Adaptation and Development: Changing Paradigms and Practices* [Inderberg, T.H., S. Eriksen, K. O'Brien, and L. Sygna (eds.)]. Routledge, Abingdon, UK and New York, NY, USA, pp. 273–289.

O'Neill, B.C. et al., 2017a: The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change*, **42**, 169–180, doi:10.1016/j.gloenvcha.2015.01.004.

O'Neill, B.C. et al., 2017b: IPCC reasons for concern regarding climate change risks. *Nature Climate Change*, **7(1)**, 28–37, doi:10.1038/nclimate3179.

O'Neill, D.W., A.L. Fanning, W.F. Lamb, and J.K. Steinberger, 2018: A good life for all within planetary boundaries. *Nature Sustainability*, **1(2)**, 88–95, doi:10.1038/s41893-018-0021-4.

5

Ober, K. and P. Sakdapolrak, 2017: How do social practices shape policy? Analysing the field of 'migration as adaptation' with Bourdieu's 'Theory of Practice'. *The Geographical Journal*, **183(4)**, 359–369, doi:10.1111/geoj.12225.

Obersteiner, M. et al., 2016: Assessing the land resource-food price nexus of the Sustainable Development Goals. *Science Advances*, **2(9)**, e1501499–e1501499, doi:10.1126/sciadv.1501499.

OECD, 2017: The Government Role in Mobilising Investment and Innovation in Renewable Energy. *OECD Investment Insights,* August 2017, Organisation for Economic Co-operation and Development (OECD), Paris, France, 4 pp.

Oei, P.-Y. and R. Mendelevitch, 2016: European Scenarios of CO_2 Infrastructure Investment until 2050. *The Energy Journal*, **37(01)**, doi:10.5547/01956574.37.si3.poei.

Ojea, E., 2015: Challenges for mainstreaming Ecosystem-based Adaptation into the international climate agenda. *Current Opinion in Environmental Sustainability*, **14**, 41–48, doi:10.1016/j.cosust.2015.03.006.

Okereke, C. and P. Coventry, 2016: Climate justice and the international regime: before, during, and after Paris. *Wiley Interdisciplinary Reviews: Climate Change*, **7(6)**, 834–851, doi:10.1002/wcc.419.

Olawuyi, D.S., 2017: From technology transfer to technology absorption: addressing climate technology gaps in Africa. Fixing Climate Governance Series Paper No. 5, Centre for International Governance Innovation, Waterloo, Canada, 16 pp.

Olsson, L. et al., 2014: Livelihoods and Poverty. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 793–832.

Oosterhuis, F.H. and P. Ten Brink (eds.), 2014: *Paying the Polluter: Environmentally Harmful Subsidies and their Reform*. Edward Elgar Publishing, Cheltenham, UK and Northampton, MA, USA, 368 pp.

Oppenheimer, M., M. Campos, and R. Warren, 2014: Emergent risks and key vulnerabilities. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 659–708.

Orindi, V., Y. Elhadi, and C. Hesse, 2017: Democratising climate finance at local levels. In: *Building a Climate Resilient Economy and Society: Challenges and Opportunities* [Ninan, K.N. and M. Inoue (eds.)]. Edward Elgar Publishing, Cheltenham, UK and Northampton, MA, USA, pp. 250–264.

Otto, F.E.L., R.B. Skeie, J.S. Fuglestvedt, T. Berntsen, and M.R. Allen, 2017: Assigning historic responsibility for extreme weather events. *Nature Climate Change*, **7(11)**, 757–759, doi:10.1038/nclimate3419.

Page, E.A. and C. Heyward, 2017: Compensating for climate change Loss and Damage. *Political Studies*, **65(2)**, 356–372, doi:10.1177/0032321716647401.

Pal, J.S. and E.A.B. Eltahir, 2016: Future temperature in southwest Asia projected to exceed a threshold for human adaptability. *Nature Climate Change*, **18203**, 1–4, doi:10.1038/nclimate2833.

Palazzo, A. et al., 2017: Linking regional stakeholder scenarios and shared socioeconomic pathways: Quantified West African food and climate futures in a global context. *Global Environmental Change*, **45**, 227–242, doi:10.1016/j.gloenvcha.2016.12.002.

Pan, X., M. Elzen, N. Höhne, F. Teng, and L. Wang, 2017: Exploring fair and ambitious mitigation contributions under the Paris Agreement goals. *Environmental Science & Policy*, **74**, 49–56, doi:10.1016/j.envsci.2017.04.020.

Pandey, U.C. and C. Kumar, 2018: Emerging Paradigms of Capacity Building in the Context of Climate Change. In: *Climate Literacy and Innovations in Climate Change Education: Distance Learning for Sustainable Development* [Azeiteiro, U.M., W. Leal Filho, and L. Aires (eds.)]. Springer International Publishing, Cham, pp. 193–214, doi:10.1007/978-3-319-70199-8_11.

Parikh, K.S., J.K. Parikh, and P.P. Ghosh, 2018: Can India grow and live within a 1.5 degree CO_2 emissions budget? *Energy Policy*, **120**, 24–37, doi:10.1016/j.enpol.2018.05.014.

Park, J., S. Hallegatte, M. Bangalore, and E. Sandhoefner, 2015: Households and heat stress estimating the distributional consequences of climate change. Policy Research Working Paper no. WPS7479, World Bank Group, Washington, DC, USA, 58 pp.

Parkinson, S.C. et al., 2016: Impacts of Groundwater Constraints on Saudi Arabia's Low-Carbon Electricity Supply Strategy. *Environmental Science & Technology*, **50(4)**, 1653–1662, doi:10.1021/acs.est.5b05852.

Parnell, S., 2017: Africa's urban risk and resilience. *International Journal of Disaster Risk Reduction*, **26**, 1–6, doi:10.1016/j.ijdrr.2017.09.050.

Patterson, J.J. et al., 2016: Exploring the governance and politics of transformations towards sustainability. *Environmental Innovation and Societal Transitions*, 1–16, doi:10.1016/j.eist.2016.09.001.

Patterson, J.J. et al., 2018: Political feasibility of 1.5°C societal transformations: the role of social justice. *Current Opinion in Environmental Sustainability*, **31**, 1–9, doi:10.1016/j.cosust.2017.11.002.

Pearce, T., J. Ford, A.C. Willox, and B. Smit, 2015: Inuit Traditional Ecological Knowledge (TEK), subsistence hunting and adaptation to climate change in the Canadian Arctic. *Arctic*, **68(2)**, 233–245, doi:10.2307/43871322.

Pelling, M., T. Abeling, and M. Garschagen, 2016: Emergence and Transition in London's Climate Change Adaptation Pathways. *Journal of Extreme Events*, **3(3)**, 1650012, doi:10.1142/s2345737616500123.

Pelling, M. et al., 2018: Africa's urban adaptation transition under a 1.5° climate. *Current Opinion in Environmental Sustainability*, **31**, 10–15, doi:10.1016/j.cosust.2017.11.005.

Petkova, E.P. et al., 2017: Towards more comprehensive projections of urban heat-related mortality: estimates for New York city under multiple population, adaptation, and climate scenarios. *Environmental Health Perspectives*, **125(1)**, 47–55, doi:10.1289/ehp166.

Pfeiffer, A., R. Millar, C. Hepburn, and E. Beinhocker, 2016: The '2°C carbon stock' for electricity generation: cumulative committed carbon emissions from the electricity generation sector and the transition to a green economy. *Applied Energy*, **179**, 1395–1408, doi:10.1016/j.apenergy.2016.02.093.

Phillips, J., P. Newell, and A. Pueyo, 2017: Triple wins? Prospects for pro-poor, low carbon, climate resilient energy services in Kenya. In: *Making Climate Compatible Development Happen* [Nunan, F. (ed.)]. Routledge, Abingdon, UK and New York, NY, USA, pp. 114–129.

Popescu, G.H. and F.C. Ciurlau, 2016: Can environmental sustainability be attained by incorporating nature within the capitalist economy? *Economics, Management, and Financial Markets*, **11(4)**, 75–81.

Popp, A. et al., 2014: Land-use transition for bioenergy and climate stabilization: Model comparison of drivers, impacts and interactions with other land use based mitigation options. *Climatic Change*, **123(3–4)**, 495–509, doi:10.1007/s10584-013-0926-x.

Popp, A. et al., 2017: Land-use futures in the shared socio-economic pathways. *Global Environmental Change*, **42**, 331–345, doi:10.1016/j.gloenvcha.2016.10.002.

Potouroglou, M. et al., 2017: Measuring the role of seagrasses in regulating sediment surface elevation. *Scientific Reports*, **7(1)**, 1–11, doi:10.1038/s41598-017-12354-y.

Pradhan, A., C. Chan, P.K. Roul, J. Halbrendt, and B. Sipes, 2018: Potential of conservation agriculture (CA) for climate change adaptation and food security under rainfed uplands of India: a transdisciplinary approach. *Agricultural Systems*, **163**, 27–35, doi:10.1016/j.agsy.2017.01.002.

Preston, F. and J. Lehne, 2017: *A wider circle? The circular economy in developing countries*. Chatham House: The Royal Institute of International Affairs, London, 24 pp.

Pretis, F., M. Schwarz, K. Tang, K. Haustein, and M.R. Allen, 2018: Uncertain impacts on economic growth when stabilizing global temperatures at 1.5°C or 2°C warming. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376(2119)**, 20160460, doi:10.1098/rsta.2016.0460.

Purdon, M., 2015: Opening the black box of carbon finance "additionality": the political economy of carbon finance effectiveness across Tanzania, Uganda, and Moldova. *World Development*, **74**, 462–478, doi:10.1016/j.worlddev.2015.05.024.

Quan, J., L.O. Naess, A. Newsham, A. Sitoe, and M.C. Fernandez, 2017: The Political Economy of REDD+ in Mozambique: Implications for Climate Compatible Development. In: *Making Climate Compatible Development Happen* [Nunan, F. (ed.)]. Routledge, Abingdon, UK and New York, NY, USA, pp. 151–181.

Rai, N. and S. Fisher (eds.), 2017: *The Political Economy of Low Carbon Resilient Development: Planning and implementation*. Routledge, Abingdon, UK and New York, NY, USA, 172 pp.

Rao, N.D., 2014: International and intranational equity in sharing climate change mitigation burdens. *International Environmental Agreements: Politics, Law and Economics*, **14(2)**, 129–146, doi:10.1007/s10784-013-9212-7.

5

Rao, N.D. and J. Min, 2018: Less global inequality can improve climate outcomes. *Wiley Interdisciplinary Reviews: Climate Change*, **9**, e513, doi:10.1002/wcc.513.
Rao, N.D., B.J. van Ruijven, V. Bosetti, and K. Riahi, 2017: Improving poverty and inequality modeling in climate research. *Nature Climate Change*, **7**, 857–862, doi:10.1038/s41558-017-0004-x.
Rao, S. et al., 2016: Future Air Pollution in the Shared Socio-Economic Pathways. *Global Environmental Change*, **42**, 346–358, doi:10.1016/j.gloenvcha.2016.05.012.
Rasch, R., 2017: Income Inequality and Urban Vulnerability to Flood Hazard in Brazil. *Social Science Quarterly*, **98(1)**, 299–325, doi:10.1111/ssqu.12274.
Rasul, G. and B. Sharma, 2016: The nexus approach to water-energy-food security: an option for adaptation to climate change. *Climate Policy*, **16(6)**, 682–702, doi:10.1080/14693062.2015.1029865.
Raworth, K., 2017: A Doughnut for the Anthropocene: humanity's compass in the 21st century. *The Lancet Planetary Health*, **1(2)**, e48–e49, doi:10.1016/s2542-5196(17)30028-1.
Redclift, M. and D. Springett (eds.), 2015: *Routledge International Handbook of Sustainable Development*. Routledge, Abingdon, UK and New York, NY, USA, 448 pp.
Regmi, B.R. and C. Star, 2015: Exploring the policy environment for mainstreaming community-based adaptation (CBA) in Nepal. *International Journal of Climate Change Strategies and Management*, **7(4)**, 423–441, doi:10.1108/ijccsm-04-2014-0050.
Reid, H., 2016: Ecosystem- and community-based adaptation: learning from community-based natural resource management. *Climate and Development*, **8(1)**, 4–9, doi:10.1080/17565529.2015.1034233.
Reid, H. and S. Huq, 2014: Mainstreaming community-based adaptation into national and local planning. *Climate and Development*, **6(4)**, 291–292, doi:10.1080/17565529.2014.973720.
Reij, C. and R. Winterbottom, 2015: *Scaling up Regreening: Six Steps to Success. A Practical Approach to Forest Landscape Restoration*. World Resource Institute (WRI), Washington DC, USA, 72 pp.
Republic of Vanuatu, 2016: *Vanuatu 2030: The People's Plan*. Government of the Republic of Vanuatu, Port Villa, Vanuatu, 28 pp.
Republic of Vanuatu, 2017: *Vanuatu 2030: The People's Plan. National Sustainable Development Plan 2016–2030. Monitoring and Evaluation Framework*. The Government of the Republic of Vanuatu, Port Vila, Vanuatu, 48 pp.
Revi, A. et al., 2014: Urban areas. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 535–612.
Rey, T., L. Le De, F. Leone, and D. Gilbert, 2017: An integrative approach to understand vulnerability and resilience post-disaster: the 2015 cyclone Pam in urban Vanuatu as case study. *Disaster Prevention and Management: An International Journal*, **26(3)**, 259–275, doi:10.1108/dpm-07-2016-0137.
Reyer, C.P.O. et al., 2017a: Climate change impacts in Latin America and the Caribbean and their implications for development. *Regional Environmental Change*, **17(6)**, 1601–1621, doi:10.1007/s10113-015-0854-6.
Reyer, C.P.O. et al., 2017b: Turn down the heat: regional climate change impacts on development. *Regional Environmental Change*, **17(6)**, 1563–1568, doi:10.1007/s10113-017-1187-4.
Riahi, K. et al., 2015: Locked into Copenhagen pledges – Implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technological Forecasting and Social Change*, **90**, 8–23, doi:10.1016/j.techfore.2013.09.016.
Riahi, K. et al., 2017: The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview. *Global Environmental Change*, **42**, 153–168, doi:10.1016/j.gloenvcha.2016.05.009.
Robertson, M., 2014: *Sustainability Principles and Practice*. Routledge, London, UK, 392 pp., doi:10.4324/9780203768747.
Robinson, M. and T. Shine, 2018: Achieving a climate justice pathway to 1.5°C. *Nature Climate Change*, **8(7)**, 564–569, doi:10.1038/s41558-018-0189-7.
Robinson, S. and M. Dornan, 2017: International financing for climate change adaptation in small island developing states. *Regional Environmental Change*, **17(4)**, 1103–1115, doi:10.1007/s10113-016-1085-1.
Robiou du Pont, Y. et al., 2017: Equitable mitigation to achieve the Paris Agreement goals. *Nature Climate Change*, **7(1)**, 38–43, doi:10.1038/nclimate3186.
Rockström, J. et al., 2017: Sustainable intensification of agriculture for human prosperity and global sustainability. *Ambio*, **46(1)**, 4–17, doi:10.1007/s13280-016-0793-6.
Rogelj, J. et al., 2018: Scenarios towards limiting global mean temperature increase below 1.5°C. *Nature Climate Change*, 1–8, doi:10.1038/s41558-018-0091-3.
Roger, C., T. Hale, and L. Andonova, 2017: The comparative politics of transnational climate governance. *International Interactions*, **43(1)**, 1–25, doi:10.1080/03050629.2017.1252248.
Rose, S.K. et al., 2014: Bioenergy in energy transformation and climate management. *Climatic Change*, **123(3–4)**, 477–493, doi:10.1007/s10584-013-0965-3.
Rosenbloom, D., 2017: Pathways: An emerging concept for the theory and governance of low-carbon transitions. *Global Environmental Change*, **43**, 37–50, doi:10.1016/j.gloenvcha.2016.12.011.
Rosenzweig, C. et al., 2018: *Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 811 pp., doi:10.1017/9781316563878.
Roser, D. and C. Seidel, 2017: *Climate justice*. Routledge, Abingdon, UK, 230 pp.
Roser, D., C. Huggel, M. Ohndorf, and I. Wallimann-Helmer, 2015: Advancing the interdisciplinary dialogue on climate justice. *Climatic Change*, **133(3)**, 349–359, doi:10.1007/s10584-015-1556-2.
Rozenberg, J. and S. Hallegatte, 2016: Modeling the Impacts of Climate Change on Future Vietnamese Households: A Micro-Simulation Approach. World Bank Policy Research Working Paper No. 7766, World Bank, 20 pp.
Runhaar, H., B. Wilk, Persson, C. Uittenbroek, and C. Wamsler, 2018: Mainstreaming climate adaptation: taking stock about "what works" from empirical research worldwide. *Regional Environmental Change*, **18(4)**, 1201–1210, doi:10.1007/s10113-017-1259-5.
Rutledge, D. et al., 2017: *Identifying Feedbacks, Understanding Cumulative Impacts and Recognising Limits: A National Integrated Assessment. Synthesis Report RA3. Climate Changes, Impacts and Implications for New Zealand to 2100*. CCII (Climate Changes, Impacts & Implications), 84 pp.
Sachs, J., G. Schmidt-Traub, C. Kroll, D. Durand-Delacre, and K. Teksoz, 2017: *SDG Index and Dashboards Report 2017*. Bertelsmann Stiftung and Sustainable Development Solutions Network (SDSN), New York, NY, USA, 479 pp.
Salleh, A., 2016: Climate, Water, and Livelihood Skills: A Post-Development Reading of the SDGs. *Globalizations*, **13(6)**, 952–959, doi:10.1080/14747731.2016.1173375.
Sánchez, A. and M. Izzo, 2017: Micro hydropower: an alternative for climate change mitigation, adaptation, and development of marginalized local communities in Hispaniola Island. *Climatic Change*, **140(1)**, 79–87, doi:10.1007/s10584-016-1865-0.
Santarius, T., H.J. Walnum, and C. Aall (eds.), 2016: *Rethinking Climate and Energy Policies: New Perspectives on the Rebound Phenomenon*. Springer, Cham, Switzerland, 294 pp., doi:10.1007/978-3-319-38807-6.
Santos, P., P. Bacelar-Nicolau, M.A. Pardal, L. Bacelar-Nicolau, and U.M. Azeiteiro, 2016: Assessing Student Perceptions and Comprehension of Climate Change in Portuguese Higher Education Institutions. In: *Implementing Climate Change Adaptation in Cities and Communities: Integrating Strategies and Educational Approaches* [Filho, W.L., K. Adamson, R.M. Dunk, U.M. Azeiteiro, S. Illingworth, and F. Alves (eds.)]. Springer, Cham, Switzerland, pp. 221–236, doi:10.1007/978-3-319-28591-7_12.
Satterthwaite, D., 2016: Missing the Millennium Development Goal targets for water and sanitation in urban areas. *Environment and Urbanization*, **28(1)**, 99–118, doi:10.1177/0956247816628435.
Satterthwaite, D. et al., 2018: *Responding to climate change in cities and in their informal settlements and economies*. International Institute for Environment and Development, Edmonton, Canada, 61 pp.
Savo, V. et al., 2016: Observations of climate change among subsistence-oriented communities around the world. *Nature Climate Change*, **6(5)**, 462–473, doi:10.1038/nclimate2958.
Schade, J. and W. Obergassel, 2014: Human rights and the Clean Development Mechanism. *Cambridge Review of International Affairs*, **27(4)**, 717–735, doi:10.1080/09557571.2014.961407.
Schaeffer, M. et al., 2015: *Feasibility of limiting warming to 1.5 and 2°C*. Climate Analytics, Berlin, Germany, 20 pp.
Schaller, N. et al., 2016: Human influence on climate in the 2014 southern England winter floods and their impacts. *Nature Climate Change*, **6(6)**, 627–634, doi:10.1038/nclimate2927.

Schirmer, J. and L. Bull, 2014: Assessing the likelihood of widespread landholder adoption of afforestation and reforestation projects. *Global Environmental Change*, **24**, 306–320, doi:10.1016/j.gloenvcha.2013.11.009.

Schleussner, C.-F. et al., 2016: Differential climate impacts for policy-relevant limits to global warming: the case of 1.5°C and 2°C. *Earth System Dynamics*, **7(2)**, 327–351, doi:10.5194/esd-7-327-2016.

Schlosberg, D., L.B. Collins, and S. Niemeyer, 2017: Adaptation policy and community discourse: risk, vulnerability, and just transformation. *Environmental Politics*, **26(3)**, 1–25, doi:10.1080/09644016.2017.1287628.

Schwan, S. and X. Yu, 2017: Social protection as a strategy to address climate-induced migration. *International Journal of Climate Change Strategies and Management*, 10(1), 43–64, doi:10.1108/ijccsm-01-2017-0019.

Scoones, I. et al., 2017: *Pathways to Sustainable Agriculture*. Routledge, Abingdon, UK and New York, NY, USA, 132 pp.

Scott, F.L., C.R. Jones, and T.L. Webb, 2014: What do people living in deprived communities in the UK think about household energy efficiency interventions? *Energy Policy*, **66**, 335–349, doi:10.1016/j.enpol.2013.10.084.

Sealey-Huggins, L., 2017: '1.5°C to stay alive': climate change, imperialism and justice for the Caribbean. *Third World Quarterly*, **6597**, 1–20, doi:10.1080/01436597.2017.1368013.

Serdeczny, O.M., S. Bauer, and S. Huq, 2017: Non-economic losses from climate change: opportunities for policy-oriented research. *Climate and Development*, 1–5, doi:10.1080/17565529.2017.1372268.

Seto, K.C. et al., 2016: Carbon Lock-In: Types, Causes, and Policy Implications. *Annual Review of Environment and Resources*, **41(1)**, 425–452, doi:10.1146/annurev-environ-110615-085934.

Sgouridis, S. et al., 2016: RE-mapping the UAE's energy transition: an economy-wide assessment of renewable energy options and their policy implications. *Renewable and Sustainable Energy Reviews*, **55**, 1166–1180, doi:10.1016/j.rser.2015.05.039.

Shackleton, S., G. Ziervogel, S. Sallu, T. Gill, and P. Tschakert, 2015: Why is socially-just climate change adaptation in sub-Saharan Africa so challenging? A review of barriers identified from empirical cases. *Wiley Interdisciplinary Reviews: Climate Change*, **6(3)**, 321–344, doi:10.1002/wcc.335.

Shaffrey, L.C. et al., 2009: U.K. HiGEM: the new U.K. high-resolution global environment model – model description and basic evaluation. *Journal of Climate*, **22(8)**, 1861–1896, doi:10.1175/2008jcli2508.1.

Shah, N., M. Wei, V. Letschert, and A. Phadke, 2015: *Benefits of leapfrogging to superefficiency and low global warming potential refrigerants in room air conditioning*. LBNL-1003671, Ernest Orlando Lawrence Berkeley National Laboratory(LBNL), Berkeley, CA, USA, 58 pp.

Sharpe, R.A., C.R. Thornton, V. Nikolaou, and N.J. Osborne, 2015: Higher energy efficient homes are associated with increased risk of doctor diagnosed asthma in a UK subpopulation. *Environment International*, **75**, 234–244, doi:10.1016/j.envint.2014.11.017.

Shaw, C., S. Hales, P. Howden-Chapman, and R. Edwards, 2014: Health co-benefits of climate change mitigation policies in the transport sector. *Nature Climate Change*, **4(6)**, 427–433, doi:10.1038/nclimate2247.

Shi, L. et al., 2016: Roadmap towards justice in urban climate adaptation research. *Nature Climate Change*, **6(2)**, 131–137, doi:10.1038/nclimate2841.

Shi, Y., J. Liu, H. Shi, H. Li, and Q. Li, 2017: The ecosystem service value as a new eco-efficiency indicator for industrial parks. *Journal of Cleaner Production*, **164**, 597–605, doi:10.1016/j.jclepro.2017.06.187.

Shindell, D.T., G. Faluvegi, K. Seltzer, and C. Shindell, 2018: Quantified, localized health benefits of accelerated carbon dioxide emissions reductions. *Nature Climate Change*, **8(4)**, 291–295, doi:10.1038/s41558-018-0108-y.

Shindell, D.T. et al., 2017: A climate policy pathway for near- and long-term benefits. *Science*, **356(6337)**, 493–494, doi:10.1126/science.aak9521.

Shine, T., 2017: *Integrating climate action into national development planning – Coherent Implementation of the Paris Agreement and Agenda 2030*. Swedish International Development Cooperation Agency (SIDA), Stockholm, Sweden, 26 pp.

Shine, T. and G. Campillo, 2016: The Role of Development Finance in Climate Action Post-2015. OECD Development Co-operation Working Papers, No. 31, OECD Publishing, Paris, France, 38 pp.

Shue, H., 2014: *Climate Justice: Vulnerability and Protection*. Oxford University Press, Oxford, UK, 368 pp.

Shue, H., 2017: Responsible for what? Carbon producer CO_2 contributions and the energy transition. *Climatic Change*, 1–6, doi:10.1007/s10584-017-2042-9.

Shue, H., 2018: Mitigation gambles: uncertainty, urgency and the last gamble possible. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376(2119)**, 20170105, doi:10.1098/rsta.2017.0105.

Shultz, J.M., M.A. Cohen, S. Hermosilla, Z. Espinel, and Andrew McLean, 2016: Disaster risk reduction and sustainable development for small island developing states. *Disaster Health*, **3(1)**, 32–44, doi:10.1080/21665044.2016.1173443.

Sinclair, F.L., 2016: Systems science at the scale of impact: Reconciling bottom-up participation with the production of widely applicable research outputs. In: *Sustainable Intensification in Smallholder Agriculture: An Integrated Systems Research Approach* [Oborn, I., B. Vanlauwe, M. Phillips, R. Thomas, W. Brooijmans, and K. Atta-Krah (eds.)]. Earthscan, London, UK, pp. 43–57.

Singh, C., 2018: Is participatory watershed development building local adaptive capacity? Findings from a case study in Rajasthan, India. *Environmental Development*, **25**, 43–58, doi:10.1016/j.envdev.2017.11.004.

Singh, C. et al., 2017: The utility of weather and climate information for adaptation decision-making: current uses and future prospects in Africa and India. *Climate and Development*, 1–17, doi:10.1080/17565529.2017.1318744.

Singh, R., K.K. Garg, S.P. Wani, R.K. Tewari, and S.K. Dhyani, 2014: Impact of water management interventions on hydrology and ecosystem services in Garhkundar-Dabar watershed of Bundelkhand region, Central India. *Journal of Hydrology*, **509**, 132–149, doi:10.1016/j.jhydrol.2013.11.030.

Skeie, R.B. et al., 2017: Perspective has a strong effect on the calculation of historical contributions to global warming. *Environmental Research Letters*, **12(2)**, 024022, doi:10.1088/1748-9326/aa5b0a.

SLoCaT, 2017: *Marrakech Partnership for Global Climate Action (MPGCA) Transport Initiatives: Stock-take on action toward implementation of the Paris Agreement and the 2030 Agenda on Sustainable Development. Second Progress Report*. Partnership on Sustainable Low Carbon Transport (SLoCaT), Bonn, Germany, 72 pp.

Smith, K.R. and A. Sagar, 2014: Making the clean available: escaping India's Chulha Trap. *Energy Policy*, **75**, 410–414, doi:10.1016/j.enpol.2014.09.024.

Smith, K.R. et al., 2014: Human health: impacts, adaptation, and co-benefits. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 709–754.

Smith, P. et al., 2014: Agriculture, Forestry and Other Land Use (AFOLU). In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 811–922.

Smith, P. et al., 2016: Biophysical and economic limits to negative CO_2 emissions. *Nature Climate Change*, **6(1)**, 42–50, doi:10.1038/nclimate2870.

Smits, M. and C. Middleton, 2014: New Arenas of Engagement at the Water Governance-Climate Finance Nexus? An Analysis of the Boom and Bust of Hydropower CDM Projects in Vietnam. *Water Alternatives*, **7(3)**, 561–583, www.water-alternatives.org/index.php/alldoc/articles/vol7/v8issue3/264-a7-3-7/file.

Smucker, T.A. et al., 2015: Differentiated livelihoods, local institutions, and the adaptation imperative: Assessing climate change adaptation policy in Tanzania. *Geoforum*, **59**, 39–50, doi:10.1016/j.geoforum.2014.11.018.

Solecki, W. et al., 2018: City transformations in a 1.5°C warmer world. *Nature Climate Change*, **8(3)**, 177–181, doi:10.1038/s41558-018-0101-5.

Sondak, C.F.A. et al., 2017: Carbon dioxide mitigation potential of seaweed aquaculture beds (SABs). *Journal of Applied Phycology*, **29(5)**, 2363–2373, doi:10.1007/s10811-016-1022-1.

Sonwa, D.J. et al., 2017: Drivers of climate risk in African agriculture. *Climate and Development*, **9(5)**, 383–398, doi:10.1080/17565529.2016.1167659.

Sorrell, S., 2015: Reducing energy demand: A review of issues, challenges and approaches. *Renewable and Sustainable Energy Reviews*, **47**, 74–82, doi:10.1016/j.rser.2015.03.002.

Sovacool, B.K., B.-O. Linnér, and M.E. Goodsite, 2015: The political economy of climate adaptation. *Nature Climate Change*, **5(7)**, 616–618, doi:10.1038/nclimate2665.

Sovacool, B.K., B.-O. Linnér, and R.J.T. Klein, 2017: Climate change adaptation and the Least Developed Countries Fund (LDCF): qualitative insights from policy implementation in the Asia-Pacific. *Climatic Change*, **140(2)**, 209–226, doi:10.1007/s10584-016-1839-2.

SPC, 2015: *Vanuatu climate change and disaster risk reduction policy 2016–2030*. Secretariat of the Pacific Community (SPC), Suva, Fiji, 48 pp.
SPC, 2016: *Framework for Resilient Development in the Pacific: An Integrated Approach to Address Climate Change and Disaster Risk Management (FRDP) 2017–2030*. Pacific Community (SPC), Suva, Fiji, 40 pp.
Spencer, T. et al., 2018: The 1.5°C target and coal sector transition: at the limits of societal feasibility. *Climate Policy*, **18(3)**, 335–331, doi:10.1080/14693062.2017.1386540.
Staggenborg, S. and C. Ogrodnik, 2015: New environmentalism and Transition Pittsburgh. *Environmental Politics*, **24(5)**, 723–741, doi:10.1080/09644016.2015.1027059.
Steering Committee on Partnerships for SIDS and UN DESA, 2016: *Partnerships for Small Island Developing States 2016*. The Steering Committee on Partnerships for Small Island Developing States and the United Nations Department of Economic and Social Affairs, 49 pp.
Sterrett, C.L., 2015: *Final evaluation of the Vanuatu NGO Climate Change Adaptation Program*. Climate Concern, 96 pp.
Stevens, C., R. Winterbottom, J. Springer, and K. Reytar, 2014: *Securing Rights, Combating Climate Change: How Strengthening Community Forest Rights Mitigates Climate Change*. World Resources Institute, Washington DC, USA, 64 pp.
Stirling, A., 2014: *Emancipating Transformations: From controlling 'the transition' to culturing plural radical progress*. STEPS Centre (Social, Technological and Environmental Pathways to Sustainability), Brighton, UK, 48 pp.
Striessnig, E. and E. Loichinger, 2015: Future differential vulnerability to natural disasters by level of education. *Vienna Yearbook of Population Research*, **13**, 221–240, www.jstor.org/stable/24770031.
Stringer, L.C., S.M. Sallu, A.J. Dougill, B.T. Wood, and L. Ficklin, 2017: Reconsidering climate compatible development as a new development landscape in southern Africa. In: *Making Climate Compatible Development Happen* [Nunan, F. (ed.)]. Routledge, Abingdon, UK and New York, NY, USA, pp. 22–43.
Stringer, L.C. et al., 2014: Advancing climate compatible development: Lessons from southern Africa. *Regional Environmental Change*, **14(2)**, 713–725, doi:10.1007/s10113-013-0533-4.
Suckall, N., E. Tompkins, and L. Stringer, 2014: Identifying trade-offs between adaptation, mitigation and development in community responses to climate and socio-economic stresses: Evidence from Zanzibar, Tanzania. *Applied Geography*, **46**, 111–121, doi:10.1016/j.apgeog.2013.11.005.
Suckall, N., L.C. Stringer, and E.L. Tompkins, 2015: Presenting Triple-Wins? Assessing Projects That Deliver Adaptation, Mitigation and Development Co-benefits in Rural Sub-Saharan Africa. *Ambio*, **44(1)**, 34–41, doi:10.1007/s13280-014-0520-0.
Suffolk, C. and W. Poortinga, 2016: Behavioural changes after energy efficiency improvements in residential properties. In: *Rethinking Climate and Energy Policies: New Perspectives on the Rebound Phenomenon* [Santarius, T., H.J. Walnum, and C. Aall (eds.)]. Springer International Publishing, Cham, Switzerland, pp. 121–142, doi:10.1007/978-3-319-38807-6_8.
Surminski, S., L.M. Bouwer, and J. Linnerooth-Bayer, 2016: How insurance can support climate resilience. *Nature Climate Change*, **6(4)**, 333–334, doi:10.1038/nclimate2979.
Szabo, S. et al., 2015: Sustainable Development Goals Offer New Opportunities for Tropical Delta Regions. *Environment: Science and Policy for Sustainable Development*, **57(4)**, 16–23, doi:10.1080/00139157.2015.1048142.
Tàbara, J.D., A.L. St. Clair, and E.A.T. Hermansen, 2017: Transforming communication and knowledge production processes to address high-end climate change. *Environmental Science & Policy*, **70**, 31–37, doi:10.1016/j.envsci.2017.01.004.
Tàbara, J.D. et al., 2018: Positive tipping points in a rapidly warming world. *Current Opinion in Environmental Sustainability*, **31**, 120–129, doi:10.1016/j.cosust.2018.01.012.
Tait, L. and M. Euston-Brown, 2017: What role can African cities play in low-carbon development? A multilevel governance perspective of Ghana, Uganda and South Africa. *Journal of Energy in Southern Africa*, **28(3)**, 43–53, doi:10.17159/2413-3051/2017/v28i3a1959.
Tanner, T. et al., 2017: Political economy of climate compatible development: artisanal fisheries and climate change in Ghana. In: *Making Climate Compatible Development Happen* [Nunan, F. (ed.)]. Routledge, Abingdon, UK and New York, NY, USA, pp. 223–241, doi:10.1111/j.2040-0209.2014.00446.x.
Taylor, M., 2017: Climate-smart agriculture: what is it good for? *The Journal of Peasant Studies*, **45(1)**, 89–107, doi:10.1080/03066150.2017.1312355.
Taylor Aiken, G., 2015: (Local-) community for global challenges: carbon conversations, transition towns and governmental elisions. *Local Environment*, **20(7)**, 764–781, doi:10.1080/13549839.2013.870142.
Taylor Aiken, G., 2016: Prosaic state governance of community low carbon transitions. *Political Geography*, **55**, 20–29, doi:10.1016/j.polgeo.2016.04.002.
Taylor Aiken, G., L. Middlemiss, S. Sallu, and R. Hauxwell-Baldwin, 2017: Researching climate change and community in neoliberal contexts: an emerging critical approach. *Wiley Interdisciplinary Reviews: Climate Change*, **8(4)**, e463, doi:10.1002/wcc.463.
Teferi, Z.A. and P. Newman, 2018: Slum upgrading: can the 1.5°C carbon reduction work with SDGs in these settlements? *Urban Planning*, **3(2)**, 52–63, doi:10.17645/up.v3i2.1239.
Thomas, A. and L. Benjamin, 2017: Management of loss and damage in small island developing states: implications for a 1.5°C or warmer world. *Regional Environmental Change*, **17(81)**, 1–10, doi:10.1007/s10113-017-1184-7.
Thompson-Hall, M., E.R. Carr, and U. Pascual, 2016: Enhancing and expanding intersectional research for climate change adaptation in agrarian settings. *Ambio*, **45(s3)**, 373–382, doi:10.1007/s13280-016-0827-0.
Thornton, T.F. and C. Comberti, 2017: Synergies and trade-offs between adaptation, mitigation and development. *Climatic Change*, 1–14, doi:10.1007/s10584-013-0884-3.
Thorp, T.M., 2014: *Climate Justice: A Voice for the Future*. Palgrave Macmillan UK, New York, 439 pp., doi:10.1057/9781137394644.
Tilman, D. and M. Clark, 2014: Global diets link environmental sustainability and human health. *Nature*, **515(7528)**, 518–522, doi:10.1038/nature13959.
Tokar, B., 2014: *Toward climate justice: perspectives on the climate crisis and social change (2nd edition)*. New Compass Press, Porsgrunn, Norway, 182 pp.
Toole, S., N. Klocker, and L. Head, 2016: Re-thinking climate change adaptation and capacities at the household scale. *Climatic Change*, **135(2)**, 203–209, doi:10.1007/s10584-015-1577-x.
Tschakert, P. et al., 2016: Micropolitics in collective learning spaces for adaptive decision making. *Global Environmental Change*, **40**, 182–194, doi:10.1016/j.gloenvcha.2016.07.004.
Tschakert, P. et al., 2017: Climate change and loss, as if people mattered: Values, places, and experiences. *Wiley Interdisciplinary Reviews: Climate Change*, **8(5)**, e476, doi:10.1002/wcc.476.
Tung, R.L., 2016: Opportunities and Challenges Ahead of China's "New Normal". *Long Range Planning*, **49(5)**, 632–640, doi:10.1016/j.lrp.2016.05.001.
UN, 2014: *World urbanisation prospects, 2014 revisions*. Department of Economic and Social Affairs, New York, NY, USA.
UN, 2015a: *The Millennium Development Goals Report 2015*. United Nations (UN), New York, NY, USA, 75 pp.
UN, 2015b: *Transforming Our World: The 2030 Agenda for Sustainable Development*. A/RES/70/1, United Nations General Assembly (UNGA), New York, 35 pp.
UN Women, 2016: *Time to Act on Gender, Climate Change and Disaster Risk Reduction: An overview of progress in the Pacific region with evidence from The Republic of Marshall Islands, Vanuatu and Samoa*. United Nations Entity for Gender Equality and the Empowerment of Women (UN Women) Regional Office for Asia and the Pacific, Bangkok, Thailand, 92 pp.
UN Women and MRFCJ, 2016: *The Full View: Ensuring a comprehensive approach to achieve the goal of gender balance in the UNFCCC process*. UN Women and Mary Robinson Foundation Climate Justice (MRFCJ), 80 pp.
UNDP, 2016: *Risk Governance: Building Blocks for Resilient Development in the Pacific*. Policy Brief: October 2016, United Nations Development Programme (UNDP) and Pacific Risk Resilience Programme (PRRP), Suva, Fiji, 20 pp.
UNEP, 2017: *The Emissions Gap Report 2017*. United Nations Environment Programme (UNEP), Nairobi, Kenya, 89 pp.
UNFCCC, 2011a: Decision 1/CP.16: *The Cancun Agreements: Outcome of the work of the Ad Hoc Working Group on Long-term Cooperative Action under the Convention*. United Nations Framework Convention on Climate Change (UNFCCC), 31 pp.
UNFCCC, 2011b: Decision 7/CP.17: Work programme on loss and damage. In: *Report of the Conference of the Parties on its seventeenth session, held in Durban from 28 November to 11 December 2011. Addendum. Part Two: Action taken by the Conference of the Parties at its seventeenth session*. FCCC/CP/2011/9/Add.2, United Nations Framework Convention on Climate Change (UNFCCC), pp. 5–8.
UNFCCC, 2014: Decision 2/CP.19: Warsaw international mechanism for loss and damage associated with climate change impact. In: *Report of the Conference of the Parties on its nineteenth session, held in Warsaw from 11 to 23 November 2013. Addendum. Part two: Action taken by the Conference of the Parties at its nineteenth session*. FCCC/CP/2013/10/Add.1, United Nations Framework Convention on Climate Change (UNFCCC), pp. 6–8.

UNFCCC, 2015: *Adoption of the Paris Agreement*. FCCC/CP/2015/L.9, United Nations Framework Convention on Climate Change (UNFCCC), 32 pp.
UNGA, 2014: *Resolution adopted by the General Assembly on 14 November 2014: SIDS accelerated modalities of action (SAMOA) pathway*. A/RES/69/15, United Nations General Assembly (UNGA), 30 pp.
UNRISD, 2016: *Policy Innovations for Transformative Change: Implementing the 2030 Agenda for Sustainable Development*. United Nations Research Institute for Social Development (UNRISD), Geneva, Switzerland, 248 pp.
UNU-EHS, 2016: *World Risk Report 2016. Focus: Logistics and infrastructure*. United Nations University, Institute for Environment and Human Security (UNU-EHS), Bonn, Germany, 74 pp.
Ürge-Vorsatz, D., S.T. Herrero, N.K. Dubash, and F. Lecocq, 2014: Measuring the co-benefits of climate change mitigation. *Annual Review of Environment and Resources*, **39**, 549–582, doi:10.1146/annurev-environ-031312-125456.
Ürge-Vorsatz, D. et al., 2016: Measuring multiple impacts of low-carbon energy options in a green economy context. *Applied Energy*, **179**, 1409–1426, doi:10.1016/j.apenergy.2016.07.027.
Ustadi, I., T. Mezher, and M.R.M. Abu-Zahra, 2017: The effect of the carbon capture and storage (CCS) technology deployment on the natural gas market in the United Arab Emirates. *Energy Procedia*, **114**, 6366–6376, doi:10.1016/j.egypro.2017.03.1773.
Vale, L.J., 2014: The politics of resilient cities: whose resilience and whose city? *Building Research and Information*, **42(2)**, 191–201, doi:10.1080/09613218.2014.850602.
Van Aelst, K. and N. Holvoet, 2016: Intersections of gender and marital status in accessing climate change adaptation: evidence from rural Tanzania. *World Development*, **79**, 40–50, doi:10.1016/j.worlddev.2015.11.003.
Van de Graaf, T. and A. Verbruggen, 2015: The oil endgame: strategies of oil exporters in a carbon-constrained world. *Environmental Science & Policy*, **54**, 456–462, doi:10.1016/j.envsci.2015.08.004.
van der Geest, K. and K. Warner, 2015: Editorial: Loss and damage from climate change: emerging perspectives. *International Journal of Global Warming*, **8(2)**, 133–140, doi:10.1504/ijgw.2015.071964.
Van der Heijden, J., 2018: The limits of voluntary programs for low-carbon buildings for staying under 1.5°C. *Current Opinion in Environmental Sustainability*, **30**, 59–66, doi:10.1016/j.cosust.2018.03.006.
van der Voorn, T., J. Quist, C. Pahl-Wostl, and M. Haasnoot, 2017: Envisioning robust climate change adaptation futures for coastal regions: a comparative evaluation of cases in three continents. *Mitigation and Adaptation Strategies for Global Change*, **22(3)**, 519–546, doi:10.1007/s11027-015-9686-4.
van Noorloos, F. and M. Kloosterboer, 2017: Africa's new cities: The contested future of urbanisation. *Urban Studies*, 1–19, doi:10.1177/0042098017700574.
van Vuuren, D.P. et al., 2017a: The Shared Socio-economic Pathways: Trajectories for human development and global environmental change. *Global Environmental Change*, **42**, 148–152, doi:10.1016/j.gloenvcha.2016.10.009.
van Vuuren, D.P. et al., 2017b: Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. *Global Environmental Change*, **42**, 237–250, doi:10.1016/j.gloenvcha.2016.05.008.
van Vuuren, D.P. et al., 2018: Alternative pathways to the 1.5°C target reduce the need for negative emission technologies. *Nature Climate Change*, **8**, 1–7, doi:10.1038/s41558-018-0119-8.
Vanhala, L. and C. Hestbaek, 2016: Framing climate change Loss and Damage in UNFCCC negotiations. *Global Environmental Politics*, **16(4)**, 111–129, doi:10.1162/glep_a_00379.
Vardakoulias, O. and N. Nicholles, 2014: *Managing uncertainty: An economic evaluation of community-based adaptation in Dakoro, Niger*. nef consulting, London, UK, 53 pp.
Veland, S. et al., 2018: Narrative matters for sustainability: the transformative role of storytelling in realizing 1.5°C futures. *Current Opinion in Environmental Sustainability*, **31**, 41–47, doi:10.1016/j.cosust.2017.12.005.
Vermeulen, S. et al., 2016: *The Economic Advantage: Assessing the value of climate change actions in agriculture*. International Fund for Agricultural Development (IFAD), Rome, Italy, 77 pp.
Vierros, M., 2017: Communities and blue carbon: the role of traditional management systems in providing benefits for carbon storage, biodiversity conservation and livelihoods. *Climatic Change*, **140(1)**, 89–100, doi:10.1007/s10584-013-0920-3.
Vinyeta, K., K.P. Whyte, and K. Lynn, 2015: *Climate Change Through an Intersectional Lens: Gendered Vulnerability and Resilience in Indigenous Communities in the United States*. General Technical Report PNW-GTR-923, US Department of Agriculture Forest Service, Pacific Northwest Research Station, Corvallis, Oregon, USA, 72 pp.
Vogt-Schilb, A. and S. Hallegatte, 2017: Climate Policies and Nationally Determined Contributions: Reconciling the Needed Ambition with the Political Economy. IDB Working Paper Series No. IDB-WP-818, Inter-American Development Bank, Washington DC, USA, 35 pp., doi:10.18235/0000714.
Volz, U. et al., 2015: *Financing the Green Transformation: How to Make Green Finance Work in Indonesia*. Palgrave Macmillan, Basingstoke, Hampshire, UK, 174 pp., doi:10.1057/9781137486127.
von Stechow, C. et al., 2015: Integrating Global Climate Change Mitigation Goals with Other Sustainability Objectives: A Synthesis. *Annual Review of Environment and Resources*, **40(1)**, 363–394, doi:10.1146/annurev-environ-021113-095626.
von Stechow, C. et al., 2016: 2°C and SDGs: United they stand, divided they fall? *Environmental Research Letters*, **11(3)**, 034022, doi:10.1088/1748-9326/11/3/034022.
Wachsmuth, D., D. Cohen, and H. Angelo, 2016: Expand the frontiers of urban sustainability. *Nature*, **536**, 391–393, doi:10.1038/536391a.
Waisman, H.-D., C. Guivarch, and F. Lecocq, 2013: The transportation sector and low-carbon growth pathways: modelling urban, infrastructure, and spatial determinants of mobility. *Climate Policy*, **13(sup01)**, 106–129, doi:10.1080/14693062.2012.735916.
Wallimann-Helmer, I., 2015: Justice for climate loss and damage. *Climatic Change*, **133(3)**, 469–480, doi:10.1007/s10584-015-1483-2.
Walsh-Dilley, M. and W. Wolford, 2015: (Un)Defining resilience: subjective understandings of 'resilience' from the field. *Resilience*, **3(3)**, 173–182, doi:10.1080/21693293.2015.1072310.
Wamsler, C., C. Luederitz, E. Brink, C. Wamsler, and C. Luederitz, 2014: Local levers for change: mainstreaming ecosystem-based adaptation into municipal planning to foster sustainability transitions. *Global Environmental Change*, **29**, 189–201, doi:10.1016/j.gloenvcha.2014.09.008.
Wang, X., 2017: The role of attitudinal motivations and collective efficacy on Chinese consumers' intentions to engage in personal behaviors to mitigate climate change. *The Journal of Social Psychology*, 1–13, doi:10.1080/00224545.2017.1302401.
Wang, Y., Q. Song, J. He, and Y. Qi, 2015: Developing low-carbon cities through pilots. *Climate Policy*, **15**, 81–103, doi:10.1080/14693062.2015.1050347.
Wanner, T., 2014: The new 'Passive Revolution' of the green economy and growth discourse: Maintaining the 'Sustainable Development' of Neoliberal capitalism. *New Political Economy*, **20(1)**, 1–21, doi:10.1080/13563467.2013.866081.
Warner, B.P. and C.P. Kuzdas, 2017: The role of political economy in framing and producing transformative adaptation. *Current Opinion in Environmental Sustainability*, **29**, 69–74, doi:10.1016/j.cosust.2017.12.012.
Warner, B.P., C. Kuzdas, M.G. Yglesias, and D.L. Childers, 2015: Limits to adaptation to interacting global change risks among smallholder rice farmers in Northwest Costa Rica. *Global Environmental Change*, **30**, 101–112, doi:10.1016/j.gloenvcha.2014.11.002.
Warner, K. and K. Geest, 2013: Loss and damage from climate change: local-level evidence from nine vulnerable countries. *International Journal of Global Warming*, **5(4)**, 367–386, doi:10.1504/ijgw.2013.057289.
Watts, N. et al., 2015: Health and climate change: policy responses to protect public health. *The Lancet*, **386(10006)**, 1861–1914, doi:10.1016/s0140-6736(15)60854-6.
Wegner, G.I., 2016: Payments for ecosystem services (PES): a flexible, participatory, and integrated approach for improved conservation and equity outcomes. *Environment, Development and Sustainability*, **18(3)**, 617–644, doi:10.1007/s10668-015-9673-7.
Weisser, F., M. Bollig, M. Doevenspeck, and D. Müller-Mahn, 2014: Translating the 'adaptation to climate change' paradigm: the politics of a travelling idea in Africa. *The Geographical Journal*, **180(2)**, 111–119, doi:10.1111/geoj.12037.
Wells, E.M. et al., 2015: Indoor air quality and occupant comfort in homes with deep versus conventional energy efficiency renovations. *Building and Environment*, **93(Part 2)**, 331–338, doi:10.1016/j.buildenv.2015.06.021.
Welsch, M. et al., 2014: Adding value with CLEWS – Modelling the energy system and its interdependencies for Mauritius. *Applied Energy*, **113**, 1434–1445, doi:10.1016/j.apenergy.2013.08.083.
Weng, X., Z. Dong, Q. Wu, and Y. Qin, 2015: *China's path to a green economy: decoding China's green economy concepts and policies*. IIED Country Report, International Institute for Environment and Development (IIED), London, UK, 40 pp.

Werfel, S.H., 2017: Household behaviour crowds out support for climate change policy when sufficient progress is perceived. *Nature Climate Change*, **7(7)**, 512–515, doi:10.1038/nclimate3316.

Wesseling, J.H. et al., 2017: The transition of energy intensive processing industries towards deep decarbonization: Characteristics and implications for future research. *Renewable and Sustainable Energy Reviews*, **79**, 1303–1313, doi:10.1016/j.rser.2017.05.156.

Weston, P., R. Hong, C. Kaboré, and C.A. Kull, 2015: Farmer-managed natural regeneration enhances rural livelihoods in dryland West Africa. *Environmental Management*, **55(6)**, 1402–1417, doi:10.1007/s00267-015-0469-1.

Wewerinke-Singh, M., 2018a: Climate migrants' right to enjoy their culture. In: *Climate Refugees: Beyond the Legal Impasse?* [Behrman, S. and A. Kent (eds.)]. Earthscan/Routledge, Abingdon, UK and New York, NY, USA, pp. 194–213.

Wewerinke-Singh, M., 2018b: State Responsibility for Human Rights Violations Associated with Climate Change. In: *Routledge Handbook of Human Rights and Climate Governance* [Duyck, S., S. Jodoin, and A. Johl (eds.)]. Routledge, Abingdon, UK and New York, NY, USA, pp. 75–89.

WHO, 2014: Quantitative risk assessment of the effects of climate change on selected causes of death, 2030s and 2050s. [Hales, S., S. Kovats, S. Lloyd, and D. Campbell-Lendrum (eds.)]. World Health Organization (WHO), Geneva, Switzerland, 128 pp.

Wiebe, K. et al., 2015: Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios. *Environmental Research Letters*, **10(8)**, 085010, doi:10.1088/1748-9326/10/8/085010.

Wiktorowicz, J., T. Babaeff, J. Eggleston, and P. Newman, 2018: WGV: an Australian urban precinct case study to demonstrate the 1.5C agenda including multiple SDGs. *Urban Planning*, **3(2)**, 64–81, doi:10.17645/up.v3i2.1245.

Wilkinson, E., A. Kirbyshire, L. Mayhew, P. Batra, and A. Milan, 2016: *Climate-induced migration and displacement: closing the policy gap*. Overseas Development Institute (ODI), London, UK, 12 pp.

Willand, N., I. Ridley, and C. Maller, 2015: Towards explaining the health impacts of residential energy efficiency interventions – A realist review. Part 1: Pathways. *Social Science and Medicine*, **133**, 191–201, doi:10.1016/j.socscimed.2015.02.005.

Winkler, H. and N.K. Dubash, 2016: Who determines transformational change in development and climate finance? *Climate Policy*, **16(6)**, 783–791, doi:10.1080/14693062.2015.1033674.

Winkler, H. et al., 2018: Countries start to explain how their climate contributions are fair: more rigour needed. *International Environmental Agreements: Politics, Law and Economics*, **18(1)**, 99–115, doi:10.1007/s10784-017-9381-x.

Winsemius, H.C. et al., 2018: Disaster risk, climate change, and poverty: assessing the global exposure of poor people to floods and droughts. *Environment and Development Economics*, **17**, 1–21, doi:10.1017/s1355770X17000444.

Wise, R.M. et al., 2014: Reconceptualising adaptation to climate change as part of pathways of change and response. *Global Environmental Change*, **28**, 325–336, doi:10.1016/j.gloenvcha.2013.12.002.

Wood, B.T., 2017: Socially just triple-wins? An evaluation of projects that pursue climate compatible development goals in Malawi. PhD Thesis, School of Earth and Environment, University of Leeds, Leeds, UK, 278 pp.

Wood, B.T., S.M. Sallu, and J. Paavola, 2016a: Can CDM finance energy access in Least Developed Countries? Evidence from Tanzania. *Climate Policy*, **16(4)**, 456–473, doi:10.1080/14693062.2015.1027166.

Wood, B.T., A.J. Dougill, C.H. Quinn, and L.C. Stringer, 2016b: Exploring Power and Procedural Justice Within Climate Compatible Development Project Design: Whose Priorities Are Being Considered? *The Journal of Environment & Development*, **25(4)**, 363–395, doi:10.1177/1070496516664179.

Work, C., 2015: Intersections of Climate Change Mitigation Policies, Land Grabbing and Conflict in a Fragile State: Insights from Cambodia. MOSAIC Working Paper Series No. 2, MOSAIC Research project, International Institute of Social Studies (IISS), RCSD Chiang Mai University, 34 pp.

Wright, H., S. Huq, and J. Reeves, 2015: Impact of climate change on least developed countries: are the SDGs possible? IIED Briefing May 2015, International Institute for Environment and Development (IIED), London, UK, 4 pp.

WWF, 2017: *Responsible sourcing of forest products: The business case for retailers*. World Wide Fund for Nature (WWF), Gland, Switzerland, 47 pp.

Wyborn, C., L. Yung, D. Murphy, and D.R. Williams, 2015: Situating adaptation: how governance challenges and perceptions of uncertainty influence adaptation in the Rocky Mountains. *Regional Environmental Change*, **15(4)**, 669–682, doi:10.1007/s10113-014-0663-3.

Yang, S., B. Chen, and S. Ulgiati, 2016: Co-benefits of CO_2 and PM2.5 Emission Reduction. *Energy Procedia*, **104**, 92–97, doi:10.1016/j.egypro.2016.12.017.

Yaro, J.A., J. Teye, and S. Bawakyillenuo, 2015: Local institutions and adaptive capacity to climate change/variability in the northern savannah of Ghana. *Climate and Development*, **7(3)**, 235–245, doi:10.1080/17565529.2014.951018.

Zeng, H., X. Chen, X. Xiao, and Z. Zhou, 2017: Institutional pressures, sustainable supply chain management, and circular economy capability: Empirical evidence from Chinese eco-industrial park firms. *Journal of Cleaner Production*, **155**, 54–65, doi:10.1016/j.jclepro.2016.10.093.

Zhang, H. and W. Chen, 2015: The role of biofuels in China's transport sector in carbon mitigation scenarios. *Energy Procedia*, **75**, 2700–2705, doi:10.1016/j.egypro.2015.07.682.

Zhang, S., E. Worrell, and W. Crijns-Graus, 2015: Cutting air pollution by improving energy efficiency of China's cement industry. *Energy Procedia*, **83**, 10–20, doi:10.1016/j.egypro.2015.12.191.

Zhang, Y. et al., 2017: Processes of coastal ecosystem carbon sequestration and approaches for increasing carbon sink. *Science China Earth Sciences*, **60(5)**, 809–820, doi:10.1007/s11430-016-9010-9.

Zhao, D., A.P. McCoy, J. Du, P. Agee, and Y. Lu, 2017: Interaction effects of building technology and resident behavior on energy consumption in residential buildings. *Energy and Buildings*, **134**, 223–233, doi:10.1016/j.enbuild.2016.10.049.

Ziervogel, G., A. Cowen, and J. Ziniades, 2016: Moving from adaptive to transformative capacity: Building foundations for inclusive, thriving, and regenerative urban settlements. *Sustainability*, **8(9)**, 955, doi:10.3390/su8090955.

Ziervogel, G. et al., 2017: Inserting rights and justice into urban resilience: a focus on everyday risk. *Environment and Urbanization*, **29(1)**, 123–138, doi:10.1177/0956247816686905.

Zimm, C., F. Sperling, and S. Busch, 2018: Identifying sustainability and knowledge gaps in socio-economic pathways vis-à-vis the Sustainable Development Goals. *Economies*, **6(2)**, 20, doi:10.3390/economies6020020.

REF

Reference list for Table 5.2.

Aamaas, B. and G.P. Peters, 2017: The climate impact of Norwegians' travel behavior. *Travel Behaviour and Society*, **6**, 10–18, doi:10.1016/j.tbs.2016.04.001.

Abanda, F.H., M.B. Manjia, K.E. Enongene, J.H.M. Tah, and C. Pettang, 2016: A feasibility study of a residential photovoltaic system in Cameroon. *Sustainable Energy Technologies and Assessments*, **17**, 38–49, doi:10.1016/j.seta.2016.08.002.

Abdelouas, A., 2006: Uranium mill tailings: geochemistry, mineralogy, and environmental impact. *Elements*, **2(6)**, 335–341, doi:10.2113/gselements.2.6.335.

Abdul Quader, M., S. Ahmed, S.Z. Dawal, and Y. Nukman, 2016: Present needs, recent progress and future trends of energy-efficient Ultra-Low Carbon Dioxide (CO_2) Steelmaking (ULCOS) program. *Renewable and Sustainable Energy Reviews*, **55**, 537–549, doi:10.1016/j.rser.2015.10.101.

Acemoglu, D., 2009: *Introduction to modern economic growth*. Princeton University Press, Princeton, NJ, USA, 1008 pp.

Acemoglu, D., F.A. Gallego, and J.A. Robinson, 2014: Institutions, human Capital, and development. *Annual Review of Economics*, **6(1)**, 875–912, doi:10.1146/annurev-economics-080213-041119.

Acheampong, M., F.C. Ertem, B. Kappler, and P. Neubauer, 2017: In pursuit of Sustainable Development Goal (SDG) number 7: Will biofuels be reliable? *Renewable and Sustainable Energy Reviews*, **75(7)**, 927–937, doi:10.1016/j.rser.2016.11.074.

Adamantiades, A. and I. Kessides, 2009: Nuclear power for sustainable development: Current status and future prospects. *Energy Policy*, **37(12)**, 5149–5166, doi:10.1016/j.enpol.2009.07.052.

Aggarwal, P., 2017: 2°C target, India's climate action plan and urban transport sector. *Travel Behaviour and Society*, **6**, 110–116, doi:10.1016/j.tbs.2016.11.001.

Ahearne, J.F., 2011: Prospects for nuclear energy. *Energy Economics*, **33(4)**, 572–580, doi:10.1016/j.eneco.2010.11.014.

Ahmad, S. and J.A. Puppim de Oliveira, 2016: Determinants of urban mobility in India: lessons for promoting sustainable and inclusive urban transportation in developing countries. *Transport Policy*, **50**, 106–114, doi:10.1016/j.tranpol.2016.04.014.

Åhman, M., L.J. Nilsson, and B. Johansson, 2017: Global climate policy and deep decarbonization of energy-intensive industries. *Climate Policy*, **17(5)**, 634–649, doi:10.1080/14693062.2016.1167009.

Ahmed, N., W.W.L. Cheung, S. Thompson, and M. Glaser, 2017a: Solutions to blue carbon emissions: Shrimp cultivation, mangrove deforestation and climate change in coastal Bangladesh. *Marine Policy*, **82**, 68–75, doi:10.1016/j.marpol.2017.05.007.

Ahmed, N., S.W. Bunting, M. Glaser, M.S. Flaherty, and J.S. Diana, 2017b: Can greening of aquaculture sequester blue carbon? *Ambio*, **46(4)**, 468–477, doi:10.1007/s13280-016-0849-7.

Ajanovic, A., 2015: The future of electric vehicles: prospects and impediments. *Wiley Interdisciplinary Reviews: Energy and Environment*, **4(6)**, 521–536, doi:10.1002/wene.160.

Alahakoon, S., 2017: Significance of energy storages in future power networks. *Energy Procedia*, **110**, 14–19, doi:10.1016/j.egypro.2017.03.098.

Alho, C.J.R., 2011: Environmental Effects of Hydropower Reservoirs on Wild Mammals and Freshwater Turtles in Amazonia: A Review. *Oecologia Australis*, **15(3)**, 593–604, doi:10.4257/oeco.2011.1503.11.

Ali, S.M.H., M.J.S. Zuberi, M.A. Tariq, D. Baker, and A. Mohiuddin, 2015: A study to incorporate renewable energy technologies into the power portfolio of Karachi, Pakistan. *Renewable and Sustainable Energy Reviews*, **47**, 14–22, doi:10.1016/j.rser.2015.03.009.

Allen, S., T. Dietz, and A.M. McCright, 2015: Measuring household energy efficiency behaviors with attention to behavioral plasticity in the United States. *Energy Research & Social Science*, **10**, 133–140, doi:10.1016/j.erss.2015.07.014.

Alongi, D.M., 2012: Carbon sequestration in mangrove forests. *Carbon Management*, **3(3)**, 313–322, doi:10.4155/cmt.12.20.

AlSabbagh, M., Y.L. Siu, A. Guehnemann, and J. Barrett, 2017: Integrated approach to the assessment of CO_2e-mitigation measures for the road passenger transport sector in Bahrain. *Renewable and Sustainable Energy Reviews*, **71**, 203–215, doi:10.1016/j.rser.2016.12.052.

Altieri, K.E. et al., 2016: Achieving development and mitigation objectives through a decarbonization development pathway in South Africa. *Climate Policy*, **16(sup1)**, S78–S91, doi:10.1080/14693062.2016.1150250.

Al-Zoughool, M. and D. Krewski, 2009: Health effects of radon: A review of the literature. *International Journal of Radiation Biology*, **85(1)**, 57–69, doi:10.1080/09553000802635054.

Anda, M. and J. Temmen, 2014: Smart metering for residential energy efficiency: the use of community based social marketing for behavioural change and smart grid introduction. *Renewable Energy*, **67**, 119–127, doi:10.1016/j.renene.2013.11.020.

Anderson, A. et al., 2017: Empowering smart communities: electrification, education, and sustainable entrepreneurship in IEEE Smart Village Initiatives. *IEEE Electrification Magazine*, **5(2)**, 6–16, doi:10.1109/mele.2017.2685738.

Andrew, D., 2017: *Trade and Sustainable Development Goal (SDG) 15: Promoting "Life on Land" through Mandatory and Voluntary Approaches*. ADBI Working Paper Series, No. 700, Asian Development Bank Institute (ADBI), Tokyo, Japan, 33 pp.

Anenberg, S.C. et al., 2013: Cleaner cooking solutions to achieve health, climate, and economic cobenefits. *Environmental Science & Technology*, **47(9)**, 3944–3952, doi:10.1021/es304942e.

Apeaning, R.W. and P. Thollander, 2013: Barriers to and driving forces for industrial energy efficiency improvements in African industries: a case study of Ghana's largest industrial area. *Journal of Cleaner Production*, **53**, 204–213, doi:10.1016/j.jclepro.2013.04.003.

Apps, J.A., L. Zheng, Y. Zhang, T. Xu, and J.T. Birkholzer, 2010: Evaluation of Potential Changes in Groundwater Quality in Response to CO_2 Leakage from Deep Geologic Storage. *Transport in Porous Media*, **82(1)**, 215–246, doi:10.1007/s11242-009-9509-8.

Aranda, C., A.C. Kuesel, and E.R. Fletcher, 2014: *A systematic review of linkages between access to electricity in healthcare facilities, health services delivery, and health outcomes: findings for emergency referrals, maternal and child services*. UBS Optimus Foundation & Liberian Institute for Biomedical Research, Zurich, Switzerland.

Asaduzzaman, M., D.F. Barnes, and S.R. Khandker, 2010: *Restoring Balance: Bangladesh's Rural Energy Realities*. World Bank Working Paper: No. 181, World Bank, Washington DC, USA, 170 pp., doi:10.1596/978-0-8213-7897-7.

Asfaw, A., C. Mark, and R. Pana-Cryan, 2013: Profitability and occupational injuries in US underground coal mines. *Accident Analysis & Prevention*, **50**, 778–786, doi:10.1016/j.aap.2012.07.002.

Ashworth, P. et al., 2012: What's in store: Lessons from implementing CCS. *International Journal of Greenhouse Gas Control*, **9**, 402–409, doi:10.1016/j.ijggc.2012.04.012.

Atchley, A.L., R.M. Maxwell, and A.K. Navarre-Sitchler, 2013: Human health risk assessment of CO_2 leakage into overlying aquifers using a stochastic, geochemical reactive transport approach. *Environmental Science & Technology*, **47(11)**, 5954–5962.

Azevedo, I. and V.M.S. Leal, 2017: Methodologies for the evaluation of local climate change mitigation actions: A review. *Renewable and Sustainable Energy Reviews*, **79**, 681–690, doi:10.1016/j.rser.2017.05.100.

Babiker, M.H. and R.S. Eckaus, 2007: Unemployment effects of climate policy. *Environmental Science & Policy*, **10(7–8)**, 600–609, doi:10.1016/j.envsci.2007.05.002.

Bailis, R., R. Drigo, A. Ghilardi, and O. Masera, 2015: The carbon footprint of traditional woodfuels. *Nature Climate Change*, **5(3)**, 266–272, doi:10.1038/nclimate2491.

Bajželj, B. et al., 2014: Importance of food-demand management for climate mitigation. *Nature Climate Change*, **4(10)**, 924–929, doi:10.1038/nclimate2353.

Balishter, G.V.K. and R. Singh, 1991: Impact of mechanization on employment and farm productivity. *Productivity*, **32(3)**, 484–489.

Banerjee, R. et al., 2012: Energy End-Use: Industry. In: *Global Energy Assessment – Toward a Sustainable Future* [Johansson, T.B., N. Nakicenovic, A. Patwardhan, and L. Gomez-Echeverri (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA and the International Institute for Applied Systems Analysis, pp. 513–574.

Bartley, T., 2010: Transnational Private Regulation in Practice: The Limits of Forest and Labor Standards Certification in Indonesia. *Business and Politics*, **12(03)**, 1–34, doi:10.2202/1469-3569.1321.

Bartos, M.D. and M. Chester, 2014: The Conservation Nexus: Valuing Interdependent Water and Energy Savings in Arizona. *Environmental Science & Technology*, **48(4)**, 2139–2149, doi:10.1021/es4033343.

Bastos Lima, M.G., W. Ashely-Cantello, I. Visseren-Hamakers, A. Gupta, and J. Braña-Varela, 2015: *Forests Post-2015: Maximizing Synergies between the Sustainable Development Goals and REDD+*. WWF-WUR Policy Brief No. 3, World Wildlife Fund (WWF) and Wageningen University & Research (WUR), 5 pp.

Bastos Lima, M.G., G. Kissinger, I.J. Visseren-Hamakers, J. Braña-Varela, and A. Gupta, 2017: The Sustainable Development Goals and REDD+: assessing institutional interactions and the pursuit of synergies. *International Environmental Agreements: Politics, Law and Economics*, **17(4)**, 589–606, doi:10.1007/s10784-017-9366-9.

Bazilian, M. et al., 2011: Considering the energy, water and food nexus: towards an integrated modelling approach. *Energy Policy*, **39(12)**, 7896–7906, doi:10.1016/j.enpol.2011.09.039.

Beddington, J. et al., 2012: *Achieving food security in the face of climate change: Final report from the Commission on Sustainable Agriculture and Climate Change*. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Copenhagen, Denmark, 59 pp.

Behnassi, M., M. Boussaid, and R. Gopichandran, 2014: Achieving Food Security in a Changing Climate: The Potential of Climate-Smart Agriculture. In: *Environmental Cost and Face of Agriculture in the Gulf Cooperation Council Countries* [Shahid, S.A. and M. Ahmed (eds.)]. Springer International Publishing, Cham, Switzerland, pp. 27–42, doi:10.1007/978-3-319-05768-2_2.

Bellarby, J. et al., 2013: Livestock greenhouse gas emissions and mitigation potential in Europe. *Global Change Biology*, **19(1)**, 3–18, doi:10.1111/j.1365-2486.2012.02786.x.

Belton Chevallier, L., B. Motte-Baumvol, S. Fol, and Y. Jouffe, 2018: Coping with the costs of car dependency: A system of expedients used by low-income households on the outskirts of Dijon and Paris. *Transport Policy*, **65**, 79–88, doi:10.1016/j.tranpol.2017.06.006.

Benson, S.M. and D.R. Cole, 2008: CO_2 Sequestration in Deep Sedimentary Formations. *Elements*, **4(5)**, 325–331, doi:10.2113/gselements.4.5.325.

Bernard, T. and M. Torero, 2015: Social interaction effects and connection to electricity: experimental evidence from rural Ethiopia. *Economic Development and Cultural Change*, **63(3)**, 459–484, doi:10.1086/679746.

Bernier, Q. et al., 2013: *Addressing Gender in Climate-Smart Smallholder Agriculture*. ICRAF Policy Brief 14, World Agroforestry Centre (ICRAF), Nairobi, Kenya, 4 pp.

Berrueta, V.M., M. Serrano-Medrano, C. Garcia-Bustamante, M. Astier, and O.R. Masera, 2017: Promoting sustainable local development of rural communities and mitigating climate change: the case of Mexico's Patsari improved cookstove project. *Climatic Change*, **140(1)**, 63–77, doi:10.1007/s10584-015-1523-y.

Bertram, C. et al., 2015: Carbon lock-in through capital stock inertia associated with weak near-term climate policies. *Technological Forecasting and Social Change*, **90(PA)**, 62–72, doi:10.1016/j.techfore.2013.10.001.

Bhattacharyya, A., J.P. Meltzer, J. Oppenheim, Z. Qureshi, and N. Stern, 2016: *Delivering on better infrastructure for better development and better climate*. The Brookings Institution, The New Climate Economy, and Grantham Research Institute on Climate Change and the Environment, 160 pp.

Bhojvaid, V. et al., 2014: How do People in Rural India Perceive Improved Stoves and Clean Fuel? Evidence from Uttar Pradesh and Uttarakhand. *International Journal of Environmental Research and Public Health*, **11(2)**, 1341–1358, doi:10.3390/ijerph110201341.

Bickerstaff, K., P. Simmons, and N. Pidgeon, 2008: Constructing Responsibilities for Risk: Negotiating Citizen – State Relationships. *Environment and Planning A: Economy and Space*, **40(6)**, 1312–1330, doi:10.1068/a39150.

Bilton, A.M., R. Wiesman, A.F.M. Arif, S.M. Zubair, and S. Dubowsky, 2011: On the feasibility of community-scale photovoltaic-powered reverse osmosis desalination systems for remote locations. *Renewable Energy*, **36(12)**, 3246–3256, doi:10.1016/j.renene.2011.03.040.

Blyth, W. et al., 2014: *Low carbon jobs: the evidence for net job creation from policy support for energy efficiency and renewable energy*. Technical Report, UK Energy Research Centre, London, UK, 66 pp.

Bogdanski, A., 2012: Integrated food-energy systems for climate-smart agriculture. *Agriculture & Food Security*, **1(1)**, 9, doi:10.1186/2048-7010-1-9.

Bonan, J., S. Pareglio, and M. Tavoni, 2014: *Access to Modern Energy: A Review of Impact Evaluations*. Fondazione Eni Enrico Mattei, Milan, Italy, 30 pp.

Bongardt, D. et al., 2013: *Low-Carbon Land Transport: Policy Handbook*. Routledge, Abingdon, UK and New York, NY, USA, 264 pp.

Bonsch, M. et al., 2016: Trade-offs between land and water requirements for large-scale bioenergy production. *GCB Bioenergy*, **8(1)**, 11–24, doi:10.1111/gcbb.12226.

Borenstein, S., 2012: The private and public economics of renewable electricity generation. *Journal of Economic Perspectives*, **26**, 67–92, doi:10.1257/jep.26.1.67.

Branca, G., N. McCarthy, L. Lipper, and M.C. Jolejole, 2011: *Climate-smart agriculture: a synthesis of empirical evidence of food security and mitigation benefits from improved cropland management*. Mitigation of Climate Change in Agriculture Series 3, Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, 35 pp.

Brandl, P., S.M. Soltani, P.S. Fennell, and N. Mac Dowell, 2017: Evaluation of cooling requirements of post-combustion CO_2 capture applied to coal-fired power plants. *Chemical Engineering Research and Design*, **122**, 1–10, doi:10.1016/j.cherd.2017.04.001.

Brown, H.C.P., 2011: Gender, climate change and REDD+ in the Congo Basin forests of Central Africa. *International Forestry Review*, **13(2)**, 163–176, doi:10.1505/146554811797406651.

Brugge, D. and V. Buchner, 2011: Health effects of uranium: new research findings. *Reviews on Environmental Health*, **26(4)**, 231–249, doi:10.1515/reveh.2011.032.

Buck, B.H. and G. Krause, 2012: Integration of Aquaculture and Renewable Energy Systems. In: *Encyclopedia of Sustainability Science and Technology Vol. 1*. Springer Science+ Business Media, New York, NY, USA, pp. 511–533, doi:10.1007/978-1-4419-0851-3_180.

Burgherr, P., P. Eckle, and S. Hirschberg, 2012: Comparative assessment of severe accident risks in the coal, oil and natural gas chains. *Reliability Engineering & System Safety*, **105**, 97–103, doi:10.1016/j.ress.2012.03.020.

Burlig, F. and L. Preonas, 2016: *Out of the darkness and into the light? Development effects of rural electrification*. EI @ Haas WP 268, Energy Institute at Haas, University of California, Berkeley, CA, USA, 52 pp.

Burney, J., H. Alaofè, R. Naylor, and D. Taren, 2017: Impact of a rural solar electrification project on the level and structure of women's empowerment. *Environmental Research Letters*, **12(9)**, 095007, doi:10.1088/1748-9326/aa7f38.

Burton, C.H., 2007: The potential contribution of separation technologies to the management of livestock manure. *Livestock Science*, **112(3)**, 208–216, doi:10.1016/j.livsci.2007.09.004.

Bustamante, M. et al., 2014: Co-benefits, trade-offs, barriers and policies for greenhouse gas mitigation in the agriculture, forestry and other land use (AFOLU) sector. *Global Change Biology*, **20(10)**, 3270–3290, doi:10.1111/gcb.12591.

Byers, E.A., J.W. Hall, J.M. Amezaga, G.M. O'Donnell, and A. Leathard, 2016: Water and climate risks to power generation with carbon capture and storage. *Environmental Research Letters*, **11(2)**, 024011, doi:10.1088/1748-9326/11/2/024011.

Byravan, S. et al., 2017: Quality of life for all: A sustainable development framework for India's climate policy reduces greenhouse gas emissions. *Energy for Sustainable Development*, **39**, 48–58, doi:10.1016/j.esd.2017.04.003.

Cabraal, A.R., D.F. Barnes, and S.G. Agarwal, 2005: Productive uses of energy for rural development. *Annual Review of Environment and Resources*, **30(1)**, 117–144, doi:10.1146/annurev.energy.30.050504.144228.

CAF, 2017: *Crecimiento urbano y accesso a Oportunidades: un desafío para América Latina (in Spanish)*. Corporacion Andina de Fomento (CAF), Bogotá, Colombia, 287 pp.

Cameron, C. et al., 2016: Policy trade-offs between climate mitigation and clean cook-stove access in South Asia. *Nature Energy*, **1**, 1–5, doi:10.1038/nenergy.2015.10.

Cameron, R.W.F., J. Taylor, and M. Emmett, 2015: A Hedera green facade – energy performance and saving under different maritime-temperate, winter weather conditions. *Building and Environment*, **92**, 111–121, doi:10.1016/j.buildenv.2015.04.011.

Campbell, B.M., P. Thornton, R. Zougmoré, P. van Asten, and L. Lipper, 2014: Sustainable intensification: What is its role in climate smart agriculture? *Current Opinion in Environmental Sustainability*, **8**, 39–43, doi:10.1016/j.cosust.2014.07.002.

Cardis, E. et al., 2006: Estimates of the cancer burden in Europe from radioactive fallout from the Chernobyl accident. *International Journal of Cancer*, **119(6)**, 1224–1235, doi:10.1002/ijc.22037.

Carrara, S. and T. Longden, 2017: Freight futures: The potential impact of road freight on climate policy. *Transportation Research Part D: Transport and Environment*, **55**, 359–372, doi:10.1016/j.trd.2016.10.007.

5

Cascajo, R., A. Garcia-Martinez, and A. Monzon, 2017: Stated preference survey for estimating passenger transfer penalties: design and application to Madrid. *European Transport Research Review*, **9(3)**, 42, doi:10.1007/s12544-017-0260-x.

Casillas, C.E. and D.M. Kammen, 2010: The Energy-Poverty-Climate Nexus. *Science*, **330(6008)**, 1181–1182, doi:10.1126/science.1197412.

Casillas, C.E. and D.M. Kammen, 2012: Quantifying the social equity of carbon mitigation strategies. *Climate Policy*, **12(6)**, 690–703, doi:10.1080/14693062.2012.669097.

Cass, N., G. Walker, and P. Devine-Wright, 2010: Good neighbours, public relations and bribes: the politics and perceptions of community benefit provision in renewable energy development in the UK. *Journal of Environmental Policy & Planning*, **12(3)**, 255–275, doi:10.1080/1523908x.2010.509558.

Cayla, J.-M. and D. Osso, 2013: Does energy efficiency reduce inequalities? Impact of policies in Residential sector on household budget. In: *ECEEE Summer Study Proceedings*. European Council for an Energy Efficient Economy (ECEEE), Toulon/Hyeres, France, pp. 1247–1257.

CDP, 2015: *CDP Global Climate Change Report 2015 – At the tipping point?* Carbon Disclosure Project (CDP) Worldwide, 91 pp.

Chakrabarti, S. and E.J. Shin, 2017: Automobile dependence and physical inactivity: insights from the California Household Travel Survey. *Journal of Transport and Health*, **6**, 262–271, doi:10.1016/j.jth.2017.05.002.

Chakravarty, D., S. Dasgupta, and J. Roy, 2013: Rebound effect: how much to worry? *Current Opinion in Environmental Sustainability*, **5(2)**, 216–228, doi:10.1016/j.cosust.2013.03.001.

Chakravorty, U., M. Pelli, and B. Ural Marchand, 2014: Does the quality of electricity matter? Evidence from rural India. *Journal of Economic Behavior & Organization*, **107**, 228–247, doi:10.1016/j.jebo.2014.04.011.

Chan, E.Y.Y. and S.M. Griffiths, 2010: The epidemiology of mine accidents in China. *The Lancet*, **376(9741)**, 575–577, doi:10.1016/s0140-6736(10)60660-5.

Chaturvedi, V. and P.R. Shukla, 2014: Role of energy efficiency in climate change mitigation policy for India: assessment of co-benefits and opportunities within an integrated assessment modeling framework. *Climatic Change*, **123(3)**, 597–609, doi:10.1007/s10584-013-0898-x.

Chen, B. and X. Qi, 2018: Protest response and contingent valuation of an urban forest park in Fuzhou City, China. *Urban Forestry & Urban Greening*, **29**, 68–76, doi:10.1016/j.ufug.2017.11.005.

Chen, H., H. Qi, R. Long, and M. Zhang, 2012: Research on 10-year tendency of China coal mine accidents and the characteristics of human factors. *Safety science*, **50(4)**, 745–750, doi:10.1016/j.ssci.2011.08.040.

Cherian, A., 2015: *Energy and Global Climate Change: Bridging the Sustainable Development Divide*. John Wiley & Sons Ltd, Chichester, UK, 304 pp., doi:10.1002/9781118846070.

Chowdhury, S.K., 2010: Impact of infrastructures on paid work opportunities and unpaid work burdens on rural women in Bangladesh. *Journal of International Development*, **22(7)**, 997–1017, doi:10.1002/jid.1607.

Cibin, R., E. Trybula, I. Chaubey, S.M. Brouder, and J.J. Volenec, 2016: Watershed-scale impacts of bioenergy crops on hydrology and water quality using improved SWAT model. *GCB Bioenergy*, **8(4)**, 837–848, doi:10.1111/gcbb.12307.

Clancy, J.S., T. Winther, M. Matinga, and S. Oparaocha, 2012: *Gender equity in access to and benefits from modern energy and improved energy technologies: world development report background paper*. Gender and Energy WDR Background Paper 44, ETC/ENERGIA in association Nord/Sør-konsulentene, 44 pp.

Clarke, L.E. et al., 2009: International climate policy architectures: Overview of the EMF 22 International Scenarios. *Energy Economics*, **31**, S64–S81, doi:10.1016/j.eneco.2009.10.013.

Clarke, L.E. et al., 2014: Assessing transformation pathways. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 413–510.

Clifton, K.J., 2004: Mobility Strategies and Food Shopping for Low-Income Families: A Case Study. *Journal of Planning Education and Research*, **23(4)**, 402–413, doi:10.1177/0739456x04264919.

Colenbrander, S. et al., 2016: Can low-carbon urban development be pro-poor? The case of Kolkata, India. *Environment and Urbanization*, **29(1)**, 139–158, doi:10.1177/0956247816677775.

Connolly, D. et al., 2014: Heat Roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system. *Energy Policy*, **65**, 475–489, doi:10.1016/j.enpol.2013.10.035.

Cook, P., 2011: Infrastructure, rural electrification and development. *Energy for Sustainable Development*, **15(3)**, 304–313, doi:10.1016/j.esd.2011.07.008.

Cooke, S.J. et al., 2016: On the sustainability of inland fisheries: finding a future for the forgotten. *Ambio*, **45(7)**, 753–764, doi:10.1007/s13280-016-0787-4.

Corbera, E. and U. Pascual, 2012: Ecosystem Services: Heed Social Goals. *Science*, **335(6069)**, 655–656, doi:10.1126/science.335.6069.655-c.

Corner, A. et al., 2011: Nuclear power, climate change and energy security: Exploring British public attitudes. *Energy Policy*, **39(9)**, 4823–4833, doi:10.1016/j.enpol.2011.06.037.

Corsten, M., A. Ramirez, L. Shen, J. Koornneef, and A. Faaij, 2013: Environmental impact assessment of CCS chains – lessons learned and limitations from LCA literature. *International Journal of Greenhouse Gas Control*, **13**, 59–71.

Crane, R., 2007: Is There a Quiet Revolution in Women's Travel? Revisiting the Gender Gap in Commuting. *Journal of the American Planning Association*, **73(3)**, 298–316, doi:10.1080/01944360708977979.

Creutzig, F., R. Mühlhoff, and J. Römer, 2012: Decarbonizing urban transport in European cities: four cases show possibly high co-benefits. *Environmental Research Letters*, **7(4)**, 044042, doi:10.1088/1748-9326/7/4/044042.

Creutzig, F., C. Esteve, B. Simon, and H. Carol, 2013: Integrating place-specific livelihood and equity outcomes into global assessments of bioenergy deployment. *Environmental Research Letters*, **8(3)**, 035047, doi:10.1088/1748-9326/8/3/035047.

Creutzig, F. et al., 2014: Catching two European birds with one renewable stone: mitigating climate change and Eurozone crisis by an energy transition. *Renewable and Sustainable Energy Reviews*, **38**, 1015–1028, doi:10.1016/j.rser.2014.07.028.

Creutzig, F. et al., 2015: Transport: A roadblock to climate change mitigation? *Science*, **350(6263)**, 911–912, doi:10.1126/science.aac8033.

Creutzig, F. et al., 2016: Beyond technology: demand-side solutions for climate change mitigation. *Annual Review of Environment and Resources*, **41(1)**, 173–198, doi:10.1146/annurev-environ-110615-085428.

Cumbers, A., 2012: *Reclaiming Public Ownership: Making Space for Economic Democracy*. Zed Books Ltd, London, UK and New York, NY, USA, 192 pp.

Dagevos, H. and J. Voordouw, 2013: Sustainability and meat consumption: is reduction realistic? *Sustainability: Science, Practice, & Policy*, **9(2)**, 1–10, doi:10.1080/15487733.2013.11908115.

Dahl, E.L., K. Bevanger, T. Nygård, E. Røskaft, and B.G. Stokke, 2012: Reduced breeding success in white-tailed eagles at Smøla windfarm, western Norway, is caused by mortality and displacement. *Biological Conservation*, **145(1)**, 79–85, doi:10.1016/j.biocon.2011.10.012.

Daut, I., M. Adzrie, M. Irwanto, P. Ibrahim, and M. Fitra, 2013: Solar Powered Air Conditioning System. *Energy Procedia*, **36**, 444–453, doi:10.1016/j.egypro.2013.07.050.

Davis, S.C. et al., 2013: Management swing potential for bioenergy crops. *GCB Bioenergy*, **5(6)**, 623–638, doi:10.1111/gcbb.12042.

de Best-Waldhober, M., D. Daamen, and A. Faaij, 2009: Informed and uninformed public opinions on CO_2 capture and storage technologies in the Netherlands. *International Journal of Greenhouse Gas Control*, **3(3)**, 322–332, doi:10.1016/j.ijggc.2008.09.001.

de Koning, J.I.J.C., T.H. Ta, M.R.M. Crul, R. Wever, and J.C. Brezet, 2016: GetGreen Vietnam: towards more sustainable behaviour among the urban middle class. *Journal of Cleaner Production*, **134(Part A)**, 178–190, doi:10.1016/j.jclepro.2016.01.063.

de Lucas, M., M. Ferrer, M.J. Bechard, and A.R. Muñoz, 2012: Griffon vulture mortality at wind farms in southern Spain: distribution of fatalities and active mitigation measures. *Biological Conservation*, **147(1)**, 184–189, doi:10.1016/j.biocon.2011.12.029.

de Moraes, M.A.F.D., C.C. Costa, J.J.M. Guilhoto, L.G.A. Souza, and F.C.R. Oliveira, 2010: Social Externalities of Fuels. In: *Ethanol and Bioelectricity: Sugarcane in the Future of the Energy Matrix* [Leão de Sousa, E.L. and I. de Carvalho Macedo (eds.)]. UNICA Brazilian Sugarcane Industry Association, São Paulo, Brazil, pp. 44–75.

De Stefano, L., J.D. Petersen-Perlman, E.A. Sproles, J. Eynard, and A.T. Wolf, 2017: Assessment of transboundary river basins for potential hydro-political tensions. *Global Environmental Change*, **45**, 35–46, doi:10.1016/j.gloenvcha.2017.04.008.

5

Dechezleprêtre, A. and M. Sato, 2014: *The impacts of environmental regulations on competitiveness*. London School of Economics (LSE) and Global Green Growth Institute (GGGI), 28 pp.

Demetriades, J. and E. Esplen, 2009: The Gender Dimensions of Poverty and Climate Change Adaptation. *IDS Bulletin*, **39(4)**, 24–31, doi:10.1111/j.1759-5436.2008.tb00473.x.

Denis-Ryan, A., C. Bataille, and F. Jotzo, 2016: Managing carbon-intensive materials in a decarbonizing world without a global price on carbon. *Climate Policy*, **16(sup1)**, S110–S128, doi:10.1080/14693062.2016.1176008.

Denman, K.L., 2008: Climate change, ocean processes and ocean iron fertilization. *Marine Ecology Progress Series*, **364**, 219–225, doi:10.3354/meps07542.

Denton, F., 2002: Climate Change Vulnerability, Impacts, and Adaptation: Why Does Gender Matter? *Gender and Development*, **10(2)**, 10–20, www.jstor.org/stable/4030569.

Derbez, M. et al., 2014: Indoor air quality and comfort in seven newly built, energy-efficient houses in France. *Building and Environment*, **72**, 173–187, doi:10.1016/j.buildenv.2013.10.017.

Dinkelman, T., 2011: The Effects of Rural Electrification on Employment: New Evidence from South Africa. *The American Economic Review*, **101(7)**, 3078–3108, doi:10.1257/aer.101.7.3078.

Djamila, H., C.-M. Chu, and S. Kumaresan, 2013: Field study of thermal comfort in residential buildings in the equatorial hot-humid climate of Malaysia. *Building and Environment*, **62**, 133–142, doi:10.1016/j.buildenv.2013.01.017.

Dodson, J. and N. Sipe, 2008: Shocking the Suburbs: Urban Location, Homeownership and Oil Vulnerability in the Australian City. *Housing Studies*, **23(3)**, 377–401, doi:10.1080/02673030802015619.

Dodson, J., B. Gleeson, and N. Sipe, 2004: *Transport Disadvantage and Social Status: A review of literature and methods*. Urban Policy Program Research Monograph 5, Griffith University, Brisbane, Australia, 55 pp.

Dooley, K. and S. Kartha, 2018: Land-based negative emissions: risks for climate mitigation and impacts on sustainable development. *International Environmental Agreements: Politics, Law and Economics*, **18(1)**, 79–98, doi:10.1007/s10784-017-9382-9.

Duarte, C.M., J. Wu, X. Xiao, A. Bruhn, and D. Krause-Jensen, 2017: Can Seaweed Farming Play a Role in Climate Change Mitigation and Adaptation? *Frontiers in Marine Science*, **4**, 100, doi:10.3389/fmars.2017.00100.

Dulac, J., 2013: *Global land transport infrastructure requirements: Estimating road and railway infrastructure capacity and costs to 2050*. 50 pp.

ECF, 2014: *Europe's low-carbon transition: Understanding the challenges and opportunities for the chemical sector*. European Climate Foundation (ECF), 60 pp.

Echegaray, F., 2016: Consumers' reactions to product obsolescence in emerging markets: the case of Brazil. *Journal of Cleaner Production*, **134**, 191–203, doi:10.1016/j.jclepro.2015.08.119.

Einsiedel, E.F., A.D. Boyd, J. Medlock, and P. Ashworth, 2013: Assessing socio-technical mindsets: Public deliberations on carbon capture and storage in the context of energy sources and climate change. *Energy Policy*, **53**, 149–158, doi:10.1016/j.enpol.2012.10.042.

Eis, J., R. Bishop, and P. Gradwell, 2016: *Galvanising Low-Carbon Innovation. A New Climate Economy working paper for Seizing the Global Opportunity: Partnerships for Better Growth and a Better Climate*. New Climate Economy (NCE), Washington DC, USA and London, UK, 28 pp.

Epstein, A.H. and S.L.H. Theuer, 2017: Sustainable development and climate action: thoughts on an integrated approach to SDG and climate policy implementation. In: *Papers from Interconnections 2017*. Interconnections 2017.

Epstein, P.R. et al., 2011: Full cost accounting for the life cycle of coal. *Annals of the New York Academy of Sciences*, **1219(1)**, 73–98, doi:10.1111/j.1749-6632.2010.05890.x.

Ertem, F.C., P. Neubauer, and S. Junne, 2017: Environmental life cycle assessment of biogas production from marine macroalgal feedstock for the substitution of energy crops. *Journal of Cleaner Production*, **140**, 977–985, doi:10.1016/j.jclepro.2016.08.041.

Evenson, R.E., 1999: Global and local implications of biotechnology and climate change for future food supplies. *Proceedings of the National Academy of Sciences*, **96(11)**, 5921–8, doi:10.1073/pnas.96.11.5921.

Fan, Y., Q. Qiao, L. Fang, and Y. Yao, 2017: Energy analysis on industrial symbiosis of an industrial park: a case study of Hefei economic and technological development area. *Journal of Cleaner Production*, **141**, 791–798, doi:10.1016/j.jclepro.2016.09.159.

Fankhaeser, S., F. Sehlleier, and N. Stern, 2008: Climate change, innovation and jobs. *Climate Policy*, **8(4)**, 421–429, doi:10.3763/cpol.2008.0513.

Fankhauser, S. and S. Tepic, 2007: Can poor consumers pay for energy and water? An affordability analysis for transition countries. *Energy Policy*, **35(2)**, 1038–1049, doi:10.1016/j.enpol.2006.02.003.

Fay, M. et al., 2015: *Decarbonizing Development: Three Steps to a Zero-Carbon Future*. World Bank, Washington DC, USA, 185 pp., doi:10.1596/978-1-4648-0479-3.

Fernando, L. and S. Evans, 2015: Case Studies in Transformation towards Industrial Sustainability. *International Journal of Knowledge and Systems Science*, **6(3)**, 1–17, doi:10.4018/ijkss.2015070101.

Figueroa, M.J. and S.K. Ribeiro, 2013: Energy for road passenger transport and sustainable development: assessing policies and goals interactions. *Current Opinion in Environmental Sustainability*, **5(2)**, 152–162, doi:10.1016/j.cosust.2013.04.004.

Figueroa, M.J., L. Fulton, and G. Tiwari, 2013: Avoiding, transforming, transitioning: Pathways to sustainable low carbon passenger transport in developing countries. *Current Opinion in Environmental Sustainability*, **5(2)**, 184–190, doi:10.1016/j.cosust.2013.02.006.

Figueroa, M.J., O. Lah, L.M. Fulton, A. McKinnon, and G. Tiwari, 2014: Energy for transport. *Annual Review of Environment and Resources*, **39**, 295–325, doi:10.1146/annurev-environ-031913-100450.

Finco, M.V.A. and W. Doppler, 2010: Bioenergy and sustainable development: The dilemma of food security and climate change in the Brazilian savannah. *Energy for Sustainable Development*, **14**, 194–199, doi:10.1016/j.esd.2010.04.006.

Fricko, O. et al., 2016: Energy sector water use implications of a 2°C degree climate policy. *Environmental Research Letters*, **11(3)**, 034011, doi:10.1088/1748-9326/11/3/034011.

Frondel, M., N. Ritter, C.M. Schmidt, and C. Vance, 2010: Economic impacts from the promotion of renewable energy technologies: The German experience. *Energy Policy*, **38(8)**, 4048–4056, doi:10.1016/j.enpol.2010.03.029.

Fu, W., Y. Lü, P. Harris, A. Comber, and L. Wu, 2018: Peri-urbanization may vary with vegetation restoration: A large scale regional analysis. *Urban Forestry & Urban Greening*, **29**, 77–87, doi:10.1016/j.ufug.2017.11.006.

Gallego, F., J.P. Montero, and C. Salas, 2013: The effect of transport policies on car use: A bundling model with applications. *Energy Economics*, **40**, S85–S97, doi:10.1016/j.eneco.2013.09.018.

Gao, L. and B.A. Bryan, 2017: Finding pathways to national-scale land-sector sustainability. *Nature*, **544(7649)**, 217–222, doi:10.1038/nature21694.

Garnett, T., 2011: Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)? *Food Policy*, **36**, S23–S32, doi:10.1016/j.foodpol.2010.10.010.

Garvin, J.C., C.S. Jennelle, D. Drake, and S.M. Grodsky, 2011: Response of raptors to a windfarm. *Journal of Applied Ecology*, **48(1)**, 199–209, doi:10.1111/j.1365-2664.2010.01912.x.

Ghosh-Dastidar, B. et al., 2014: Distance to Store, Food Prices, and Obesity in Urban Food Deserts. *American Journal of Preventive Medicine*, **47(5)**, 587–595, doi:10.1016/j.amepre.2014.07.005.

Gnanadesikan, A., J.L. Sarmiento, and R.D. Slater, 2003: Effects of patchy ocean fertilization on atmospheric carbon dioxide and biological production. *Global Biogeochemical Cycles*, **17(2)**, 1050, doi:10.1029/2002gb001940.

Godfray, H.C.J. and T. Garnett, 2014: Food security and sustainable intensification. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **369(1639)**, doi:10.1098/rstb.2012.0273.

Gohin, A., 2008: Impacts of the European Biofuel Policy on the Farm Sector: A General Equilibrium Assessment. *Review of Agricultural Economics*, **30(4)**, 623–641, www.jstor.org/stable/30225908.

Goldthau, A., 2014: Rethinking the governance of energy infrastructure: Scale, decentralization and polycentrism. *Energy Research & Social Science*, **1**, 134–140, doi:10.1016/j.erss.2014.02.009.

Gössling, S. and D. Metzler, 2017: Germany's climate policy: Facing an automobile dilemma. *Energy Policy*, **105**, 418–428, doi:10.1016/j.enpol.2017.03.019.

Gouldson, A. et al., 2015: Exploring the economic case for climate action in cities. *Global Environmental Change*, **35**, 93–105, doi:10.1016/j.gloenvcha.2015.07.009.

Greenberg, H.R., J.A. Blink, and T.A. Buscheck, 2013: *Repository Layout and Required Ventilation Trade Studies in Clay/Shale using the DSEF Thermal Analytical Model*. LLNL-TR-638880, Lawrence Livermore National Laboratory (LLNL), Livermore, CA, USA, 33 pp.

Griffin, P.W., G.P. Hammond, and J.B. Norman, 2018: Industrial energy use and carbon emissions reduction in the chemicals sector: A UK perspective. *Applied Energy*, **227**, 587–602, doi:10.1016/j.apenergy.2017.08.010.

Griffiths, N.A. et al., 2017: Water quality effects of short-rotation pine management for bioenergy feedstocks in the southeastern United States. *Forest Ecology and Management*, **400**, 181–198, doi:10.1016/j.foreco.2017.06.011.
Grill, G. et al., 2015: An index-based framework for assessing patterns and trends in river fragmentation and flow regulation by global dams at multiple scales. *Environmental Research Letters*, **10(1)**, 015001, doi:10.1088/1748-9326/10/1/015001.
Grodsky, S.M. et al., 2011: Investigating the causes of death for wind turbine-associated bat fatalities. *Journal of Mammalogy*, **92(5)**, 917–925, doi:10.1644/10-mamm-a-404.1.
Grogan, L. and A. Sadanand, 2013: Rural Electrification and Employment in Poor Countries: Evidence from Nicaragua. *World Development*, **43**, 252–265, doi:10.1016/j.worlddev.2012.09.002.
Grubert, E.A., 2016: Water consumption from hydroelectricity in the United States. *Advances in Water Resources*, **96**, 88–94, doi:10.1016/j.advwatres.2016.07.004.
Grubler, A. and D. Fisk (eds.), 2013: *Energizing Sustainable Cities: Assessing Urban Energy*. Routledge Earthscan, Abingdon, UK and New York, NY, USA, 222 pp.
Guivarch, C., R. Crassous, O. Sassi, and S. Hallegatte, 2011: The costs of climate policies in a second-best world with labour market imperfections. *Climate Policy*, **11(1)**, 768–788, doi:10.3763/cpol.2009.0012.
Güssow, K., A. Proelss, A. Oschlies, K. Rehdanz, and W. Rickels, 2010: Ocean iron fertilization: why further research is needed. *Marine Policy*, **34(5)**, 911–918, doi:10.1016/j.marpol.2010.01.015.
Gyamfi, S., S. Krumdieck, and T. Urmee, 2013: Residential peak electricity demand response – Highlights of some behavioural issues. *Renewable and Sustainable Energy Reviews*, **25**, 71–77, doi:10.1016/j.rser.2013.04.006.
Ha, M. and M. Wu, 2017: Land management strategies for improving water quality in biomass production under changing climate. *Environmental Research Letters*, **12(3)**, 034015, doi:10.1088/1748-9326/aa5f32.
Haileselassie, M., H. Taddele, K. Adhana, and S. Kalayou, 2013: Food safety knowledge and practices of abattoir and butchery shops and the microbial profile of meat in Mekelle City, Ethiopia. *Asian Pacific Journal of Tropical Biomedicine*, **3(5)**, 407–412, doi:10.1016/s2221-1691(13)60085-4.
Haines, A. and C. Dora, 2012: How the low carbon economy can improve health. *BMJ*, **344**, 1–6, doi:10.1136/bmj.e1018.
Haines, A. et al., 2007: Policies for accelerating access to clean energy, improving health, advancing development, and mitigating climate change. *The Lancet*, **370(9594)**, 1264–1281, doi:10.1016/s0140-6736(07)61257-4.
Hallegatte, S. et al., 2016a: *Shock Waves: Managing the Impacts of Climate Change on Poverty*. The World Bank, Washington, DC, USA, 227 pp., doi:10.1596/978-1-4648-0673-5.
Hallegatte, S. et al., 2016b: Mapping the climate change challenge. *Nature Climate Change*, **6(7)**, 663–668, doi:10.1038/nclimate3057.
Hammond, J. et al., 2017: The Rural Household Multi-Indicator Survey (RHoMIS) for rapid characterisation of households to inform climate smart agriculture interventions: Description and applications in East Africa and Central America. *Agricultural Systems*, **151**, 225–233, doi:10.1016/j.agsy.2016.05.003.
Hartmann, J. et al., 2013: Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification. *Reviews of Geophysics*, **51(2)**, 113–149, doi:10.1002/rog.20004.
Harvey, C.A. et al., 2014: Climate-Smart Landscapes: Opportunities and Challenges for Integrating Adaptation and Mitigation in Tropical Agriculture. *Conservation Letters*, **7(2)**, 77–90, doi:10.1111/conl.12066.
Hasegawa, T. et al., 2015: Consequence of climate mitigation on the risk of hunger. *Environmental Science & Technology*, **49(12)**, 7245–7253, doi:10.1021/es5051748.
Haves, E., 2012: *Does energy access help women? Beyond anecdotes: a review of the evidence*. Ashden, London, UK, 9 pp.
Havlík, P. et al., 2014: Climate change mitigation through livestock system transitions. *Proceedings of the National Academy of Sciences*, **111(10)**, 3709–14, doi:10.1073/pnas.1308044111.
He, R., Y. Xiong, and Z. Lin, 2016: Carbon emissions in a dual channel closed loop supply chain: the impact of consumer free riding behavior. *Journal of Cleaner Production*, **134(Part A)**, 384–394, doi:10.1016/j.jclepro.2016.02.142.
Hedenus, F., S. Wirsenius, and D.J.A. Johansson, 2014: The importance of reduced meat and dairy consumption for meeting stringent climate change targets. *Climatic Change*, **124(1–2)**, 79–91, doi:10.1007/s10584-014-1104-5.
Heinävaara, S. et al., 2010: Cancer incidence in the vicinity of Finnish nuclear power plants: an emphasis on childhood leukemia. *Cancer Causes & Control*, **21(4)**, 587–595, doi:10.1007/s10552-009-9488-7.
Heinonen, J., M. Jalas, J.K. Juntunen, S. Ala-Mantila, and S. Junnila, 2013: Situated lifestyles: II. The impacts of urban density, housing type and motorization on the greenhouse gas emissions of the middle-income consumers in Finland. *Environmental Research Letters*, **8(3)**, 035050, doi:10.1088/1748-9326/8/3/035050.
Hejazi, M.I. et al., 2015: 21st century United States emissions mitigation could increase water stress more than the climate change it is mitigating. *Proceedings of the National Academy of Sciences*, **112(34)**, 10635–40, doi:10.1073/pnas.1421675112.
Hendrickson, T.P. and A. Horvath, 2014: A perspective on cost-effectiveness of greenhouse gas reduction solutions in water distribution systems. *Environmental Research Letters*, **9(2)**, 024017, doi:10.1088/1748-9326/9/2/024017.
Herrero, M. and P.K. Thornton, 2013: Livestock and global change: Emerging issues for sustainable food systems. *Proceedings of the National Academy of Sciences*, **110(52)**, 20878–20881, doi:10.1073/pnas.1321844111.
Herrero, M. et al., 2013: Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. *Proceedings of the National Academy of Sciences*, **110(52)**, 20888–20893, doi:10.1073/pnas.1308149110.
Hertwich, E.G., M. Aaberg, B. Singh, and A.H. Strømman, 2008: Life-cycle Assessment of Carbon Dioxide Capture for Enhanced Oil Recovery. *Chinese Journal of Chemical Engineering*, **16(3)**, 343–353, doi:10.1016/s1004-9541(08)60085-3.
Hiç, C., P. Pradhan, D. Rybski, and J.P. Kropp, 2016: Food Surplus and Its Climate Burdens. *Environmental Science & Technology*, **50(8)**, 4269–4277, doi:10.1021/acs.est.5b05088.
Hillier, J., 2011: Strategic navigation across multiple planes: Towards a Deleuzean-inspired methodology for strategic spatial planning. *Town Planning Review*, **82(5)**, 503–527, doi:10.3828/tpr.2011.30.
Hirth, L. and F. Ueckerdt, 2013: Redistribution effects of energy and climate policy: The electricity market. *Energy Policy*, **62**, 934–947, doi:10.1016/j.enpol.2013.07.055.
Hiyama, A. et al., 2013: The Fukushima nuclear accident and the pale grass blue butterfly: evaluating biological effects of long-term low-dose exposures. *BMC evolutionary biology*, **13(1)**, 168, doi:10.1186/1471-2148-13-168.
Holland, R.A. et al., 2015: Global impacts of energy demand on the freshwater resources of nations. *Proceedings of the National Academy of Sciences*, **112(48)**, E6707–E6716, doi:10.1073/pnas.1507701112.
Holopainen, R. et al., 2014: Comfort assessment in the context of sustainable buildings: Comparison of simplified and detailed human thermal sensation methods. *Building and Environment*, **71**, 60–70, doi:10.1016/j.buildenv.2013.09.009.
Hontelez, J., 2016: Advancing SDG Implementation through Forest Certification. International Institute for Sustainable Development (IISD), Winnipeg, MN, Canada. Retrieved from: http://sdg.iisd.org/commentary/guest-articles/advancing-sdg-implementation-through-forest-certification.
Hori, S., K. Kondo, D. Nogata, and H. Ben, 2013: The determinants of household energy-saving behavior: Survey and comparison in five major Asian cities. *Energy Policy*, **52**, 354–362, doi:10.1016/j.enpol.2012.09.043.
Huang, W., A. Wilkes, X. Sun, and A. Terheggen, 2013: Who is importing forest products from Africa to China? An analysis of implications for initiatives to enhance legality and sustainability. *Environment, Development and Sustainability*, **15(2)**, 339–354, doi:10.1007/s10668-012-9413-1.
Huebner, G.M., J. Cooper, and K. Jones, 2013: Domestic energy consumption – What role do comfort, habit, and knowledge about the heating system play? *Energy and Buildings*, **66**, 626–636, doi:10.1016/j.enbuild.2013.07.043.
Hult, A. and J. Larsson, 2016: Possibilities and problems with applying a consumption perspective in local climate strategies – the case of Gothenburg, Sweden. *Journal of Cleaner Production*, **134**, 434–442, doi:10.1016/j.jclepro.2015.10.033.
Hwang, J., K. Joh, and A. Woo, 2017: Social inequalities in child pedestrian traffic injuries: Differences in neighborhood built environments near schools in Austin, TX, USA. *Journal of Transport and Health*, **6**, 40–49, doi:10.1016/j.jth.2017.05.003.
ICSU and ISSC, 2015: *Review of targets for the Sustainable Development Goals: The Science Perspective*. International Council for Science (ICSU), Paris, France, 92 pp., doi:978-0-930357-97-9.

5

IEA, 2016: *Energy and Air Pollution: World Energy Outlook Special Report*. International Energy Agency (IEA), Paris, France, 266 pp.

Inger, R. et al., 2009: Marine renewable energy: potential benefits to biodiversity? An urgent call for research. *Journal of Applied Ecology*, **46(6)**, 1145–1153, doi:10.1111/j.1365-2664.2009.01697.x.

Ingram, J., 2011: A food systems approach to researching food security and its interactions with global environmental change. *Food Security*, **3(4)**, 417–431, doi:10.1007/s12571-011-0149-9.

IPCC, 2005: IPCC Special Report on Carbon Dioxide Capture and Storage. [Metz, B., O. Davidson, H.C. de Coninck, M. Loos, and L.A. Meyer (eds.)]. Prepared by Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp.

IPCC, 2014: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1454 pp.

IRENA, 2016: *Renewable Energy and Jobs – Annual Review 2016*. International Renewable Energy Agency (IRENA), Abu Dhabi, UAE, 19 pp.

Isenhour, C. and K. Feng, 2016: Decoupling and displaced emissions: on Swedish consumers, Chinese producers and policy to address the climate impact of consumption. *Journal of Cleaner Production*, **134(Part A)**, 320–329, doi:10.1016/j.jclepro.2014.12.037.

Islar, M., S. Brogaard, and M. Lemberg-Pedersen, 2017: Feasibility of energy justice: Exploring national and local efforts for energy development in Nepal. *Energy Policy*, **105**, 668–676, doi:10.1016/j.enpol.2017.03.004.

Jackson, T. and P. Senker, 2011: Prosperity without Growth: Economics for a Finite Planet. *Energy & Environment*, **22(7)**, 1013–1016, doi:10.1260/0958-305x.22.7.1013.

Jain, A.A., R.R. Koford, A.W. Handcock, and G.G. Zenner, 2011: Bat mortality and activity at a northern Iowa wind resource area. *The American Midland Naturalist*, **165(1)**, 185–200, doi:10.1674/0003-0031-165.1.185.

Jain, R.K., R. Gulbinas, J.E. Taylor, and P.J. Culligan, 2013: Can social influence drive energy savings? Detecting the impact of social influence on the energy consumption behavior of networked users exposed to normative eco-feedback. *Energy and Buildings*, **66**, 119–127, doi:10.1016/j.enbuild.2013.06.029.

Jain, S. and M.P. Sharma, 2010: Prospects of biodiesel from Jatropha in India: A review. *Renewable and Sustainable Energy Reviews*, **14(2)**, 763–771, doi:10.1016/j.rser.2009.10.005.

Jakob, M. and J.C. Steckel, 2014: How climate change mitigation could harm development in poor countries. *Wiley Interdisciplinary Reviews: Climate Change*, **5(2)**, 161–168, doi:10.1002/wcc.260.

Jin, X. and N. Gruber, 2003: Offsetting the radiative benefit of ocean iron fertilization by enhancing N_2O emissions. *Geophysical Research Letters*, **30(24)**, 1–4, doi:10.1029/2003gl018458.

Jingura, R. and R. Kamusoko, 2016: The energy-development nexus in Sub-Saharan Africa. In: *Handbook on Africa: Challenges and Issues for the 21st Century* [Sherman, W. (ed.)]. Nova Science Publishers, Hauppauge, NY, USA, pp. 25–46.

Johansson, M.T. and P. Thollander, 2018: A review of barriers to and driving forces for improved energy efficiency in Swedish industry – Recommendations for successful in-house energy management. *Renewable and Sustainable Energy Reviews*, **82**, 618–628, doi:10.1016/j.rser.2017.09.052.

Johnson, J.M.-F., A.J. Franzluebbers, S.L. Weyers, and D.C. Reicosky, 2007: Agricultural opportunities to mitigate greenhouse gas emissions. *Environmental Pollution*, **150(1)**, 107–124, doi:10.1016/j.envpol.2007.06.030.

Johnson, N. et al., 2015: Stranded on a low-carbon planet: implications of climate policy for the phase-out of coal-based power plants. *Technological Forecasting and Social Change*, **90(Part A)**, 89–102, doi:10.1016/j.techfore.2014.02.028.

Jones, B.A. and S.M. McDermott, 2018: The economics of urban afforestation: Insights from an integrated bioeconomic-health model. *Journal of Environmental Economics and Management*, **89**, 116–135, doi:10.1016/j.jeem.2018.03.007.

Jost, C. et al., 2016: Understanding gender dimensions of agriculture and climate change in smallholder farming communities. *Climate and Development*, **8(2)**, 133–144, doi:10.1080/17565529.2015.1050978.

Kaatsch, P., C. Spix, R. Schulze-Rath, S. Schmiedel, and M. Blettner, 2008: Leukaemia in young children living in the vicinity of German nuclear power plants. *International Journal of Cancer*, **122(4)**, 721–726, doi:10.1002/ijc.23330.

Kagawa, S. et al., 2015: CO_2 emission clusters within global supply chain networks: Implications for climate change mitigation. *Global Environmental Change*, **35**, 486–496, doi:10.1016/j.gloenvcha.2015.04.003.

Kahn Ribeiro, S. et al., 2012: Energy End-Use: Transport. In: *Global Energy Assessment – Toward a Sustainable Future* [Johansson, T.B., N. Nakicenovic, A. Patwardhan, and L. Gomez-Echeverri (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 575–648.

Karekezi, S., S. McDade, B. Boardman, and J. Kimani, 2012: Energy, Poverty and Development. In: *Global Energy Assessment – Toward a Sustainable Future* [Johansson, T.B., N. Nakicenovic, A. Patwardhan, and L. Gomez-Echeverri (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 151–190.

Karner, K., M. Theissing, and T. Kienberger, 2015: Energy efficiency for industries through synergies with urban areas. *Journal of Cleaner Production*, **2020**, 1–11, doi:10.1016/j.jclepro.2016.02.010.

Katila, P., W. de Jong, G. Galloway, B. Pokorny, and P. Pacheco, 2017: *Building on synergies: Harnessing community and smallholder forestry for Sustainable Development Goals*. International Union of Forest Research Organizations (IUFRO), 23 pp.

Kaygusuz, K., 2011: Energy services and energy poverty for sustainable rural development. *Renewable and Sustainable Energy Reviews*, **15**, 936–947, doi:10.1016/j.rser.2010.11.003.

Kern, J.D., D. Patino-Echeverri, and G.W. Characklis, 2014: The Impacts of Wind Power Integration on Sub-Daily Variation in River Flows Downstream of Hydroelectric Dams. *Environmental Science & Technology*, **48(16)**, 9844–9851, doi:10.1021/es405437h.

Khan, M., G. Srafeim, and A. Yoon, 2015: *Corporate Sustainability: First Evidence on Materiality*. HBS Working Paper Number: 15-073, Harvard Business School, Cambridge, MA, USA, 55 pp.

Khan, S., M.A. Hanjra, and J. Mu, 2009: Water management and crop production for food security in China: A review. *Agricultural Water Management*, **96(3)**, 349–360, doi:10.1016/j.agwat.2008.09.022.

Kibria, G., 2015: *Climate Resilient Development (CRD), Sustainable Development Goals (SDGs) & Climate Finance (CF) – A Case Study*. ResearchGate, 4 pp., doi:10.13140/rg.2.1.4393.2240.

Kim, Y. and C. Sun, 2017: The Energy-Efficient Adaptation Scheme for Residential Buildings in Kazakhstan. *Energy Procedia*, **118**, 28–34, doi:10.1016/j.egypro.2017.07.005.

Kim, Y. et al., 2017: A perspective on climate-resilient development and national adaptation planning based on USAID's experience. *Climate and Development*, **9(2)**, 141–151, doi:10.1080/17565529.2015.1124037.

Kirubi, C., A. Jacobson, D.M. Kammen, and A. Mills, 2009: Community-Based Electric Micro-Grids Can Contribute to Rural Development: Evidence from Kenya. *World Development*, **37(7)**, 1208–1221, doi:10.1016/j.worlddev.2008.11.005.

Klausbruckner, C., H. Annegarn, L.R.F. Henneman, and P. Rafaj, 2016: A policy review of synergies and trade-offs in South African climate change mitigation and air pollution control strategies. *Environmental Science & Policy*, **57**, 70–78, doi:10.1016/j.envsci.2015.12.001.

Köhler, P., J. Hartmann, and D.A. Wolf-Gladrow, 2010: Geoengineering potential of artificially enhanced silicate weathering of olivine. *Proceedings of the National Academy of Sciences*, **107(47)**, 20228–20233, doi:10.1073/pnas.1000545107.

Köhler, P., J.F. Abrams, C. Völker, J. Hauck, and D.A. Wolf-Gladrow, 2013: Geoengineering impact of open ocean dissolution of olivine on atmospheric CO_2, surface ocean pH and marine biology. *Environmental Research Letters*, **8(1)**, 014009, doi:10.1088/1748-9326/8/1/014009.

Köhlin, G., E.O. Sills, S.K. Pattanayak, and C. Wilfong, 2011: *Energy, Gender and Development: What are the Linkages? Where is the Evidence?* A background paper for the World Development Report 2012 on Gender Equality and Development. Paper No. 125, World Bank, Washington DC, USA, 75 pp.

Kong, X. et al., 2016: Groundwater Depletion by Agricultural Intensification in China's HHH Plains, Since 1980s. *Advances in Agronomy*, **135**, 59–106, doi:10.1016/bs.agron.2015.09.003.

Koornneef, J., A. Ramírez, W. Turkenburg, and A. Faaij, 2011: The environmental impact and risk assessment of CO_2 capture, transport and storage-an evaluation of the knowledge base using the DPSIR framework. *Energy Procedia*, **4**, 2293–2300, doi:10.1016/j.egypro.2011.02.119.

Kowarik, I., 2018: Urban wilderness: Supply, demand, and access. *Urban Forestry & Urban Greening*, **29**, 336–347, doi:10.1016/j.ufug.2017.05.017.

Krukowski, R.A., C. Sparks, M. Dicarlo, J. McSweeney, and D.S. West, 2013: There's more to food store choice than proximity: A questionnaire development study. *BMC Public Health*, **13(1)**, 586, doi:10.1186/1471-2458-13-586.

Kumar, A. et al., 2011: Hydropower. In: *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, and C. von Stechow (eds.)]. Prepared by Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 437–496.

Kumar, N., P. Besuner, S. Lefton, D. Agan, and D. Hilleman, 2012: *Power Plant Cycling Costs*. NREL/SR-5500-55433, National Renewable Energy Laboratory (NREL), Golden, CO, USA, 80 pp.

Kummu, M. et al., 2012: Lost food, wasted resources: Global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use. *Science of The Total Environment*, **438**, 477–489, doi:10.1016/j.scitotenv.2012.08.092.

Kunz, M.J., A. Wüest, B. Wehrli, J. Landert, and D.B. Senn, 2011: Impact of a large tropical reservoir on riverine transport of sediment, carbon, and nutrients to downstream wetlands. *Water Resources Research*, **47(12)**, doi:10.1029/2011wr010996.

Kunze, C. and S. Becker, 2015: Collective ownership in renewable energy and opportunities for sustainable degrowth. *Sustainability Science*, **10**, 425–437, doi:10.1007/s11625-015-0301-0.

Kwong, Q.J., N.M. Adam, and B.B. Sahari, 2014: Thermal comfort assessment and potential for energy efficiency enhancement in modern tropical buildings: A review. *Energy and Buildings*, **68(Part A)**, 547–557, doi:10.1016/j.enbuild.2013.09.034.

Lakshmi, K., C. Anuradha, K. Boomiraj, and A. Kalaivani, 2015: Applications of Biotechnological Tools to Overcome Climate Change and its Effects on Agriculture. *Research News For U (RNFU)*, **20**, 218–222.

Lall, S.V. et al., 2017: *Africa's Cities: Opening Doors to the World*. World Bank, Washington DC, USA, 162 pp., doi:10.1596/978-1-4648-1044-2.

Lam, N.L., K.R. Smith, A. Gauthier, and M.N. Bates, 2012: Kerosene: A Review of Household Uses and their Hazards in Low- and Middle-Income Countries. *Journal of Toxicology and Environmental Health, Part B*, **15(6)**, 396–432, doi:10.1080/10937404.2012.710134.

Lamb, A. et al., 2016: The potential for land sparing to offset greenhouse gas emissions from agriculture. *Nature Climate Change*, **6**, 488–492, doi:10.1038/nclimate2910.

Lampitt, R.S. et al., 2008: Ocean fertilization: a potential means of geoengineering? *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **366(1882)**, 3919–3945, doi:10.1098/rsta.2008.0139.

Larson, A.M., T. Dokken, and A.E. Duchelle, 2014: The role of women in early REDD+ implementation. *REDD+ on the ground: A case book of subnational initiatives across the globe*, **17(1)**, 440–441, doi:10.1505/146554815814725031.

Launiainen, S. et al., 2014: Is the Water Footprint an Appropriate Tool for Forestry and Forest Products: The Fennoscandian Case. *Ambio*, **43(2)**, 244–256, doi:10.1007/s13280-013-0380-z.

Lawrence, A., M. Karlsson, and P. Thollander, 2018: Effects of firm characteristics and energy management for improving energy efficiency in the pulp and paper industry. *Energy*, **153**, 825–835, doi:10.1016/j.energy.2018.04.092.

LeDoux, T.F. and I. Vojnovic, 2013: Going outside the neighborhood: The shopping patterns and adaptations of disadvantaged consumers living in the lower eastside neighborhoods of Detroit, Michigan. *Health & Place*, **19**, 1–14, doi:10.1016/j.healthplace.2012.09.010.

Li, T. et al., 2016: Aging will amplify the heat-related mortality risk under a changing climate: projection for the elderly in Beijing, China. *Scientific Reports*, **6(1)**, 28161, doi:10.1038/srep28161.

Liddell, C. and C. Guiney, 2015: Living in a cold and damp home: Frameworks for understanding impacts on mental well-being. *Public Health*, **129(3)**, 191–199, doi:10.1016/j.puhe.2014.11.007.

Lieder, M. and A. Rashid, 2016: Towards circular economy implementation: A comprehensive review in context of manufacturing industry. *Journal of Cleaner Production*, **115**, 36–51, doi:10.1016/j.jclepro.2015.12.042.

Lim, S.S. et al., 2012: A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990-2010: a systematic analysis for the Global Burden of Disease Study 2010. *The Lancet*, **380(9859)**, 2224–2260, doi:10.1016/s0140-6736(12)61766-8.

Lin, J., Y. Hu, S. Cui, J. Kang, and A. Ramaswami, 2015: Tracking urban carbon footprints from production and consumption perspectives. *Environmental Research Letters*, **10(5)**, 054001, doi:10.1088/1748-9326/10/5/054001.

Lipper, L. et al., 2014: Climate-smart agriculture for food security. *Nature Climate Change*, **4(12)**, 1068–1072, doi:10.1038/nclimate2437.

Lipscomb, M., A.M. Mobarak, and T. Barham, 2013: Development Effects of Electrification: Evidence from the Topographic Placement of Hydropower Plants in Brazil. *American Economic Journal: Applied Economics*, **5(2)**, 200–231, doi:10.1257/app.5.2.200.

Liu, Y. and Y. Bai, 2014: An exploration of firms' awareness and behavior of developing circular economy: An empirical research in China. *Resources, Conservation and Recycling*, **87**, 145–152, doi:10.1016/j.resconrec.2014.04.002.

Long, T.B., V. Blok, and I. Coninx, 2016: Barriers to the adoption and diffusion of technological innovations for climate-smart agriculture in Europe: evidence from the Netherlands, France, Switzerland and Italy. *Journal of Cleaner Production*, **112**, 9–21, doi:10.1016/j.jclepro.2015.06.044.

Lotze-Campen, H. et al., 2014: Impacts of increased bioenergy demand on global food markets: an AgMIP economic model intercomparison. *Agricultural Economics*, **45(1)**, 103–116, doi:10.1111/agec.12092.

Lovich, J.E. and J.R. Ennen, 2013: Assessing the state of knowledge of utility-scale wind energy development and operation on non-volant terrestrial and marine wildlife. *Applied Energy*, **103**, 52–60, doi:10.1016/j.apenergy.2012.10.001.

Lowery, B., D. Sloane, D. Payán, J. Illum, and L. Lewis, 2016: Do Farmers' Markets Increase Access to Healthy Foods for All Communities? Comparing Markets in 24 Neighborhoods in Los Angeles. *Journal of the American Planning Association*, **82(3)**, 252–266, doi:10.1080/01944363.2016.1181000.

Lucas, K. and K. Pangbourne, 2014: Assessing the equity of carbon mitigation policies for transport in Scotland. *Case Studies on Transport Policy*, **2(2)**, 70–80, doi:10.1016/j.cstp.2014.05.003.

Lybbert, T. and D. Sumner, 2010: *Agricultural Technologies for Climate Change Mitigation and Adaptation in Developing Countries: Policy Options for Innovation and Technology Diffusion*. ICTSD–IPC Platform on Climate Change, Agriculture and Trade, Issue Brief No.6, International Centre for Trade and Sustainable Development, Geneva, Switzerland and International Food & Agricultural Trade Policy Council, Washington DC, USA, 32 pp.

Brander, L.M. et al., 2012: Ecosystem service values for mangroves in Southeast Asia: a meta-analysis and value transfer application. *Ecosystem Services*, **1(1)**, 62–69, doi:10.1016/j.ecoser.2012.06.003.

Maidment, C.D., C.R. Jones, T.L. Webb, E.A. Hathway, and J.M. Gilbertson, 2014: The impact of household energy efficiency measures on health: A meta-analysis. *Energy Policy*, **65**, 583–593, doi:10.1016/j.enpol.2013.10.054.

Månsson, A., 2016: Energy security in a decarbonised transport sector: A scenario based analysis of Sweden's transport strategies. *Energy Strategy Reviews*, **13–14**, 236–247, doi:10.1016/j.esr.2016.06.004.

Manville, M., 2017: Travel and the Built Environment: Time for Change. *Journal of the American Planning Association*, **83(1)**, 29–32, doi:10.1080/01944363.2016.1249508.

Markusson, N. et al., 2012: A socio-technical framework for assessing the viability of carbon capture and storage technology. *Technological Forecasting and Social Change*, **79(5)**, 903–918, doi:10.1016/j.techfore.2011.12.001.

Marra, J.E. and R.A. Palmer, 2011: Radioactive Waste Management. In: *Waste* [Letcher, T.M. and D.A. Vallero (eds.)]. Academic Press, Boston, MA, USA, pp. 101–108, doi:10.1016/b978-0-12-381475-3.10007-5.

Martínez-Jaramillo, J.E., S. Arango-Aramburo, K.C. Álvarez-Uribe, and P. Jaramillo-Álvarez, 2017: Assessing the impacts of transport policies through energy system simulation: The case of the Medellin Metropolitan Area, Colombia. *Energy Policy*, **101**, 101–108, doi:10.1016/j.enpol.2016.11.026.

Matinga, M.N., 2012: *A socio-cultural perspective on transformation of gender roles and relations, and non-change in energy-health perceptions following electrification in rural South Africa (Case Study for World Development Report 2012)*. ETC/ENERGIA in association Nord/Sør-konsulentene, 17 pp.

Matthews, N. and M. McCartney, 2018: Opportunities for building resilience and lessons for navigating risks: Dams and the water energy food nexus. *Environmental Progress & Sustainable Energy*, **37(1)**, 56–61, doi:10.1002/ep.12568.

Mbow, C. et al., 2014: Agroforestry solutions to address food security and climate change challenges in Africa. *Current Opinion in Environmental Sustainability*, **6**, 61–67, doi:10.1016/j.cosust.2013.10.014.

McCarthy, N., L. Lipper, and G. Branca, 2011: *Climate-Smart Agriculture: Smallholder Adoption and Implications for Climate Change Adaptation and Mitigation*. Mitigation of Climate Change Series 4, Food and Agricultural Organization of the United Nations (FAO), 25 pp.

McCollum, D.L. et al., 2018: Connecting the sustainable development goals by their energy inter-linkages. *Environmental Research Letters*, **13(3)**, 033006, doi:10.1088/1748-9326/aaafe3.

McKinney, M.L. and K. Ingo, 2018: The contribution of wild urban ecosystems to liveable cities. *Urban Forestry & Urban Greening*, **29**, 334–335, doi:10.1016/j.ufug.2017.09.004.

McLeod, R.S., C.J. Hopfe, and A. Kwan, 2013: An investigation into future performance and overheating risks in Passivhaus dwellings. *Building and Environment*, **70**, 189–209, doi:10.1016/j.buildenv.2013.08.024.

McPherson, E.G., A.M. Berry, and N.S. van Doorn, 2018: Performance testing to identify climate-ready trees. *Urban Forestry & Urban Greening*, **29**, 28–39, doi:10.1016/j.ufug.2017.09.003.

Meldrum, J., S. Nettles-Anderson, G. Heath, and J. Macknick, 2013: Life cycle water use for electricity generation: a review and harmonization of literature estimates. *Environmental Research Letters*, **8(1)**, 015031.

Meltzer, J.P., 2016: *Financing Low Carbon, Climate Resilient Sustainable Infrastructure: The Role of Climate Finance and Green Financial Systems*. Global Economy & Development Working Paper 96, Brookings Institution, Washington DC, USA, 52 pp.

Michler-Cieluch, T., G. Krause, and B.H. Buck, 2009: Reflections on integrating operation and maintenance activities of offshore wind farms and mariculture. *Ocean & Coastal Management*, **52(1)**, 57–68, doi:10.1016/j.ocecoaman.2008.09.008.

Miles, L. and V. Kapos, 2008: Reducing Greenhouse Gas Emissions from Deforestation and Forest Degradation: Global Land-Use Implications. *Science*, **320(5882)**, 1454–1455, doi:10.1126/science.1155358.

Miller, E., L.M. Bell, and L. Buys, 2007: Public understanding of carbon sequestration in Australia: socio-demographic predictors of knowledge, engagement and trust. *International Journal of Emerging Technologies and Society*, **5(1)**, 15–33.

Mittlefehldt, S., 2016: Seeing forests as fuel: How conflicting narratives have shaped woody biomass energy development in the United States since the 1970s. *Energy Research & Social Science*, **14**, 13–21, doi:10.1016/j.erss.2015.12.023.

Møller, A.P. and T.A. Mousseau, 2011: Conservation consequences of Chernobyl and other nuclear accidents. *Biological Conservation*, **144(12)**, 2787–2798, doi:10.1016/j.biocon.2011.08.009.

Møller, A.P., F. Barnier, and T.A. Mousseau, 2012: Ecosystems effects 25 years after Chernobyl: pollinators, fruit set and recruitment. *Oecologia*, **170(4)**, 1155–1165, doi:10.1007/s00442-012-2374-0.

Møller, A.P., A. Bonisoli-Alquati, G. Rudolfsen, and T.A. Mousseau, 2011: Chernobyl Birds Have Smaller Brains. *PLOS ONE*, **6(2)**, e16862, doi:10.1371/journal.pone.0016862.

Montanarella, L. and I.L. Alva, 2015: Putting soils on the agenda: the three Rio Conventions and the post-2015 development agenda. *Current Opinion in Environmental Sustainability*, **15**, 41–48, doi:10.1016/j.cosust.2015.07.008.

Moomaw, W. et al., 2011: Annex II: Methodology. In: *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, and C. von Stechow (eds.)]. Prepared by Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 973–1000.

Morton, J.F., 2007: The impact of climate change on smallholder and subsistence agriculture. *Proceedings of the National Academy of Sciences*, **104(50)**, 19680–19685, doi:10.1073/pnas.0701855104.

Mousseau, T.A. and A.P. Møller, 2013: Elevated Frequency of Cataracts in Birds from Chernobyl. *PLOS ONE*, **8(7)**, e66939, doi:10.1371/journal.pone.0066939.

Msangi, S., M. Ewing, M.W. Rosegrant, and T. Zhu, 2010: Biofuels, Food Security, and the Environment: A 2020/2050 Perspective. In: *Global Change: Impacts on Water and food Security* [Ringler, C., A.K. Biswas, and S. Cline (eds.)]. Springer Berlin Heidelberg, Berlin and Heidelberg, Germany, pp. 65–94, doi:10.1007/978-3-642-04615-5_4.

Mtui, G.Y.S., 2011: Involvement of biotechnology in climate change adaptation and mitigation: Improving agricultural yield and food security. *International Journal for Biotechnology and Molecular Biology Research*, **2(13)**, 222–231, www.academicjournals.org/ijbmbr/abstracts/abstracts/abstracts2011/30dec/mtui.htm.

Muratori, M., K. Calvin, M. Wise, P. Kyle, and J. Edmonds, 2016: Global economic consequences of deploying bioenergy with carbon capture and storage (BECCS). *Environmental Research Letters*, **11(9)**, 1–9, doi:10.1088/1748-9326/11/9/095004.

Muys, B. et al., 2014: Integrating mitigation and adaptation into development: the case of *Jatropha curcas* in sub-Saharan Africa. *GCB Bioenergy*, **6**, 169–171, doi:10.1111/gcbb.12070.

NCE, 2014: *Better Growth, Better Climate: Global Report*. New Climate Economy (NCE), Washington DC, USA, 308 pp.

NCE, 2015: *Seizing the Global Opportunity: Partnerships for Better Growth and a Better Climate*. New Climate Economy (NCE), Washington DC, USA and London, UK, 76 pp.

Nelson, V., K. Meadows, T. Cannon, J. Morton, and A. Martin, 2002: Uncertain Predictions, Invisible Impacts, and the Need to Mainstream Gender in Climate Change Adaptations. *Gender and Development*, **10(2)**, 51–59, www.jstor.org/stable/4030574.

Nemet, G.F., T. Holloway, and P. Meier, 2010: Implications of incorporating air-quality co-benefits into climate change policymaking. *Environmental Research Letters*, **5(1)**, 014007, doi:10.1088/1748-9326/5/1/014007.

Nguyen, M.T., S. Vink, M. Ziemski, and D.J. Barrett, 2014: Water and energy synergy and trade-off potentials in mine water management. *Journal of Cleaner Production*, **84(1)**, 629–638, doi:10.1016/j.jclepro.2014.01.063.

Noonan, D.S., L.-H.C. Hsieh, and D. Matisoff, 2015: Economic, sociological, and neighbor dimensions of energy efficiency adoption behaviors: Evidence from the U.S residential heating and air conditioning market. *Energy Research & Social Science*, **10**, 102–113, doi:10.1016/j.erss.2015.07.009.

Noris, F. et al., 2013: Indoor environmental quality benefits of apartment energy retrofits. *Building and Environment*, **68**, 170–178, doi:10.1016/j.buildenv.2013.07.003.

O'Mahony, T. and J. Dufour, 2015: Tracking development paths: Monitoring driving forces and the impact of carbon-free energy sources in Spain. *Environmental Science & Policy*, **50(2007)**, 62–73, doi:10.1016/j.envsci.2015.02.005.

O'Neill, B.C. et al., 2017: The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change*, **42**, 169–180, doi:10.1016/j.gloenvcha.2015.01.004.

OECD, 2017: *Economic Outlook for Southeast Asia, China and India 2017: Addressing Energy Challenges*. Organisation for Economic Co-operation and Development (OECD) Publishing, Paris, France, 261 pp.

Oschlies, A., W. Koeve, W. Rickels, and K. Rehdanz, 2010: Side effects and accounting aspects of hypothetical large-scale Southern Ocean iron fertilization. *Biogeosciences*, **7(12)**, 4014–4035, doi:10.5194/bg-7-4017-2010.

Ozturk, M. et al., 2017: Biomass and bioenergy: An overview of the development potential in Turkey and Malaysia. *Renewable and Sustainable Energy Reviews*, **79**, 1285–1302, doi:10.1016/j.rser.2017.05.111.

Pachauri, S. and N.D. Rao, 2013: Gender impacts and determinants of energy poverty: are we asking the right questions? *Current Opinion in Environmental Sustainability*, **5(2)**, 205–215, doi:10.1016/j.cosust.2013.04.006.

Pachauri, S. et al., 2012: Energy Access for Development. In: *Global Energy Assessment – Toward a Sustainable Future* [Johansson, T.B., N. Nakicenovic, A. Patwardhan, and L. Gomez-Echeverri (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA and the International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, pp. 1401–1458.

Paquay, F.S. and R.E. Zeebe, 2013: Assessing possible consequences of ocean liming on ocean pH, atmospheric CO_2 concentration and associated costs. *International Journal of Greenhouse Gas Control*, **17**, 183–188, doi:10.1016/j.ijggc.2013.05.005.

Patel, S.J., J.H. Patel, A. Patel, and R.N. Gelani, 2016: Role of women gender in livestock sector: A review. *Journal of Livestock Science*, **7**, 92–96.

Pei, N. et al., 2018: Long-term afforestation efforts increase bird species diversity in Beijing, China. *Urban Forestry & Urban Greening*, **29**, 88–95, doi:10.1016/j.ufug.2017.11.007.

Peng, J. and L. Lu, 2013: Investigation on the development potential of rooftop PV system in Hong Kong and its environmental benefits. *Renewable and Sustainable Energy Reviews*, **27**, 149–162, doi:10.1016/j.rser.2013.06.030.

Peng, W., J. Yang, F. Wagner, and D.L. Mauzerall, 2017: Substantial air quality and climate co-benefits achievable now with sectoral mitigation strategies in China. *Science of The Total Environment*, **598**, 1076–1084, doi:10.1016/j.scitotenv.2017.03.287.

Pettit, L.R., C.W. Smart, M.B. Hart, M. Milazzo, and J.M. Hall-Spencer, 2015: Seaweed fails to prevent ocean acidification impact on foraminifera along a shallow-water CO_2 gradient. *Ecology and Evolution*, **5(9)**, 1784–1793, doi:10.1002/ece3.1475.

5

Pietzcker, R.C. et al., 2014: Long-term transport energy demand and climate policy: Alternative visions on transport decarbonization in energy-economy models. *Energy*, **64**, 95–108, doi:10.1016/j.energy.2013.08.059.

Pode, R., 2013: Financing LED solar home systems in developing countries. *Renewable and Sustainable Energy Reviews*, **25**, 596–629, doi:10.1016/j.rser.2013.04.004.

Potouroglou, M. et al., 2017: Measuring the role of seagrasses in regulating sediment surface elevation. *Scientific Reports*, **7(1)**, 1–11, doi:10.1038/s41598-017-12354-y.

Pueyo, A., F. Gonzalez, C. Dent, and S. DeMartino, 2013: *The Evidence of Benefits for Poor People of Increased Renewable Electricity Capacity: Literature Review*. Brief supporting Evidence Report 31, Institute of Development Studies (IDS), Brighton, UK, 8 pp.

Rafaj, P., W. Schöpp, P. Russ, C. Heyes, and M. Amann, 2013: Co-benefits of post-2012 global climate mitigation policies. *Mitigation and Adaptation Strategies for Global Change*, **18(6)**, 801–824, doi:10.1007/s11027-012-9390-6.

Raji, B., M.J. Tenpierik, and A. van den Dobbelsteen, 2015: The impact of greening systems on building energy performance: A literature review. *Renewable and Sustainable Energy Reviews*, **45**, 610–623, doi:10.1016/j.rser.2015.02.011.

Ramaker, J., J. Mackby, P.D. Marshall, and R. Geil, 2003: *The final test: a history of the comprehensive nuclear-test-ban treaty negotiations*. Provisional Technical Secretariat, Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization, 291 pp.

Ran, Y., M. Lannerstad, M. Herrero, C.E. Van Middelaar, and I.J.M. De Boer, 2016: Assessing water resource use in livestock production: A review of methods. *Livestock Science*, **187**, 68–79, doi:10.1016/j.livsci.2016.02.012.

Rao, N.D. and S. Pachauri, 2017: Energy access and living standards: some observations on recent trends. *Environmental Research Letters*, **12(2)**, 025011, doi:10.1088/1748-9326/aa5b0d.

Rao, N.D., K. Riahi, and A. Grubler, 2014: Climate impacts of poverty eradication. *Nature Climate Change*, **4(9)**, 749–751, doi:10.1038/nclimate2340.

Rao, S. et al., 2013: Better air for better health: forging synergies in policies for energy access, climate change and air pollution. *Global Environmental Change*, **23**, 1122–1130, doi:10.1016/j.gloenvcha.2013.05.003.

Rao, S. et al., 2016: A multi-model assessment of the co-benefits of climate mitigation for global air quality. *Environmental Research Letters*, **11(12)**, 124013, doi:10.1088/1748-9326/11/12/124013.

Raptis, C.E., M.T.H. van Vliet, and S. Pfister, 2016: Global thermal pollution of rivers from thermoelectric power plants. *Environmental Research Letters*, **11(10)**, 104011, doi:10.1088/1748-9326/11/10/104011.

Ravindranath, N.H., R.K. Chaturvedi, and I.K. Murthy, 2008: Forest conservation, afforestation and reforestation in India: Implications for forest carbon stocks. *Current Science*, **95(2)**, 216–222.

Reiner, D.M. and W.J. Nuttall, 2011: Public Acceptance of Geological Disposal of Carbon Dioxide and Radioactive Waste: Similarities and Differences. In: *Geological Disposal of Carbon Dioxide and Radioactive Waste: A Comparative Assessment* [Toth, F.L. (ed.)]. Springer Netherlands, Dordrecht, The Netherlands, pp. 295–315, doi:10.1007/978-90-481-8712-6_10.

Riahi, K. et al., 2012: Energy Pathways for Sustainable Development. In: *Global Energy Assessment – Toward a Sustainable Future* [Johansson, T.B., N. Nakicenovic, A. Patwardhan, and L. Gomez-Echeverri (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA and the International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, pp. 1203–1306.

Riahi, K. et al., 2015: Locked into Copenhagen pledges – Implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technological Forecasting and Social Change*, **90**, 8–23, doi:10.1016/j.techfore.2013.09.016.

Riahi, K. et al., 2017: The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview. *Global Environmental Change*, **42**, 153–168, doi:10.1016/j.gloenvcha.2016.05.009.

Rogalsky, J., 2010: The working poor and what GIS reveals about the possibilities of public transit. *Journal of Transport Geography*, **18(2)**, 226–237, doi:10.1016/j.jtrangeo.2009.06.008.

Rogelj, J., D.L. McCollum, and K. Riahi, 2013: The UN's 'Sustainable Energy for All' initiative is compatible with a warming limit of 2°C. *Nature Climate Change*, **3(6)**, 545–551, doi:10.1038/nclimate1806.

Rogner, H.-H., 2010: Nuclear Power and Sustainable Development. *Journal of International Affairs*, **64(1)**, 137–163, www.jstor.org/stable/24385190.

Rose, S.K. et al., 2014: Bioenergy in energy transformation and climate management. *Climatic Change*, **123(3–4)**, 477–493, doi:10.1007/s10584-013-0965-3.

Roy, J. et al., 2018: Where is the hope? Blending modern urban lifestyle with cultural practices in India. *Current Opinion in Environmental Sustainability*, **31**, 96–103, doi:10.1016/j.cosust.2018.01.010.

Rud, J.P., 2012: Electricity provision and industrial development: Evidence from India. *Journal of Development Economics*, **97(2)**, 352–367, doi:10.1016/j.jdeveco.2011.06.010.

Sagan, S.D., 2011: The Causes of Nuclear Weapons Proliferation. *Annual Review of Political Science*, **14(1)**, 225–244, doi:10.1146/annurev-polisci-052209-131042.

Salvalai, G., M.M. Sesana, and G. Iannaccone, 2017: Deep renovation of multi-storey multi-owner existing residential buildings: a pilot case study in Italy. *Energy and Buildings*, **148**, 23–36, doi:10.1016/j.enbuild.2017.05.011.

Sansoucy, R., 1995: Livestock – a driving force for food security and sustainable development. *World Animal Review*, **84/85(2)**.

Santarius, T., H.J. Walnum, and C. Aall (eds.), 2016: *Rethinking Climate and Energy Policies: New Perspectives on the Rebound Phenomenon*. Springer, Cham, Switzerland, 294 pp., doi:10.1007/978-3-319-38807-6.

Sarin, R., M. Sharma, S. Sinharay, and R.K. Malhotra, 2007: Jatropha-Palm biodiesel blends: An optimum mix for Asia. *Fuel*, **86(10–11)**, 1365–1371, doi:10.1016/j.fuel.2006.11.040.

Satolo, L. and M. Bacchi, 2013: Impacts of the Recent Expansion of the Sugarcane Sector on Municipal per Capita Income in São Paulo State. *ISRN Economics*, **2013**, 828169, doi:10.1155/2013/828169.

Saunders, L.E., J.M. Green, M.P. Petticrew, R. Steinbach, and H. Roberts, 2013: What Are the Health Benefits of Active Travel? A Systematic Review of Trials and Cohort Studies. *PLOS ONE*, **8**, e69912, doi:10.1371/journal.pone.0069912.

Schader, C. et al., 2015: Impacts of feeding less food-competing feedstuffs to livestock on global food system sustainability. *Journal of The Royal Society Interface*, **12(113)**, doi:10.1098/rsif.2015.0891.

Scherr, S.J., S. Shames, and R. Friedman, 2012: From climate-smart agriculture to climate-smart landscapes. *Agriculture & Food Security*, **1(1)**, 12, doi:10.1186/2048-7010-1-12.

Schirmer, J. and L. Bull, 2014: Assessing the likelihood of widespread landholder adoption of afforestation and reforestation projects. *Global Environmental Change*, **24**, 306–320, doi:10.1016/j.gloenvcha.2013.11.009.

Schnelzer, M., G.P. Hammer, M. Kreuzer, A. Tschense, and B. Grosche, 2010: Accounting for smoking in the radon-related lung cancer risk among German uranium miners: results of a nested case-control study. *Health Physics*, **98(1)**, 20–28, doi:10.1097/hp.0b013e3181b8ce81.

Schucht, S. et al., 2015: Moving towards ambitious climate policies: Monetised health benefits from improved air quality could offset mitigation costs in Europe. *Environmental Science & Policy*, **50**, 252–269, doi:10.1016/j.envsci.2015.03.001.

Schwanitz, V.J., F. Piontek, C. Bertram, and G. Luderer, 2014: Long-term climate policy implications of phasing out fossil fuel subsidies. *Energy Policy*, **67**, 882–894, doi:10.1016/j.enpol.2013.12.015.

Schwenk-Ferrero, A., 2013: German Spent Nuclear Fuel Legacy: Characteristics and High-Level Waste Management Issues. *Science and Technology of Nuclear Installations*, 293792, doi:10.1155/2013/293792.

Schwerhoff, G. and M. Sy, 2017: Financing renewable energy in Africa – Key challenge of the sustainable development goals. *Renewable and Sustainable Energy Reviews*, **75**, 393–401, doi:10.1016/j.rser.2016.11.004.

Scott, C.A., 2011: The water-energy-climate nexus: Resources and policy outlook for aquifers in Mexico. *Water Resources Research*, **47(6)**, doi:10.1029/2011wr010805.

Scott, C.A. et al., 2011: Policy and institutional dimensions of the water–energy nexus. *Energy Policy*, **39(10)**, 6622–6630, doi:10.1016/j.enpol.2011.08.013.

Scott, F.L., C.R. Jones, and T.L. Webb, 2014: What do people living in deprived communities in the UK think about household energy efficiency interventions? *Energy Policy*, **66**, 335–349, doi:10.1016/j.enpol.2013.10.084.

Sermage-Faure, C. et al., 2012: Childhood leukemia around French nuclear power plants – The geocap study, 2002-2007. *International Journal of Cancer*, **131(5)**, E769–E780, doi:10.1002/ijc.27425.

Shackley, S. and M. Thompson, 2012: Lost in the mix: will the technologies of carbon dioxide capture and storage provide us with a breathing space as we strive to make the transition from fossil fuels to renewables? *Climatic Change*, **110(1)**, 101–121, doi:10.1007/s10584-011-0071-3.

Shackley, S. et al., 2009: The acceptability of CO_2 capture and storage (CCS) in Europe: An assessment of the key determining factors: Part 2. The social acceptability of CCS and the wider impacts and repercussions of its implementation. *International Journal of Greenhouse Gas Control*, **3(3)**, 344–356, doi:10.1016/j.ijggc.2008.09.004.

Shah, N., M. Wei, V. Letschert, and A. Phadke, 2015: *Benefits of leapfrogging to superefficiency and low global warming potential refrigerants in room air conditioning*. LBNL-1003671, Ernest Orlando Lawrence Berkeley National Laboratory (LBNL), Berkeley, CA, USA, 58 pp.

Shahbaz, M., G. Rasool, K. Ahmed, and M.K. Mahalik, 2016: Considering the effect of biomass energy consumption on economic growth: fresh evidence from BRICS region. *Renewable and Sustainable Energy Reviews*, **60**, 1442–1450, doi:10.1016/j.rser.2016.03.037.

Sharpe, R.A., C.R. Thornton, V. Nikolaou, and N.J. Osborne, 2015: Higher energy efficient homes are associated with increased risk of doctor diagnosed asthma in a UK subpopulation. *Environment International*, **75**, 234–244, doi:10.1016/j.envint.2014.11.017.

Shaw, C., S. Hales, P. Howden-Chapman, and R. Edwards, 2014: Health co-benefits of climate change mitigation policies in the transport sector. *Nature Climate Change*, **4(6)**, 427–433, doi:10.1038/nclimate2247.

Shaw, C., S. Hales, R. Edwards, and P. Howden-Chapman, 2017: Health Co-Benefits of Policies to Mitigate Climate Change in the Transport Sector: Systematic Review. *Journal of Transport & Health*, **5**, S107–S108, doi:10.1016/j.jth.2017.05.268.

Shi, Y., J. Liu, H. Shi, H. Li, and Q. Li, 2017: The ecosystem service value as a new eco-efficiency indicator for industrial parks. *Journal of Cleaner Production*, **164**, 597–605, doi:10.1016/j.jclepro.2017.06.187.

Siirila, E.R., A.K. Navarre-Sitchler, R.M. Maxwell, and J.E. McCray, 2012: A quantitative methodology to assess the risks to human health from CO_2 leakage into groundwater. *Advances in Water Resources*, **36**, 146–164, doi:10.1016/j.advwatres.2010.11.005.

Sikkema, R. et al., 2014: Legal Harvesting, Sustainable Sourcing and Cascaded Use of Wood for Bioenergy: Their Coverage through Existing Certification Frameworks for Sustainable Forest Management. *Forests*, **5(9)**, 2163–2211, doi:10.3390/f5092163.

Singh, B., A.H. Strømman, and E.G. Hertwich, 2011: Comparative life cycle environmental assessment of CCS technologies. *International Journal of Greenhouse Gas Control*, **5(4)**, 911–921, doi:10.1016/j.ijggc.2011.03.012.

Sippo, J.Z., D.T. Maher, D.R. Tait, C. Holloway, and I.R. Santos, 2016: Are mangroves drivers or buffers of coastal acidification? Insights from alkalinity and dissolved inorganic carbon export estimates across a latitudinal transect. *Global Biogeochemical Cycles*, **30(5)**, 753–766, doi:10.1002/2015gb005324.

Sjoberg, L. and B.M.D. Sjoberg, 2009: Public risk perception of nuclear waste. *International Journal of Risk Assessment and Management*, **11(3/4)**, doi:10.1504/ijram.2009.023156.

Skipperud, L. et al., 2013: Environmental impact assessment of radionuclide and metal contamination at the former U sites Taboshar and Digmai, Tajikistan. *Journal of Environmental Radioactivity*, **123**, 50–62, doi:10.1016/j.jenvrad.2012.05.007.

SLoCaT, 2017: *Marrakech Partnership for Global Climate Action (MPGCA) Transport Initiatives: Stock-take on action toward implementation of the Paris Agreement and the 2030 Agenda on Sustainable Development. Second Progress Report*. Partnership on Sustainable Low Carbon Transport (SLoCaT), Bonn, Germany, 72 pp.

Smetacek, V. and S.W.A. Naqvi, 2008: The next generation of iron fertilization experiments in the Southern Ocean. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **366(1882)**, 3947–3967, doi:10.1098/rsta.2008.0144.

Smith, A., A. Pridmore, K. Hampshire, C. Ahlgren, and J. Goodwin, 2016: *Scoping study on the co-benefits and possible adverse side effects of climate change mitigation: Final report*. Report to the UK Department of Energy and Climate Change (DECC). Aether Ltd, Oxford, UK, 91 pp.

Smith, J. et al., 2014: What is the potential for biogas digesters to improve soil fertility and crop production in Sub-Saharan Africa? *Biomass and Bioenergy*, **70**, 58–72, doi:10.1016/j.biombioe.2014.02.030.

Smith, K.R. and A. Sagar, 2014: Making the clean available: escaping India's Chulha Trap. *Energy Policy*, **75**, 410–414, doi:10.1016/j.enpol.2014.09.024.

Smith, P., 2013: Delivering food security without increasing pressure on land. *Global Food Security*, **2(1)**, 18–23, doi:10.1016/j.gfs.2012.11.008.

Smith, P. et al., 2010: Competition for land. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **365**, 2941–2957, doi:10.1098/rstb.2010.0127.

Smith, P. et al., 2013: How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? *Global Change Biology*, **19(8)**, 2285–2302, doi:10.1111/gcb.12160.

Smith, P. et al., 2016a: Biophysical and economic limits to negative CO_2 emissions. *Nature Climate Change*, **6(1)**, 42–50, doi:10.1038/nclimate2870.

Smith, P. et al., 2016b: Global change pressures on soils from land use and management. *Global Change Biology*, **22(3)**, 1008–1028, doi:10.1111/gcb.13068.

Sola, P., C. Ochieng, J. Yila, and M. Iiyama, 2016: Links between energy access and food security in sub Saharan Africa: an exploratory review. *Food Security*, **8(3)**, 635–642, doi:10.1007/s12571-016-0570-1.

Sommerfeld, J., L. Buys, and D. Vine, 2017: Residential consumers' experiences in the adoption and use of solar PV. *Energy Policy*, **105**, 10–16, doi:10.1016/j.enpol.2017.02.021.

Sondak, C.F.A. et al., 2017: Carbon dioxide mitigation potential of seaweed aquaculture beds (SABs). *Journal of Applied Phycology*, **29(5)**, 2363–2373, doi:10.1007/s10811-016-1022-1.

Song, Y. et al., 2016: The Interplay Between Bioenergy Grass Production and Water Resources in the United States of America. *Environmental Science & Technology*, **50(6)**, 3010–3019, doi:10.1021/acs.est.5b05239.

Stahel, W.R., 2013: Policy for material efficiency – sustainable taxation as a departure from the throwaway society. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **371(1986)**, doi:10.1098/rsta.2011.0567.

Stahel, W.R., 2016: The circular economy. *Nature*, **531(7595)**, 435–438, doi:10.1038/531435a.

Stanley, J.K., D.A. Hensher, and C. Loader, 2011: Road transport and climate change: Stepping off the greenhouse gas. *Transportation Research Part A: Policy and Practice*, **45(10)**, 1020–1030, doi:10.1016/j.tra.2009.04.005.

Steenwerth, K.L. et al., 2014: Climate-smart agriculture global research agenda: scientific basis for action. *Agriculture & Food Security*, **3(1)**, 11, doi:10.1186/2048-7010-3-11.

Stefan, A. and L. Paul, 2008: Does It Pay to Be Green? A Systematic Overview. *Academy of Management Perspectives*, **22(4)**, 45–62, doi:10.5465/amp.2008.35590353.

Stehfest, E. et al., 2009: Climate benefits of changing diet. *Climatic Change*, **95(1–2)**, 83–102, doi:10.1007/s10584-008-9534-6.

Steinfeld, H. and P. Gerber, 2010: Livestock production and the global environment: Consume less or produce better? *Proceedings of the National Academy of Sciences*, **107(43)**, 18237–18238, doi:10.1073/pnas.1012541107.

Suckall, N., E. Tompkins, and L. Stringer, 2014: Identifying trade-offs between adaptation, mitigation and development in community responses to climate and socio-economic stresses: Evidence from Zanzibar, Tanzania. *Applied Geography*, **46**, 111–121, doi:10.1016/j.apgeog.2013.11.005.

Supino, S., O. Malandrino, M. Testa, and D. Sica, 2016: Sustainability in the EU cement industry: The Italian and German experiences. *Journal of Cleaner Production*, **112**, 430–442, doi:10.1016/j.jclepro.2015.09.022.

Sweeney, J.C., J. Kresling, D. Webb, G.N. Soutar, and T. Mazzarol, 2013: Energy saving behaviours: Development of a practice-based model. *Energy Policy*, **61**, 371–381, doi:10.1016/j.enpol.2013.06.121.

Tabellini, G., 2010: Culture and Institutions: Economic Development in the Regions of Europe. *Journal of the European Economic Association*, **8(4)**, 677–716, doi:10.1111/j.1542-4774.2010.tb00537.x.

Taniwaki, R.H. et al., 2017: Impacts of converting low-intensity pastureland to high-intensity bioenergy cropland on the water quality of tropical streams in Brazil. *Science of The Total Environment*, **584**, 339–347, doi:10.1016/j.scitotenv.2016.12.150.

Taylor, L.L. et al., 2016: Enhanced weathering strategies for stabilizing climate and averting ocean acidification. *Nature Climate Change*, **6(4)**, 402–406, doi:10.1038/nclimate2882.

Ten Hoeve, J.E. and M.Z. Jacobson, 2012: Worldwide health effects of the Fukushima Daiichi nuclear accident. *Energy & Environmental Science*, **5(9)**, 8743–8757, doi:10.1039/c2ee22019a.

Terry, G., 2009: No climate justice without gender justice: an overview of the issues. *Gender and Development*, **17(1)**, 5–18, www.jstor.org/stable/27809203.

Thornton, P.K., 2010: Livestock production: recent trends, future prospects. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **365(1554)**, 2853–2867, doi:10.1098/rstb.2010.0134.

Tiedeman, K., S. Yeh, B.R. Scanlon, J. Teter, and G.S. Mishra, 2016: Recent Trends in Water Use and Production for California Oil Production. *Environmental Science & Technology*, **50(14)**, 7904–7912, doi:10.1021/acs.est.6b01240.

Tilman, D. and M. Clark, 2014: Global diets link environmental sustainability and human health. *Nature*, **515(7528)**, 518–522, doi:10.1038/nature13959.

Tilman, D. et al., 2009: Beneficial Biofuels – The Food, Energy, and Environment Trilemma. *Science*, **325(5938)**, 270–271, doi:10.1126/science.1177970.

Tirmarche, M. et al., 2012: Risk of lung cancer from radon exposure: contribution of recently published studies of uranium miners. *Annals of the ICRP*, **41(3)**, 368–377, doi:10.1016/j.icrp.2012.06.033.

Treasury, H.M., 2009: *Green biotechnology and climate change*. Euro Bio, 12 pp.

Trick, C.G. et al., 2010: Iron enrichment stimulates toxic diatom production in high-nitrate, low-chlorophyll areas. *Proceedings of the National Academy of Sciences*, **107(13)**, 5887–5892, doi:10.1073/pnas.0910579107.

Tully, S., 2006: The Human Right to Access Electricity. *The Electricity Journal*, **19**, 30–39, doi:10.1016/j.tej.2006.02.003.

Turpie, J., B. Warr, and J.C. Ingram, 2015: *Benefits of Forest Ecosystems in Zambia and the Role of REDD+ in a Green Economy Transformation*. United Nations Environment Programme (UNEP), 98 pp.

Tyler, A.N. et al., 2013: The radium legacy: Contaminated land and the committed effective dose from the ingestion of radium contaminated materials. *Environment International*, **59**, 449–455, doi:10.1016/j.envint.2013.06.016.

UN, 1989: The Montreal Protocol on Substances that Deplete the Ozone Layer. In: *United Nations – Treaty Series No. 26369*. United Nations (UN), pp. 29–111.

UNSCEAR, 2011: Health effects due to radiation from the Chernobyl accident (Annex D). In: *UNSCEAR 2008 Report Vol. II: Effects. Scientific Annexes C, D and E*. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), New York, NY, USA, pp. 45–220.

UN-Women, UNDESA, and UNFCCC, 2015: *Implementation of gender-responsive climate action in the context of sustainable development*. EGM/GR-CR/Report, UN-Women, UNDESA and UNFCCC, 47 pp.

van de Walle, D., M. Ravallion, V. Mendiratta, and G. Koolwal, 2013: *Long-Term Impacts of Household Electrification in Rural India*. Policy Research working paper no. WPS 6527, World Bank, Washington DC, USA, 54 pp.

van der Horst, D. and S. Vermeylen, 2011: Spatial scale and social impacts of biofuel production. *Biomass and Bioenergy*, **35(6)**, 2435–2443, doi:10.1016/j.biombioe.2010.11.029.

van Oel, P.R. and A.Y. Hoekstra, 2012: Towards Quantification of the Water Footprint of Paper: A First Estimate of its Consumptive Component. *Water Resources Management*, **26(3)**, 733–749, doi:10.1007/s11269-011-9942-7.

van Sluisveld, M.A.E., S.H. Martínez, V. Daioglou, and D.P. van Vuuren, 2016: Exploring the implications of lifestyle change in 2°C mitigation scenarios using the IMAGE integrated assessment model. *Technological Forecasting and Social Change*, **102**, 309–319, doi:10.1016/j.techfore.2015.08.013.

van Vliet, O. et al., 2012: Synergies in the Asian energy system: Climate change, energy security, energy access and air pollution. *Energy Economics*, **34, Supple**, S470–S480, doi:10.1016/j.eneco.2012.02.001.

van Vuuren, D.P., J. van Vliet, and E. Stehfest, 2009: Future bio-energy potential under various natural constraints. *Energy Policy*, **37(11)**, 4220–4230, doi:10.1016/j.enpol.2009.05.029.

Vasconcellos, E.A. and A. Mendonça, 2016: *Observatorio de Movilidad Urbana: Informe final 2015-2016 (in Spanish)*. Corporacion Andina de Fomento (CAF) Banco de Desarrollo de América Latina, 25 pp.

Vassolo, S. and P. Döll, 2005: Global-scale gridded estimates of thermoelectric power and manufacturing water use. *Water Resources Research*, **41(4)**, W04010, doi:10.1029/2004wr003360.

Veltman, K., B. Singh, and E.G. Hertwich, 2010: Human and Environmental Impact Assessment of Postcombustion CO_2 Capture Focusing on Emissions from Amine-Based Scrubbing Solvents to Air. *Environmental Science & Technology*, **44(4)**, 1496–1502, doi:10.1021/es902116r.

Vergragt, P.J., N. Markusson, and H. Karlsson, 2011: Carbon capture and storage, bio-energy with carbon capture and storage, and the escape from the fossil-fuel lock-in. *Global Environmental Change*, **21(2)**, 282–292, doi:10.1016/j.gloenvcha.2011.01.020.

Vermeulen, S. et al., 2012: Climate change, agriculture and food security: a global partnership to link research and action for low-income agricultural producers and consumers. *Current Opinion in Environmental Sustainability*, **4(1)**, 128–133, doi:10.1016/j.cosust.2011.12.004.

Vidic, R.D., S.L. Brantley, J.M. Vandenbossche, D. Yoxtheimer, and J.D. Abad, 2013: Impact of Shale Gas Development on Regional Water Quality. *Science*, **340(6134)**, 1235009, doi:10.1126/science.1235009.

Vierros, M., 2017: Communities and blue carbon: the role of traditional management systems in providing benefits for carbon storage, biodiversity conservation and livelihoods. *Climatic Change*, **140(1)**, 89–100, doi:10.1007/s10584-013-0920-3.

Vierros, M., C. Salpin, C. Chiarolla, and S. Aricò, 2015: Emerging and unresolved issues: the example of marine genetic resources of areas beyond national jurisdiction. In: *Ocean Sustainability in the 21st Century* [Aricò, S. (ed.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 198–231, doi:10.1017/cbo9781316164624.012.

Visschers, V.H.M. and M. Siegrist, 2012: Fair play in energy policy decisions: Procedural fairness, outcome fairness and acceptance of the decision to rebuild nuclear power plants. *Energy Policy*, **46**, 292–300, doi:10.1016/j.enpol.2012.03.062.

von Hippel, D., T. Suzuki, J.H. Williams, T. Savage, and P. Hayes, 2011: Energy security and sustainability in Northeast Asia. *Energy Policy*, **39(11)**, 6719–6730, doi:10.1016/j.enpol.2009.07.001.

von Hippel, F., R. Ewing, R. Garwin, and A. Macfarlane, 2012: Time to bury plutonium. *Nature*, **485**, 167–168, doi:10.1038/485167a.

von Stechow, C. et al., 2016: 2°C and SDGs: United they stand, divided they fall? *Environmental Research Letters*, **11(3)**, 034022, doi:10.1088/1748-9326/11/3/034022.

Walker, G. and P. Devine-Wright, 2008: Community renewable energy: What should it mean? *Energy Policy*, **36**, 497–500, doi:10.1016/j.enpol.2007.10.019.

Walker, R.V., M.B. Beck, J.W. Hall, R.J. Dawson, and O. Heidrich, 2014: The energy-water-food nexus: Strategic analysis of technologies for transforming the urban metabolism. *Journal of Environmental Management*, **141**, 104–115, doi:10.1016/j.jenvman.2014.01.054.

Walks, A., 2015: *The Urban Political Economy and Ecology of Automobility: Driving Cities, Driving Inequality, Driving Politics*. Routledge, London, UK, 348 pp.

Wallquist, L., V.H.M. Visschers, and M. Siegrist, 2009: Lay concepts on CCS deployment in Switzerland based on qualitative interviews. *International Journal of Greenhouse Gas Control*, **3(5)**, 652–657, doi:10.1016/j.ijggc.2009.03.005.

Wallquist, L., V.H.M. Visschers, and M. Siegrist, 2010: Impact of Knowledge and Misconceptions on Benefit and Risk Perception of CCS. *Environmental Science & Technology*, **44(17)**, 6557–6562, doi:10.1021/es1005412.

Wang, S. and P.R. Jaffe, 2004: Dissolution of a mineral phase in potable aquifers due to CO_2 releases from deep formations; effect of dissolution kinetics. *Energy Conversion and Management*, **45(18–19)**, 2833–2848, doi:10.1016/j.enconman.2004.01.002.

WBGU, 2013: *World in Transition: Governing the Marine Heritage*. German Advisory Council on Global Change (WBGU), Berlin, Germany, 390 pp.

Webb, D., G.N. Soutar, T. Mazzarol, and P. Saldaris, 2013: Self-determination theory and consumer behavioural change: Evidence fromahousehold energy-saving behaviour study. *Journal of Environmental Psychology*, **35**, 59–66, doi:10.1016/j.jenvp.2013.04.003.

Webster, M., P. Donohoo, and B. Palmintier, 2013: Water-CO_2 trade-offs in electricity generation planning. *Nature Climate Change*, **3(12)**, 1029–1032, doi:10.1038/nclimate2032.

Wells, E.M. et al., 2015: Indoor air quality and occupant comfort in homes with deep versus conventional energy efficiency renovations. *Building and Environment*, **93(Part 2)**, 331–338, doi:10.1016/j.buildenv.2015.06.021.

Wesseling, J.H. et al., 2017: The transition of energy intensive processing industries towards deep decarbonization: Characteristics and implications for future research. *Renewable and Sustainable Energy Reviews*, **79**, 1303–1313, doi:10.1016/j.rser.2017.05.156.

West, J.J. et al., 2013: Co-benefits of Global Greenhouse Gas Mitigation for Future Air Quality and Human Health. *Nature Climate Change*, **3(10)**, 885–889, doi:10.1038/nclimate2009.

West, P.C. et al., 2014: Leverage points for improving global food security and the environment. *Science*, **345(6194)**, 325–328, doi:10.1126/science.1246067.

West, T.O. and W.M. Post, 2002: Soil Organic Carbon Sequestration Rates by Tillage and Crop Rotation. *Soil Science Society of America Journal*, **66**, 1930–1946, doi:10.2136/sssaj2002.1930.

WHO, 2013: *Health risk assessment from the nuclear accident after the 2011 Great East Japan earthquake and tsunami, based on a preliminary dose estimation*. World Health Organization (WHO), Geneva, Switzerland, 172 pp.

Willand, N., I. Ridley, and C. Maller, 2015: Towards explaining the health impacts of residential energy efficiency interventions – A realist review. Part 1: Pathways. *Social Science and Medicine*, **133**, 191–201, doi:10.1016/j.socscimed.2015.02.005.

Williamson, P. et al., 2012: Ocean fertilization for geoengineering: A review of effectiveness, environmental impacts and emerging governance. *Process Safety and Environmental Protection*, **90(6)**, 475–488, doi:10.1016/j.psep.2012.10.007.
Winter, E., A. Faße, and K. Frohberg, 2015: Food security, energy equity, and the global commons: a computable village model applied to sub-Saharan Africa. *Regional Environmental Change*, **15(7)**, 1215–1227, doi:10.1007/s10113-014-0674-0.
Wiser, R. et al., 2011: Wind Energy. In: *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, and C. von Stechow (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 535–608.
Wolosin, M., 2014: *Quantifying Benefits of the New York Declaration on Forests*. Climate Advisers, 17 pp.
Wong-Parodi, G. and I. Ray, 2009: Community perceptions of carbon sequestration: insights from California. *Environmental Research Letters*, **4(3)**, 034002, doi:10.1088/1748-9326/4/3/034002.
Woodbury, P.B., A.R. Kemanian, M. Jacobson, and M. Langholtz, 2018: Improving water quality in the Chesapeake Bay using payments for ecosystem services for perennial biomass for bioenergy and biofuel production. *Biomass and Bioenergy*, **114**, 132–142, doi:10.1016/j.biombioe.2017.01.024.
Woodcock, J. et al., 2009: Public health benefits of strategies to reduce greenhouse-gas emissions: urban land transport. *The Lancet*, **374(9705)**, 1930–1943, doi:10.1016/s0140-6736(09)61714-1.
Xi, Y., T. Fei, and W. Gehua, 2013: Quantifying co-benefit potentials in the Chinese cement sector during 12th Five Year Plan: An analysis based on marginal abatement cost with monetized environmental effect. *Journal of Cleaner Production*, **58**, 102–111, doi:10.1016/j.jclepro.2013.07.020.
Xylia, M. and S. Silveira, 2017: On the road to fossil-free public transport: the case of Swedish bus fleets. *Energy Policy*, **100**, 397–412, doi:10.1016/j.enpol.2016.02.024.
Yang, L., H. Yan, and J.C. Lam, 2014: Thermal comfort and building energy consumption implications – A review. *Applied Energy*, **115**, 164–173, doi:10.1016/j.apenergy.2013.10.062.
Yanine, F.F. and E.E. Sauma, 2013: Review of grid-tie micro-generation systems without energy storage: Towards a new approach to sustainable hybrid energy systems linked to energy efficiency. *Renewable and Sustainable Energy Reviews*, **26**, 60–95, doi:10.1016/j.rser.2013.05.002.
Yim, M.-S. and J. Li, 2013: Examining relationship between nuclear proliferation and civilian nuclear power development. *Progress in Nuclear Energy*, **66**, 108–114, doi:10.1016/j.pnucene.2013.03.005.
York, R. and J.A. McGee, 2017: Does Renewable Energy Development Decouple Economic Growth from CO_2 Emissions? *Socius*, **3**, doi:10.1177/2378023116689098.
Yu, C.-Y., 2015: How Differences in Roadways Affect School Travel Safety. *Journal of the American Planning Association*, **81(3)**, 203–220, doi:10.1080/01944363.2015.1080599.
Yue, T., R. Long, and H. Chen, 2013: Factors influencing energy-saving behavior of urban households in Jiangsu Province. *Energy Policy*, **62**, 665–675, doi:10.1016/j.enpol.2013.07.051.
Zeng, H., X. Chen, X. Xiao, and Z. Zhou, 2017: Institutional pressures, sustainable supply chain management, and circular economy capability: Empirical evidence from Chinese eco-industrial park firms. *Journal of Cleaner Production*, **155**, 54–65, doi:10.1016/j.jclepro.2016.10.093.
Zenk, S.N. et al., 2015: Prepared Food Availability in U.S. Food Stores. *American Journal of Preventive Medicine*, **49(4)**, 553–562, doi:10.1016/j.amepre.2015.02.025.
Zhang, S., E. Worrell, and W. Crijns-Graus, 2015: Cutting air pollution by improving energy efficiency of China's cement industry. *Energy Procedia*, **83**, 10–20, doi:10.1016/j.egypro.2015.12.191.
Zhang, Y. et al., 2017: Processes of coastal ecosystem carbon sequestration and approaches for increasing carbon sink. *Science China Earth Sciences*, **60(5)**, 809–820, doi:10.1007/s11430-016-9010-9.
Zhao, D., A.P. McCoy, J. Du, P. Agee, and Y. Lu, 2017: Interaction effects of building technology and resident behavior on energy consumption in residential buildings. *Energy and Buildings*, **134**, 223–233, doi:10.1016/j.enbuild.2016.10.049.
Ziv, G., E. Baran, S. Nam, I. Rodríguez-Iturbe, and S.A. Levin, 2012: Trading-off fish biodiversity, food security, and hydropower in the Mekong River Basin. *Proceedings of the National Academy of Sciences*, **109(15)**, 5609–5614, doi:10.1073/pnas.1201423109.
Zomer, R.J., A. Trabucco, D.A. Bossio, and L. Verchot, 2008: Climate change mitigation: A spatial analysis of global land suitability for clean development mechanism afforestation and reforestation. *Agriculture, Ecosystems & Environment*, **126(1–2)**, 67–80, doi:10.1016/j.agee.2008.01.014.
Zulu, L.C. and R.B. Richardson, 2013: Charcoal, livelihoods, and poverty reduction: Evidence from sub-Saharan Africa. *Energy for Sustainable Development*, **17(2)**, 127–137, doi:10.1016/j.esd.2012.07.007.

4

Transport of CO_2

Coordinating Lead Authors
Richard Doctor (United States), Andrew Palmer (United Kingdom)

Lead Authors
David Coleman (United States), John Davison (United Kingdom), Chris Hendriks (The Netherlands), Olav Kaarstad (Norway), Masahiko Ozaki (Japan)

Contributing Author
Michael Austell (United Kingdom)

Review Editors
Ramon Pichs-Madruga (Cuba), Svyatoslav Timashev (Russian Federation)

Contents

EXECUTIVE SUMMARY

Transport is that stage of carbon capture and storage that links sources and storage sites. The beginning and end of 'transport' may be defined administratively. 'Transport' is covered by the regulatory framework concerned for public safety that governs pipelines and shipping. In the context of long-distance movement of large quantities of carbon dioxide, pipeline transport is part of current practice. Pipelines routinely carry large volumes of natural gas, oil, condensate and water over distances of thousands of kilometres, both on land and in the sea. Pipelines are laid in deserts, mountain ranges, heavily-populated areas, farmland and the open range, in the Arctic and sub-Arctic, and in seas and oceans up to 2200 m deep.

Carbon dioxide pipelines are not new: they now extend over more than 2500 km in the western USA, where they carry 50 $MtCO_2$ yr^{-1} from natural sources to enhanced oil recovery projects in the west Texas and elsewhere. The carbon dioxide stream ought preferably to be dry and free of hydrogen sulphide, because corrosion is then minimal, and it would be desirable to establish a minimum specification for 'pipeline quality' carbon dioxide. However, it would be possible to design a corrosion-resistant pipeline that would operate safely with a gas that contained water, hydrogen sulphide and other contaminants. Pipeline transport of carbon dioxide through populated areas requires attention be paid to design factors, to overpressure protection, and to leak detection. There is no indication that the problems for carbon dioxide pipelines are any more challenging than those set by hydrocarbon pipelines in similar areas, or that they cannot be resolved.

Liquefied natural gas and petroleum gases such as propane and butane are routinely transported by marine tankers; this trade already takes place on a very large scale. Carbon dioxide is transported in the same way, but on a small scale because of limited demand. The properties of liquefied carbon dioxide are not greatly different from those of liquefied petroleum gases, and the technology can be scaled up to large carbon dioxide carriers. A design study discussed later has estimated costs for marine transport of 1 $MtCO_2$ yr^{-1} by one 22,000 m^3 marine tanker over a distance of 1100 km, along with the associated liquefaction, loading and unloading systems.

Liquefied gas can also be carried by rail and road tankers, but it is unlikely that they be considered attractive options for large-scale carbon dioxide capture and storage projects.

4.1 Introduction

CO_2 is transported in three states: gas, liquid and solid. Commercial-scale transport uses tanks, pipelines and ships for gaseous and liquid carbon dioxide.

Gas transported at close to atmospheric pressure occupies such a large volume that very large facilities are needed. Gas occupies less volume if it is compressed, and compressed gas is transported by pipeline. Volume can be further reduced by liquefaction, solidification or hydration. Liquefaction is an established technology for gas transport by ship as LPG (liquefied petroleum gas) and LNG (liquefied natural gas). This existing technology and experience can be transferred to liquid CO_2 transport. Solidification needs much more energy compared with other options, and is inferior from a cost and energy viewpoint. Each of the commercially viable technologies is currently used to transport carbon dioxide.

Research and development on a natural gas hydrate carrying system intended to replace LNG systems is in progress, and the results might be applied to CO_2 ship transport in the future. In pipeline transportation, the volume is reduced by transporting at a high pressure: this is routinely done in gas pipelines, where operating pressures are between 10 and 80 MPa.

A transportation infrastructure that carries carbon dioxide in large enough quantities to make a significant contribution to climate change mitigation will require a large network of pipelines. As growth continues it may become more difficult to secure rights-of-way for the pipelines, particularly in highly populated zones that produce large amounts of carbon dioxide. Existing experience has been in zones with low population densities, and safety issues will become more complex in populated areas.

The most economical carbon dioxide capture systems appear to favour CO_2 capture, first, from pure stream sources such as hydrogen reformers and chemical plants, and then from centralized power and synfuel plants: Chapter 2 discusses this issue in detail. The producers of natural gas speak of 'stranded' reserves from which transport to market is uneconomical. A movement towards a decentralized power supply grid may make CO_2 capture and transport much more costly, and it is easy to envision stranded CO_2 at sites where capture is uneconomic.

A regulatory framework will need to emerge for the low-greenhouse-gas-emissions power industry of the future to guide investment decisions. Future power plant owners may find the carbon dioxide transport component one of the leading issues in their decision-making.

4.2 Pipeline systems

4.2.1 Pipeline transportation systems

CO_2 pipeline operators have established minimum specifications for composition. Box 4.1 gives an example from the Canyon Reef project (Section 4.2.2.1). This specification is for gas for an enhanced oil recovery (EOR) project, and parts of it would not necessarily apply to a CO_2 storage project. A low nitrogen content is important for EOR, but would not be so significant for CCS. A CO_2 pipeline through populated areas might have a lower specified maximum H_2S content.

Dry carbon dioxide does not corrode the carbon-manganese steels generally used for pipelines, as long as the relative humidity is less than 60% (see, for example, Rogers and Mayhew, 1980); this conclusion continues to apply in the presence of N_2, NO_x and SO_x contaminants. Seiersten (2001) wrote:

"The corrosion rate of carbon steel in dry supercritical CO_2 is low. For AISI 1080 values around 0.01 mm yr^{-1} have been measured at 90–120 bar and 160°C–180°C for 200 days. Short-term tests confirm this. In a test conducted at 3ºC and 22°C at 140 bar CO_2, and 800 to 1000 ppm H_2S, the corrosion rate for X-60 carbon steel was measured at less than 0.5 µm yr^{-1} (0.0005 mm yr^{-1}). Field experience also indicates very few problems with transportation of high-pressure dry CO_2 in carbon steel pipelines. During 12 years, the corrosion rate in an operating pipeline amounts to 0.25-2.5 µm yr^{-1} (0.00025 to (0.0025 mm yr^{-1})".

The water solubility limit in high-pressure CO_2 (500 bar) is 5000 ppm at 75°C and 2000 ppm at 30°C. Methane lowers the solubility limit, and H_2S, O_2 and N_2 may have the same effect.

Corrosion rates are much higher if free water is present; hydrates might also form. Seiersten (2001) measured a corrosion rate of 0.7 mm yr^{-1} corrosion rate in 150 to 300 hours exposure at 40°C in water equilibrated with CO_2 at 95 bar, and higher rates at lower pressures. She found little difference between carbon-manganese steel (American Petroleum Institute grade X65) and 0.5 chromium corrosion-resistant alloy. It is unlikely to be practicable to transport wet CO_2 in low-alloy carbon steel pipelines because of this high corrosion rate. If the CO_2 cannot be dried, it may be necessary to build the pipeline of a corrosion-resistant alloy ('stainless steel'). This is an established technology. However the cost of steel has greatly increased recently and this may not be economical.

Once the CO_2 has been dried and meets the transportation criteria, the CO_2 is measured and transported to the final use site. All the pipelines have state-of-the-art metering systems that accurately account for sales and deliveries on to and out of each line, and SCADA (Supervisory Control and Data Acquisition) systems for measuring pressure drops, and redundancies built in to allow for emergencies. In the USA, these pipelines are governed by Department of Transportation regulations. Movement of CO_2 is best accomplished under high pressure: the choice of operating pressure is discussed in an example below, and the reader is referred to Annex I for a discussion of the physical properties of CO_2.

4.2.2 *Existing experience*

Table 4.1 lists existing long-distance CO_2 pipelines. Most of the projects listed below are described in greater detail in a report by the UK Department of Trade and Industry (2002). While there are CO_2 pipelines outside the USA, the Permian Basin contains over 90% of the active CO_2 floods in the world (O&GJ, April 15, 2002, EOR Survey). Since then, well over 1600 km of new CO_2 pipelines has been built to service enhanced oil recovery (EOR) in west Texas and nearby states.

4.2.2.1 Canyon Reef

The first large CO_2 pipeline in the USA was the Canyon Reef Carriers, built in 1970 by the SACROC Unit in Scurry County, Texas. Its 352 km moved 12,000 tonnes of anthropogenically produced CO_2 daily (4.4 Mt yr^{-1}) from Shell Oil Company gas processing plants in the Texas Val Verde basin.

4.2.2.2 Bravo Dome Pipeline

Oxy Permian constructed this 508 mm (20-inch) line connecting the Bravo Dome CO_2 field with other major pipelines. It is capable of carrying 7.3 $MtCO_2$ yr^{-1} and is operated by Kinder Morgan.

4.2.2.3 Cortez Pipeline

Built in 1982 to supply CO_2 from the McElmo Dome in S.E. Colorado, the 762 mm (30-inch), 803 km pipeline carries approximately 20 Mt CO_2 yr^{-1} to the CO_2 hub at Denver City, Texas. The line starts near Cortez, Colorado, and crosses the Rocky Mountains, where it interconnects with other CO_2 lines. In the present context, recall that one 1000 MW coal-fired

Box 4.1 Specimen CO_2 quality specifications

The Product delivered by Seller or Seller's representative to Buyer at the Canyon Reef Carriers Delivery Meter shall meet the following specifications, which herein are collectively called 'Quality Specifications':

(a) **Carbon Dioxide**. Product shall contain at least ninety-five mole percent (95%) of Carbon Dioxide as measured at the SACROC delivery meter.
(b) **Water.** Product shall contain no free water, and shall not contain more than 0.48 9 m^{-3} in the vapour phase.
(c) **Hydrogen Sulphide.** Product shall not contain more than fifteen hundred (1500) parts per million, by weight, of hydrogen sulphide.
(d) **Total Sulphur.** Product shall not contain more than fourteen hundred and fifty (1450) parts per million, by weight, of total sulphur.
(e) **Temperature.** Product shall not exceed a temperature of 48.9 ºC.
(f) **Nitrogen.** Product shall not contain more than four mole percent (4%) of nitrogen.
(g) **Hydrocarbons.** Product shall not contain more than five mole percent (5%) of hydrocarbons and the dew point of Product (with respect to such hydrocarbons) shall not exceed –28.9 ºC.
(h) **Oxygen.** Product shall not contain more than ten (10) parts per million, by weight, of oxygen.
(i) **Glycol.** Product shall not contain more than 4 x 10^{-5} L m^{-3} of glycol and at no time shall such glycol be present in a liquid state at the pressure and temperature conditions of the pipeline.

Table 4.1 Existing long-distance CO_2 pipelines (Gale and Davison, 2002) and CO_2 pipelines in North America (Courtesy of Oil and Gas Journal).

Pipeline	Location	Operator	Capacity ($MtCO_2$ yr^{-1})	Length (km)	Year finished	Origin of CO_2
Cortez	USA	Kinder Morgan	19.3	808	1984	McElmoDome
Sheep Mountain	USA	BP Amoco	9.5	660	-	Sheep Mountain
Bravo	USA	BP Amoco	7.3	350	1984	Bravo Dome
Canyon Reef Carriers	USA	Kinder Morgan	5.2	225	1972	Gasification plants
Val Verde	USA	Petrosource	2.5	130	1998	Val Verde Gas Plants
Bati Raman	Turkey	Turkish Petroleum	1.1	90	1983	Dodan Field
Weyburn	USA & Canada	North Dakota Gasification Co.	5	328	2000	Gasification Plant
Total			49.9	2591		

power station produces about 7 Mt CO_2 yr^{-1}, and so one Cortez pipeline could handle the emissions of three of those stations.

The Cortez Pipeline passes through two built-up areas, Placitas, New Mexico (30 km north of Albuquerque, New Mexico) and Edgewood/Moriarty, New Mexico (40 km east of Albuquerque). The line is buried at least 1 m deep and is marked within its right of way. Near houses and built-up areas it is marked more frequently to ensure the residents are aware of the pipeline locations. The entire pipeline is patrolled by air every two weeks, and in built-up areas is frequently patrolled by employees in company vehicles. The public education programme includes the mailing of a brochure describing CO_2, signs of a leak and where to report a suspected leak, together with information about the operator and the "one-call" centre.

4.2.2.4 *Sheep Mountain Pipeline*

BP Oil constructed this 610 mm (24-inch) 772 km line capable of carrying 9.2 $MtCO_2$ yr^{-1} from another naturally occurring source in southeast Colorado. It connects to the Bravo Dome line and into the other major carriers at Denver City and now is operated by Kinder Morgan.

Figure 4.1 CO_2 pipelines in North America. (Courtesy of Oil and Gas Journal).

4.2.2.5 Weyburn Pipeline

This 330 km, (305-356 mm diameter) system carries more than 5000 tonne day^{-1} (1.8 Mt yr^{-1}) of CO_2 from the Great Plains Synfuels Plant near Beulah, North Dakota to the Weyburn EOR project in Saskatchewan. The composition of the gas carried by the pipeline is typically CO_2 96%, H_2S 0.9%, CH_4 0.7%, C2+ hydrocarbons 2.3%, CO 0.1%, N_2 less than 300 ppm, O_2 less than 50 ppm and H_2O less than 20 ppm (UK Department of Trade and Industry, 2002). The delivery pressure at Weyburn is 15.2 MPa. There are no intermediate compressor stations. The amount allocated to build the pipeline was 110 US $ million (0.33×10^6 US$ km^{-1}) in 1997.

4.2.3 Design

The physical, environmental and social factors that determine the design of a pipeline are summarized in a design basis, which then forms the input for the conceptual design. This includes a system definition for the preliminary route and design aspects for cost-estimating and concept-definition purposes. It is also necessary to consider the process data defining the physical characteristics of product mixture transported, the optimal sizing and pressures for the pipeline, and the mechanical design, such as operating, valves, pumps, compressors, seals, etc. The topography of the pipeline right-of-way must be examined. Topography may include mountains, deserts, river and stream crossings, and for offshore pipelines, the differing challenges of very deep or shallow water, and uneven seabed. It is also important to include geotechnical considerations. For example, is this pipeline to be constructed on thin soil overlaying granite? The local environmental data need to be included, as well as the annual variation in temperature during operation and during construction, potentially unstable slopes, frost heave and seismic activity. Also included are water depth, sea currents, permafrost, ice gouging in Arctic seas, biological growth, aquifers, and other environmental considerations such as protected habitats. The next set of challenges is how the pipeline will accommodate existing and future infrastructure – road, rail, pipeline crossings, military/governmental restrictions and the possible impact of other activities – as well as shipping lanes, rural or urban settings, fishing restrictions, and conflicting uses such as dredging. Finally, this integrated study will serve as the basis for a safety review.

Conceptual design

The conceptual design includes the following components:

- Mechanical design: follows standard procedures, described in detail in (Palmer et al., 2004).
- Stability design: standard methods and software are used to perform stability calculations, offshore (Veritec, 1988) or onshore, though the offshore methods have been questioned. New guidelines for stability will be published in 2005 by Det Norske Veritas and will be designated DNV-RP-F109 On-Bottom Stability
- Protection against corrosion: a well-understood subject of which the application to CO_2 pipelines is described below.
- Trenching and backfilling: onshore lines are usually buried to depth of 1 m. Offshore lines are almost always buried in shallow water. In deeper water pipelines narrower than 400 mm are trenched and sometimes buried to protect them against damage by fishing gear.
- CO_2 pipelines may be more subject to longitudinal running fracture than hydrocarbon gas pipelines. Fracture arresters are installed at intervals of about 500 m.

West (1974) describes the design of the SACROC CO_2 pipeline (Section 4.2.2.1 above). The transportation options examined were:

(i) a low-pressure CO_2 gas pipeline operating at a maximum pressure of 4.8 MPa;
(ii) a high-pressure CO_2 gas pipeline operating at a minimum pressure of 9.6 MPa, so that the gas would remain in a dense phase state at all temperatures;
(iii) a refrigerated liquid CO_2 pipeline;
(iv) road tank trucks;
(v) rail tankers, possibly in combination with road tank trucks.

The tank truck and rail options cost more than twice as much as a pipeline. The refrigerated pipeline was rejected because of cost and technical difficulties with liquefaction. The dense phase (Option ii) was 20% cheaper than a low-pressure CO_2 gas pipeline (Option i). The intermediate 4.8 to 9.6 MPa pressure range was avoided so that two-phase flow would not occur. An added advantage of dense-phase transport was that high delivery pressures were required for CO_2 injection.

The final design conforms to the ANSI B31.8 code for gas pipelines and to the DOT regulations applicable at the time. The main 290 km section is 406.4 mm (16 inch) outside diameter and 9.53 mm wall thickness made from grade X65 pipe (specified minimum yield stress of 448 MPa). A shorter 60 km section is 323.85 mm (12.75 inch) outside diameter, 8.74 mm wall thickness, grade X65. Tests showed that dry CO_2 would not corrode the pipeline steel; 304L corrosion-resistant alloy was used for short sections upstream of the glycol dehydrator. The line is buried to a minimum of 0.9 m, and any point on the line is within 16 km of a block valve.

There are six compressor stations, totalling 60 MW, including a station at the SACROC delivery point. The compressor stations are not equally spaced, and the longest distance between two stations is about 160 km. This is consistent with general practice, but some long pipelines have 400 km or more between compressor stations.

Significant nitrogen and oxygen components in CO_2 would shift the boundary of the two-phase region towards higher pressures, and would require a higher operating pressure to avoid two-phase flow.

4.2.4 Construction of land pipelines

Construction planning can begin either before or after rights of way are secured, but a decision to construct will not come before a legal right to construct a pipeline is secured and all governmental regulations met. Onshore and underwater CO_2 pipelines are constructed in the same way as hydrocarbon pipelines, and for both there is an established and well-understood base of engineering experience. Subsection 4.2.5 describes underwater construction.

The construction phases of a land pipeline are outlined below. Some of the operations can take place concurrently.

Environmental and social factors may influence the season of the year in which construction takes place. The land is cleared and the trench excavated. The longest lead items come first: urban areas, river and road crossings. Pipe is received into the pipe yard and welded into double joints (24 m long); transported to staging areas for placement along the pipe route, welded, tested, coated and wrapped, and then lowered into the trench. A hydrostatic test is carried out, and the line is dried. The trench is then backfilled, and the land and the vegetation restored.

4.2.5 Underwater pipelines

Most underwater pipelines are constructed by the lay-barge method, in which 12 or 24 m lengths of pipe are brought to a dynamically positioned or anchored barge, and welded one by one to the end of the pipeline. The barge moves slowly forward, and the pipeline leaves the barge over the stern, and passes first over a support structure ('stinger') and then down through the water in a suspended span, until it reaches the seabed. Some lines up to 450 mm diameter are constructed by the reel method, in which the pipeline is welded together onshore, wound onto a reel on a ship, and then unwound from the reel into its final position. Some short lines and lines for shore crossings in shallow water are constructed by various tow and pull methods, in which the line is welded together onshore and then pulled into its final location.

If the design requires that the pipeline be trenched, that is usually done after it has been laid on the seabed, by a jetting sled, a plough or a mechanical cutting device that is pulled along the line. On the other hand, in shore crossings and in very shallow water the trench is often excavated before the pipeline is laid, and that is done by dredgers, backhoes or draglines in soft sediments, or in rock by blasting followed by clamshell excavators. Many shore crossings are drilled horizontally from the shore; this procedure eliminates many uncertainties associated with the surf zone, and reduces the environmental impact of construction.

Underwater connections are made by various kinds of mechanical connection systems, by hyperbaric welding (in air under the local hydrostatic pressure) or by lifting the pipe ends above the surface, welding them together and lowering the connected line to the bottom.

These technologies are established and understood (Palmer and King, 2004). Underwater pipelines up to 1422 mm in diameter have been constructed in many different environments, and pipelines have been laid in depths up to 2200 m. Figure 4.2 plots the diameters and maximum depths of major deepwater pipelines constructed up to 2004. The difficulty of construction is roughly proportional to the depth multiplied by the diameter, and the maximum value of that product has multiplied fourfold since 1980. Still larger and deeper pipelines are technically feasible with today's technology.

4.2.6 Operations

Operational aspects of pipelines are divided into three areas: daily operations, maintenance, and health, safety and environment. Operations of a CO_2 pipeline in the USA, for instance, must follow federal operations guidelines (49 CFR 195). Overall operational considerations include training, inspections, safety integration, signs and pipeline markers, public education, damage prevention programmes, communication, facility security and leak detection. Pipelines outside the USA generally have similar regulatory operational requirements.

Personnel form a central part of operations and must be qualified. Personnel are required to be continuously trained and updated on safety procedures, including safety procedures that apply to contractors working on or near the pipeline, as well as to the public.

Operations include daily maintenance, scheduled planning and policies for inspecting, maintaining and repairing all equipment on the line and the pipeline itself, as well as supporting the line and pipeline. This equipment and support includes valves, compressors, pumps, tanks, rights of way, public signs and line markers as well as periodic pipeline flyovers.

Long-distance pipelines are instrumented at intervals so that the flow can be monitored. The monitoring points, compressor stations and block valves are tied back to a central operations centre. Computers control much of the operation, and manual intervention is necessary only in unusual upsets or emergency conditions. The system has inbuilt redundancies to prevent loss of operational capability if a component fails.

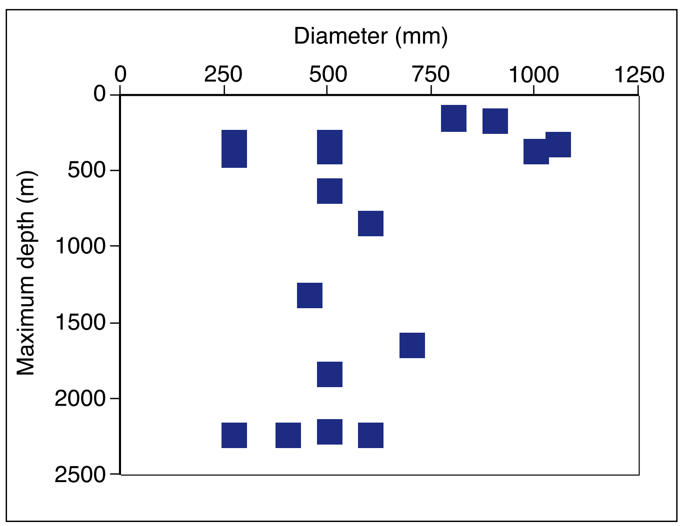


Figure 4.2 Pipelines in deep water.

Pipelines are cleaned and inspected by ‘pigs’, piston-like devices driven along the line by the gas pressure. Pigs have reached a high level of sophistication, and can measure internal corrosion, mechanical deformation, external corrosion, the precise position of the line, and the development of spans in underwater lines. Further functionality will develop as pig technology evolves, and there is no reason why pigs used for hydrocarbon pipelines should not be used for carbon dioxide.

Pipelines are also monitored externally. Land pipelines are inspected from the air, at intervals agreed between the operator and the regulatory authorities. Inspection from the air detects unauthorized excavation or construction before damage occurs. Currently, underwater pipelines are monitored by remotely operated vehicles, small unmanned submersibles that move along the line and make video records, and in the future, by autonomous underwater vehicles that do not need to be connected to a mother ship by a cable. Some pipelines have independent leak detection systems that find leaks acoustically or by measuring chemical releases, or by picking up pressure changes or small changes in mass balance. This technology is available and routine.

4.3 Ships for CO_2 transportation

4.3.1 Marine transportation system

Carbon dioxide is continuously captured at the plant on land, but the cycle of ship transport is discrete, and so a marine transportation system includes temporary storage on land and a loading facility. The capacity, service speed, number of ships and shipping schedule will be planned, taking into consideration, the capture rate of CO_2, transport distance, and social and technical restrictions. This issue is, of course, not specific to the case of CO_2 transport; CO_2 transportation by ship has a number of similarities to liquefied petroleum gas (LPG) transportation by ship.

What happens at the delivery point depends on the CO_2 storage system. If the delivery point is onshore, the CO_2 is unloaded from the ships into temporary storage tanks. If the delivery point is offshore – as in the ocean storage option – ships might unload to a platform, to a floating storage facility (similar to a floating production and storage facility routinely applied to offshore petroleum production), to a single-buoy mooring or directly to a storage system.

4.3.2 Existing experience

The use of ships for transporting CO_2 across the sea is today in an embryonic stage. Worldwide there are only four small ships used for this purpose. These ships transport liquefied food-grade CO_2 from large point sources of concentrated carbon dioxide such as ammonia plants in northern Europe to coastal distribution terminals in the consuming regions. From these distribution terminals CO_2 is transported to the customers either by tanker trucks or in pressurized cylinders. Design work is ongoing in Norway and Japan for larger CO_2 ships and their associated liquefaction and intermediate storage facilities.

4.3.3 Design

For the design of hull and tank structure of liquid gas transport ships, such as LPG carriers and LNG carriers, the International Maritime Organization adopted the International Gas Carrier Code in order to prevent the significant secondary damage from accidental damage to ships. CO_2 tankers are designed and constructed under this code.

There are three types of tank structure for liquid gas transport ships: pressure type, low temperature type and semi-refrigerated type. The pressure type is designed to prevent the cargo gas from boiling under ambient air conditions. On the other hand, the low temperature type is designed to operate at a sufficiently low temperature to keep cargo gas as a liquid under the atmospheric pressure. Most small gas carriers are pressure type, and large LPG and LNG carriers are of the low temperature type. The low temperature type is suitable for mass transport because the tank size restriction is not severe. The semi-refrigerated type, including the existing CO_2 carriers, is designed taking into consideration the combined conditions of temperature and pressure necessary for cargo gas to be kept as a liquid. Some tankers such as semi-refrigerated LPG carriers are designed for applicability to the range of cargo conditions between normal temperature/high pressure and low temperature/atmospheric pressure.

Annex I to this report includes the CO_2 phase diagram. At atmospheric pressure, CO_2 is in gas or solid phase, depending on the temperature. Lowering the temperature at atmospheric pressure cannot by itself cause CO_2 to liquefy, but only to make so-called ‘dry ice’ or solid CO_2. Liquid CO_2 can only exist at a combination of low temperature and pressures well above atmospheric pressure. Hence, a CO_2 cargo tank should be of the pressure-type or semi-refrigerated. The semi-refrigerated type is preferred by ship designers, and the design point of the cargo tank would be around –54 ºC per 6 bar to –50ºC per 7 bar, which is near the point of CO_2. In a standard design, semi-refrigerated type LPG carriers operate at a design point of –50°C and 7 bar, when transporting a volume of 22,000 m^3.

Carbon dioxide could leak into the atmosphere during transportation. The total loss to the atmosphere from ships is between 3 and 4% per 1000 km, counting both boil-off and exhaust from the ship’s engines; both components could be reduced by capture and liquefaction, and recapture onshore would reduce the loss to 1 to 2% per 1000 km.

4.3.4 Construction

Carbon dioxide tankers are constructed using the same technology as existing liquefied gas carriers. The latest LNG carriers reach more than 200,000 m^3 capacity. (Such a vessel could carry 230 kt of liquid CO_2.) The same type of yards that today build LPG and LNG ships can carry out the construction of a CO_2 tanker. The actual building time will be from one to two years, depending on considerations such as the ship’s size.

4.3.5 Operation

4.3.5.1 Loading

Liquid CO_2 is charged from the temporary storage tank to the cargo tank with pumps adapted for high pressure and low temperature CO_2 service. The cargo tanks are first filled and pressurized with gaseous CO_2 to prevent contamination by humid air and the formation of dry ice.

4.3.5.2 Transport to the site

Heat transfer from the environment through the wall of the cargo tank will boil CO_2 and raise the pressure in the tank. It is not dangerous to discharge the CO_2 boil-off gas together with the exhaust gas from the ship's engines, but doing so does, of course, release CO_2 to the air. The objective of zero CO_2 emissions during the process of capture and storage can be achieved by using a refrigeration unit to capture and liquefy boil-off and exhaust CO_2.

4.3.5.3 Unloading

Liquid CO_2 is unloaded at the destination site. The volume occupied by liquid CO_2 in the cargo tanks is replaced with dry gaseous CO_2, so that humid air does not contaminate the tanks. This CO_2 could be recycled and reliquefied when the tank is refilled.

4.3.5.4 Return to port in ballast, and dry-docking

The CO_2 tanker will return to the port for the next voyage. When the CO_2 tanker is in dock for repair or regular inspection, gas CO_2 in cargo tank should be purged with air for safe working. For the first loading after docking, cargo tanks should be fully dried, purged and filled with CO_2 gas.

Ships of similar construction with a combination of cooling and pressure are currently operated for carrying other industrial gases.

4.4 Risk, safety and monitoring

4.4.1 Introduction

There are calculable and perceivable risks for any transportation option. We are not considering perceivable risks because this is beyond the scope of the document. Risks in special cases such as military conflicts and terrorist actions have now been investigated. At least two conferences on pipeline safety and security have taken place, and additional conferences and workshops are planned. However, it is unlikely that these will lead to peer-reviewed journal articles because of the sensitivity of the issue.

Pipelines and marine transportation systems have an established and good safety record. Comparison of CO_2 systems with these existing systems for long-distance pipeline transportation of gas and oil or with marine transportation of oil, yidds that risks should be comparable in terms of failure and accident rates.For the existing transport system these incidents seem to be perceived by the broad community as acceptable in spite of occasional serious pollution incidents such as the *Exxon Valdes* and *Torrey Canyon* disasters (van Bernem and Lubbe, 1997). Because the *consequences* of CO_2 pipeline accidents potentially are of significant concern, stricter regulations for CO_2 pipelines than those for natural gas pipelines currently are in force in the USA.

4.4.2 Land pipelines

Land pipelines are built to defined standards and are subject to regulatory approval. This sometimes includes independent design reviews. Their routes are frequently the subject of public inquiries. The process of securing regulatory approval generally includes approval of a safety plan, of detailed monitoring and inspection procedures and of emergency response plans. In densely populated areas the process of planning, licensing and building new pipelines may be difficult and time-consuming. In some places it may be possible to convert existing hydrocarbon pipelines into CO_2 pipelines.

Pipelines in operation are monitored internally by pigs (internal pipeline inspection devices) and externally by corrosion monitoring and leak detection systems. Monitoring is also done by patrols on foot and by aircraft.

The incidence of failure is relatively small. Guijt (2004) and the European Gas Pipeline Incident Data Group (2002) show that the incidence of failure has markedly decreased. Guijt quotes an incident rate of almost 0.0010 km^{-1} $year^{-1}$ in 1972 falling to below 0.0002 km^{-1} $year^{-1}$ in 2002. Most of the incidents refer to very small pipelines, less than 100 mm in diameter, principally applied to gas distribution systems. The failure incidence for 500 mm and larger pipelines is very much lower, below 0.00005 km^{-1} $year^{-1}$. These figures include all unintentional releases outside the limits of facilities (such as compressor stations) originating from pipelines whose design pressures are greater than 1.5 MPa. They cover many kinds of incidents, not all of them serious, and there is substantial variation between pipelines, reflecting factors such as system age and inspection frequency.

The corresponding incident figures for western European oil pipelines have been published by CONCAWE (2002). In 1997-2001 the incident frequency was 0.0003 km^{-1} yr^{-1}. The corresponding figure for US onshore gas pipelines was 0.00011 km^{-1} yr^{-1} for the 1986-2002 period, defining an incident as an event that released gas and caused death, inpatient hospitalization or property loss of US$ 50,000: this difference in reporting threshold is thought to account for the difference between European and US statistics (Guijt, 2004).

Lelieveld et al. (2005) examined leakage in 2400 km of the Russian natural gas pipeline system, including compressor stations, valves and machine halls, and concluded that '...overall, the leakage from Russian natural gas transport systems is about 1.4% (with a range of 1.0-2.5%), which is comparable with the amount lost from pipelines in the United States (1.5±0.5%)'. Those numbers refer to total leakage, not to leakage per kilometre.

Gale and Davison (2002) quote incident statistics for CO_2

pipelines in the USA. In the 1990-2002 period there were 10 incidents, with property damage totalling US$ 469,000, and no injuries nor fatalities. The incident rate was 0.00032 km^{-1} yr^{-1}. However, unlike oil and gas, CO_2 does not form flammable or explosive mixtures with air. Existing CO_2 pipelines are mainly in areas of low population density, which would also tend to result in lower average impacts. The reasons for the incidents at CO_2 pipelines were relief valve failure (4 failures), weld/gasket/valve packing failure (3), corrosion (2) and outside force (1). In contrast, the principal cause of incidents for natural gas pipelines is outside force, such as damage by excavator buckets. Penetration by excavators can lead to loss of pipeline fluid and sometimes to fractures that propagate great distances. Preventative measures such as increasing the depth of cover and use of concrete barriers above a pipeline and warning tape can greatly reduce the risk. For example, increasing cover from 1 m to 2 m reduces the damage frequency by a factor of 10 in rural areas and by 3.5 in suburban areas (Guijt, 2004).

Carbon dioxide leaking from a pipeline forms a potential physiological hazard for humans and animals. The consequences of CO_2 incidents can be modelled and assessed on a site-specific basis using standard industrial methods, taking into account local topography, meteorological conditions, population density and other local conditions. A study by Vendrig et al. (2003) has modelled the risks of CO_2 pipelines and booster stations. A property of CO_2 that needs to be considered when selecting a pipeline route is the fact that CO_2 is denser than air and can therefore accumulate to potentially dangerous concentrations in low lying areas. Any leak transfers CO_2 to the atmosphere.

If substantial quantities of impurities, particularly H_2S, are included in the CO_2, this could affect the potential impacts of a pipeline leak or rupture. The exposure threshold at which H_2S is immediately dangerous to life or health, according to the National Institute for Occupational Safety and Health, is 100 ppm, compared to 40,000 ppm for CO_2.

If CO_2 is transported for significant distances in densely populated regions, the number of people potentially exposed to risks from CO_2 transportation facilities may be greater than the number exposed to potential risks from CO_2 capture and storage facilities. Public concerns about CO_2 transportation may form a significant barrier to large-scale use of CCS. At present most electricity generation or other fuel conversion plants are built close to energy consumers or sources of fuel supply. New plants with CO_2 capture could be built close to CO_2 storage sites, to minimize CO_2 transportation. However, this may necessitate greater transportation of fuels or electricity, which have their own environmental impacts, potential risks and public concerns. A gathering system would be needed if CO_2 were brought from distributed sources to a trunk pipeline, and for some storage options a distribution system would also be needed: these systems would need to be planned and executed with the same regard for risk outlined here.

4.4.3 Marine pipelines

Marine pipelines are subject to a similar regulatory regime. The incidence of failure in service is again low. Dragging ships' anchors causes some failures, but that only occurs in shallow water (less than 50 m). Very rarely do ships sink on to pipelines, or do objects fall on to them. Pipelines of 400 mm diameter and larger have been found to be safe from damage caused by fishing gear, but smaller pipelines are trenched to protect them. Damage to underwater pipelines was examined in detail at a conference reported on in Morris and Breaux (1995). Palmer and King (2004) examine case studies of marine pipeline failures, and the technologies of trenching and monitoring. Most failures result from human error. Ecological impacts from a CO_2 pipeline accident have yet to be assessed.

Marine pipelines are monitored internally by inspection devices called 'pigs' (as described earlier in Section 4.2.5), and externally by regular visual inspection from remotely operated vehicles. Some have independent leak detection systems.

4.4.4 Ships

Ship systems can fail in various ways: through collision, foundering, stranding and fire. Perrow's book on accidents (1984) includes many thought-provoking case studies. Many of the ships that he refers to were old, badly maintained and crewed by inadequately trained people. However, it is incorrect to think that marine accidents happen only to poorly regulated 'flag-of-convenience' ships. Gottschalch and Stadler (1990) share Perrow's opinion that many marine accidents can be attributed to system failures and human factors, whereas accidents arising as a consequence of purely technical factors are relatively uncommon.

Ship casualties are well summarized by Lloyds Maritime Information Service. Over 22.5 years between 1978 and 2000, there were 41,086 incidents of varying degrees of severity identified, of which 2,129 were classified as 'serious' (See Table 4.2).

Tankers can be seen to have higher standards than ships in general. Stranding is the source of most of the tanker incidents that have led to public concern. It can be controlled by careful navigation along prescribed routes, and by rigorous standards of operation. LNG tankers are potentially dangerous, but are carefully designed and appear to be operated to very high standards. There have been no accidental losses of cargo from LNG ships. The LNG tanker *El Paso Paul Kaiser* ran aground at 17 knots in 1979, and incurred substantial hull damage, but the LNG tanks were not penetrated and no cargo was lost. There is extensive literature on marine transport of liquefied gas, with a strong emphasis on safety, for example, in Ffooks (1993).

Carbon dioxide tankers and terminals are clearly much less at risk from fire, but there is an asphyxiation risk if collision should rupture a tank. This risk can be minimized by making certain that the high standards of construction and operation currently applied to LPG are also applied to carbon dioxide.

An accident to a liquid CO_2 tanker might release liquefied gas onto the surface of the sea. However, consideration of such an event is a knowledge gap that requires further study. CO_2 releases are anticipated not to have the long-term environmental

Table 4.2 Statistics of serious incidents, depending on the ship type.

Ship type	Number of ships 2000	Serious incidents 1978-2000	Frequency (incidents/ship year)
LPG tankers	982	20	0.00091
LNG tankers	121	1	0.00037
Oil tankers	9678	314	0.00144
Cargo/bulk carriers	21407	1203	0.00250

impacts of crude oil spills. CO_2 would behave differently from LNG, because liquid CO_2 in a tanker is not as cold as LNG but much denser. Its interactions with the sea would be complex: hydrates and ice might form, and temperature differences would induce strong currents. Some of the gas would dissolve in the sea, but some would be released to the atmosphere. If there were little wind and a temperature inversion, clouds of CO_2 gas might lead to asphyxiation and might stop the ship's engines.

The risk can be minimized by careful planning of routes, and by high standards of training and management.

4.5 Legal issues, codes and standards

Transportation of CO_2 by ships and sub-sea pipelines, and across national boundaries, is governed by various international legal conventions. Many jurisdictions/states have environmental impact assessment and strategic environmental assessment legislation that will come into consideration in pipeline building. If a pipeline is constructed across another country's territory (e.g. landlocked states), or if the pipeline is laid in certain zones of the sea, other countries may have the right to participate in the environmental assessment decision-making process or challenge another state's project.

4.5.1 International conventions

Various international conventions could have implications for storage of CO_2, the most significant being the UN Law of the Sea Convention, the London Convention, the Convention on Environmental Impact Assessment in a Transboundary Context (Espoo Convention) and OSPAR (see Chapter 5). The Espoo convention covers environmental assessment, a procedure that seeks to ensure the acquisition of adequate and early information on likely environmental consequences of development projects or activities, and on measures to mitigate harm. Pipelines are subject to environmental assessment. The most significant aspect of the Convention is that it lays down the general obligation of states to notify and consult each other if a project under consideration is likely to have a significant environmental impact across boundaries. In some cases the acceptability of CO_2 storage under these conventions could depend on the method of transportation to the storage site. Conventions that are primarily concerned with discharge and placement rather than transport are discussed in detail in the chapters on ocean and geological storage.

The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal came into force in 1992 (UNEP, 2000). The Basel Convention was conceived partly on the basis that enhanced control of transboundary movement of wastes will act as an incentive for their environmentally sound management and for the reduction of the volume of movement. However, there is no indication that CO_2 will be defined as a hazardous waste under the convention except in relation to the presence of impurities such as heavy metals and some organic compounds that may be entrained during the capture of CO_2. Adoption of schemes where emissions of SO_2 and NO_x would be included with the CO_2 may require such a review. Accordingly, the Basel Convention does not appear to directly impose any restriction on the transportation of CO_2 (IEA GHG, 2003a).

In addition to the provisions of the Basel Convention, any transport of CO_2 would have to comply with international transport regulations. There are numerous specific agreements, some of which are conventions and others protocols of other conventions that apply depending on the mode of transport. There are also a variety of regional agreements dealing with transport of goods. International transport codes and agreements adhere to the UN Recommendations on the Transport of Dangerous Goods: Model Regulations published by the United Nations (2001). CO_2 in gaseous and refrigerated liquid forms is classified as a non-flammable, non-toxic gas; while solid CO_2 (dry ice) is classified under the heading of miscellaneous dangerous substances and articles. Any transportation of CO_2 adhering to the Recommendations on the Transport of Dangerous Goods: Model Regulations can be expected to meet all relevant agreements and conventions covering transportation by whatever means. Nothing in these recommendations would imply that transportation of CO_2 would be prevented by international transport agreements and conventions (IEA GHG, 2003a).

4.5.2 National codes and standards

The transport of CO_2 by pipeline has been practiced for over 25 years. Internationally adopted standards such as ASME B31.4, Liquid transportation systems for hydrocarbons, liquid petroleum gas, anhydrous ammonia and alcohols' and the widely-applied Norwegian standard (DNV, 2000) specifically mention CO_2. There is considerable experience in the application and use of these standards. Existing standards and codes vary between different countries but gradual unification of these documents is being advanced by such international bodies as ISO and CEN as part of their function. A full review of relevant standards categorized by issues is presented in IEA GHG, 2003b.

Public concern could highlight the issue of leakage of CO_2 from transportation systems, either by rupture or minor leaks, as discussed in Section 4.4. It is possible that standards may be changed in future to address specific public concerns. Odorants are often added to domestic low-pressure gas distribution systems, but not to gas in long-distance pipelines; they could, in principle, be added to CO_2 in pipelines. Mercaptans, naturally present in the Weyburn pipeline system, are the most effective odorants but are not generally suitable for this application because they are degraded by O_2, even at very low concentrations (Katz, 1959). Disulphides, thioethers and ring compounds containing sulphur are alternatives. The value and impact of odorization could be established by a quantitative risk assessment.

4.6 Costs

4.6.1 Costs of pipeline transport

The costs of pipelines can be categorized into three items

- Construction costs
  - Material/equipment costs (pipe, pipe coating, cathodic protection, telecommunication equipment; possible booster stations)
  - Installation costs (labour)
- Operation and maintenance costs
  - Monitoring costs
  - Maintenance costs
  - (Possible) energy costs
- Other costs (design, project management, regulatory filing fees, insurances costs, right-of-way costs, contingencies allowances)

The pipeline material costs depend on the length of the pipeline, the diameter, the amount of CO_2 to be transported and the quality of the carbon dioxide. Corrosion issues are examined in Section 4.2.2 For costs it is assumed that CO_2 is delivered from the capture system at 10 MPa.

Figure 4.3 shows capital investment costs for pipelines. Investments are higher when compressor station(s) are required to compensate for pressure loss along the pipeline, or for longer pipelines or for hilly terrain. Compressor stations may be avoided by increasing the pipeline diameter and reducing the flow velocity. Reported transport velocity varies from 1 to 5 m s^{-1}. The actual design will be optimized with regard to pipeline diameter, pressure loss (required compressor stations and power) and pipeline wall thickness.

Costs depend on the terrain. Onshore pipeline costs may increase by 50 to 100% or more when the pipeline route is congested and heavily populated. Costs also increase in mountains, in nature reserve areas, in areas with obstacles such as rivers and freeways, and in heavily urbanized areas because of accessibility to construction and additional required safety measures. Offshore pipelines generally operate at higher pressures and lower temperatures than onshore pipelines, and are often, but not always, 40 to 70% more expensive.

It is cheaper to collect CO_2 from several sources into a single pipeline than to transport smaller amounts separately. Early and smaller projects will face relatively high transport costs, and therefore be sensitive to transport distance, whereas an evolution towards higher capacities (large and wide-spread application) may result in a decrease in transport costs. Implementation of a ‘backbone’ transport structure may facilitate access to large remote storage reservoirs, but infrastructure of this kind will require large initial upfront investment decisions. Further study is required to determine the possible advantages of such pipeline system.

Figure 4.4 presents onshore and offshore transport costs versus pipeline diameter; where costs are based on investment cost information from various sources. Figure 4.5 gives a cost window for specific transport as function of the flow. Steel is a cost component for both pipelines and ships, and steel prices doubled in the two years up to 2005: this may be temporary.

4.6.2 Costs of marine transportation systems

Costs of a marine transport system comprise many cost elements. Besides investments for ships, investments are required for loading and unloading facilities, intermediate storage and liquefaction units. Further costs are for operation (e.g. labour, ship fuel costs, electricity costs, harbour fees), and maintenance. An optimal use of installations and ships in the transport cycle is crucial. Extra facilities (e.g. an expanded storage requirement) have to be created to be able to anticipate on possible disruptions in the transport system.

The cost of marine transport systems is not known in detail at present, since no system has been implemented on a scale required for CCS projects (i.e. in the range of several million tonnes of carbon dioxide handling per year). Designs have been submitted for tender, so a reasonable amount of knowledge is available. Nevertheless, cost estimates vary widely, because CO_2 shipping chains of this size have never been built and economies of scale may be anticipated to have a major impact on the costs.

A ship designed for carrying CO_2 from harbour to harbour may cost about 30-50% more than a similar size semi-refrigerated LPG ship (Statoil, 2004). However, since the density of liquid CO_2 is about 1100 kg m^{-3}, CO_2 ships will carry more mass than an equivalent LNG or LPG ship, where the cargo density is about 500 kg m^{-3}. The estimated cost of ships of 20 to 30 kt capacity is between 50 and 70 M$ (Statoil, 2004). Another source (IEA GHG, 2004) estimates ship construction costs at US$ 34 million for 10 kt-sized ship, US$ 60 million with a capacity of 30 kt, or US$ 85 million with a capacity of 50 kt. A time charter rate of about 25,000 US$ day^{-1} covering capital charges, manning and maintenance is not unreasonable for a ship in the 20 kt carrying capacity range.

The cost for a liquefaction facility is estimated by Statoil (2004) at US$ 35 to US$ 50 million for a capacity of 1 Mt per year. The present largest liquefaction unit is 0.35 Mt yr^{-1}.

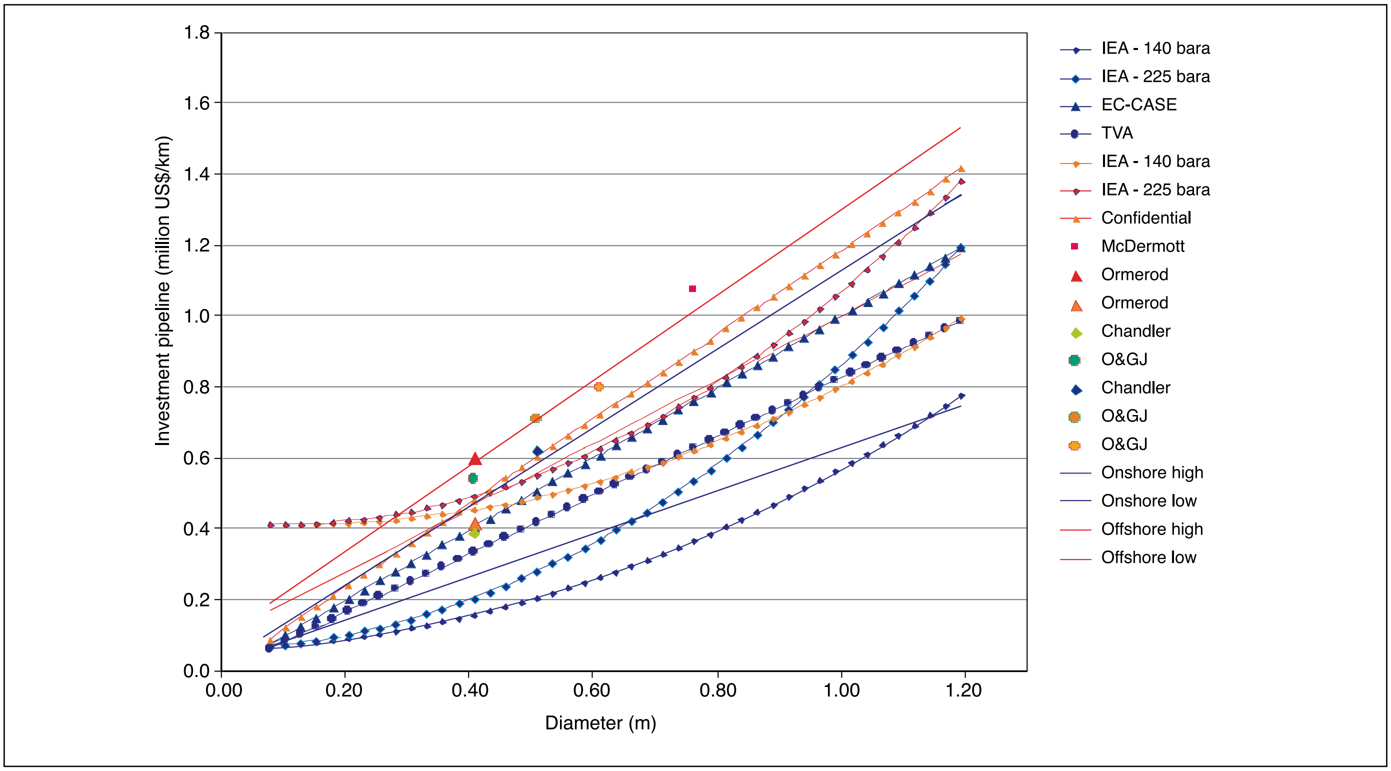


Figure 4.3 Total investment costs for pipelines from various information sources for offshore and onshore pipelines. Costs exclude possible booster stations (IEA GHG, 2002; Hendriks et al., 2005; Bock, 2003; Sarv, 2000; 2001a; 2001b; Ormerod, 1994; Chandler, 2000; O&GJ, 2000).

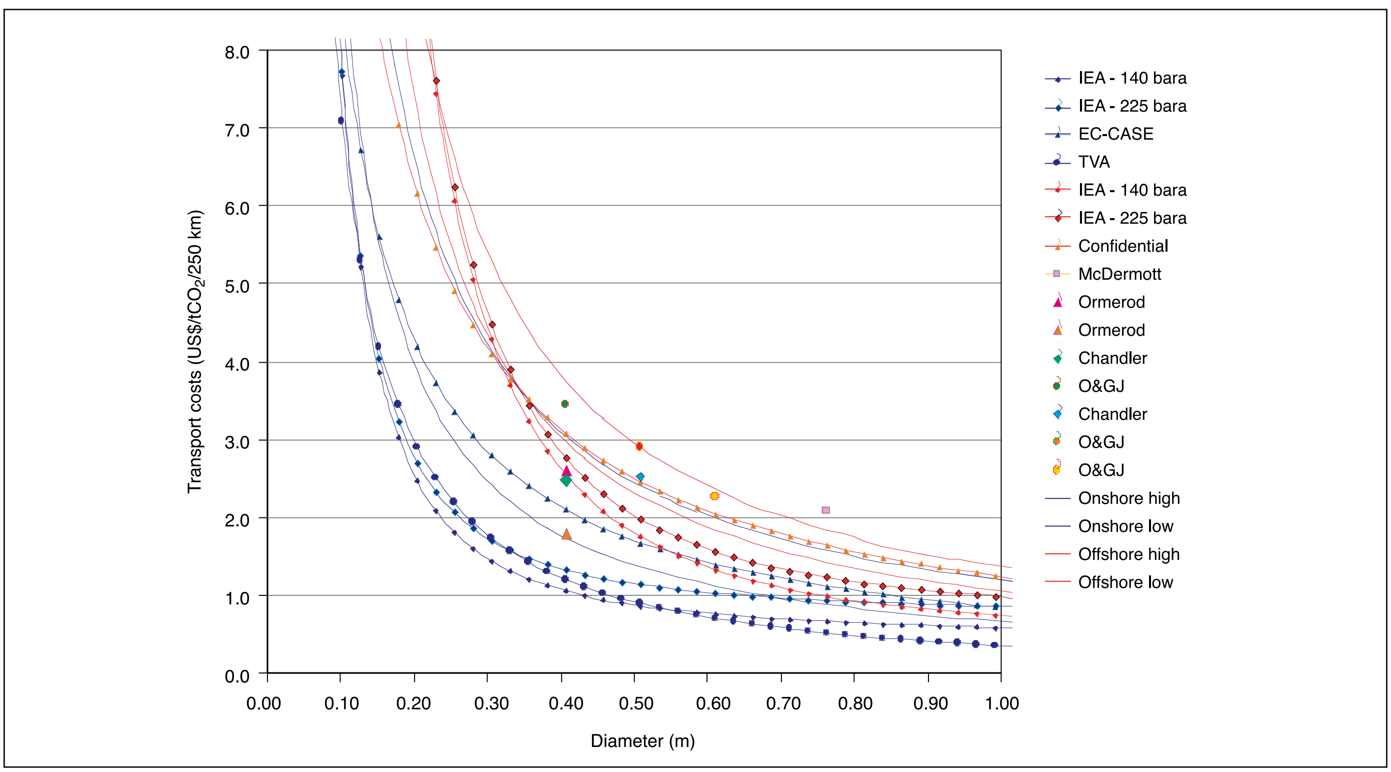


Figure 4.4 Transport costs derived from various information sources for offshore and onshore pipelines. Costs exclude possible booster stations, applying a capital charge rate of 15% and a load factor of 100% (IEA GHG, 2002; Hendriks et al., 2005; Bock, 2003; Sarv, 2000; 2001a; 2001b; Ormerod, 1994; Chandler, 2000; O&GJ, 2000)

IEA GHG (2004) estimates a considerable lower investment for a liquefaction facility, namely US$ 80 million for 6.2 Mt yr^{-1}. Investment costs are reduced to US$ 30 million when carbon dioxide at 100 bar is delivered to the plant. This pressure level is assumed to be delivered from the capture unit. Cost estimates are influenced by local conditions; for example, the absence of sufficient cooling water may call for a more expensive ammonia driven cooling cycle. The difference in numbers also reflects the uncertainty accompanied by scaling up of such facilities

A detailed study (Statoil, 2004) considered a marine transportation system for 5.5 Mt yr^{-1}. The base case had 20 kt tankers with a speed of 35 km h^{-1}, sailing 7600 km on each trip; 17 tankers were required. The annual cost was estimated at US$ 188 million, excluding linquefaction and US$ 300 million, including liquefaction, decreasing to US$ 232 million if compression is allowed (to avoid double counting). The corresponding specific transport costs are 34, 55, and 42 US$ t^{-1}. The study also considered sensitivity to distance: for the case excluding liquefaction, the specific costs were 20 US$ t^{-1} for 500 km, 22 US$ t^{-1} for 1500 km, and 28 US$ t^{-1} for 4500 km.

A study on a comparable ship transportation system carried out for the IEA shows lower costs. For a distance of 7600 km using 30 kt ships, the costs are estimated at 35 US$ t^{-1}. These costs are reduced to 30 US$ $tonne^{-1}$ for 50 kt ships. The IEA study also showed a stronger cost dependency on distance than the Statoil (2004) study.

It should be noted that marine transport induces more associated CO_2 transport emissions than pipelines due to additional energy use for liquefaction and fuel use in ships. IEA GHG (2004) estimated 2.5% extra CO_2 emissions for a transport distance of 200 km and about 18% for 12,000 km. The extra CO_2 emissions for each 1000 km pipelines come to about 1 to 2%.

Ship transport becomes cost-competitive with pipeline transport over larger distances. Figure 4.6 shows an estimate of the costs for transporting 6 Mt yr^{-1} by offshore pipeline and by ship. The break-even distance, i.e. the distance for which the costs per transport mode are the same, is about 1000 km for this example. Transport of larger quantities will shift the break-even distance towards larger distances. However, the cross-over point beyond which ship transportation becomes cheaper than pipeline transportation is not simply a matter of distance alone. It involves many other factors, including loading terminals, pipeline shore crossings, water depth, seabed stability, fuel cost, construction costs, different operating costs in different locations, security, and interaction between land and marine transportation routes.

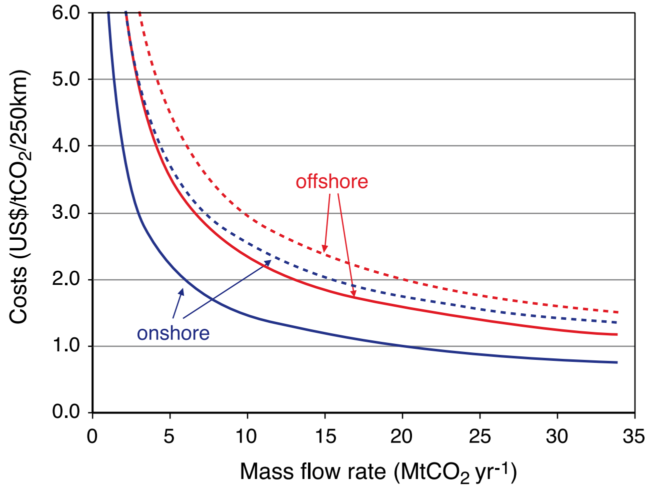


Figure 4.5 Transport costs for onshore and offshore pipelines per 250 km. High (broken lines) and low range (continuous lines) are indicated.

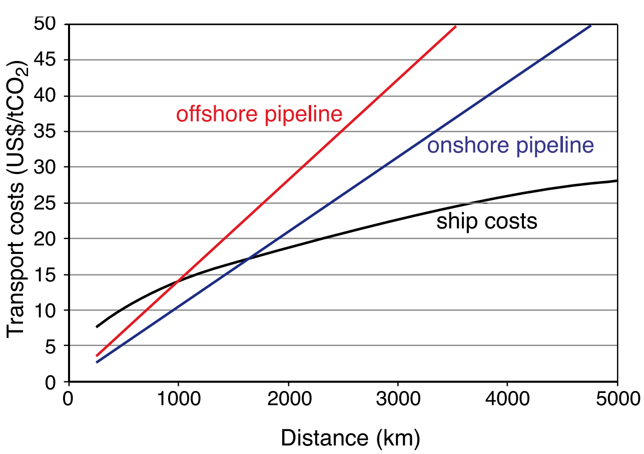


Figure 4.6 Costs, plotted as transportation cost in US$/$tCO_2$ against distance, for onshore and offshore pipelines, and ship transport. The costs include intermediate storage facilities, harbour fees, fuel costs and loading/unloading activities. Costs also include additional costs for liquefaction compared to compression. There is a capital charge factor of 11% for all transport options.

References

Bock, B.R., R. Rhudy, H. Herzog, M. Klett, J. Davison, D.G. de la Torre Ugarte, and D. Simbeck, 2003: Economic Evaluation of CO_2 Storage and Sink Enhancement Options. TVA Public Power Institute, February 2003.

Chandler, H.M. 2000: Heavy Construction Cost Data - 14th Annual Editions. R.S. Means Company, Inc. Kingston, MA, USA.

Concawe, 2002: Western European cross-country oil pipelines 30-year performance statistics, CONCAWE report.

European Gas Pipeline Incident Data Group, 2002: 5th EGIG report 1970-2001 Gas Pipeline Incidents, document EGIG 02.R.0058.

Ffooks, R., 1993: *Natural gas by sea, the development of a new technology.* Royal Institution of Naval Architects, London.

Gale, J. and J. Davison, 2002: Transmission of CO_2 - safety and economic considerations. GHGT-6.

Gottschalch, H. and M. Stadler, 1990: Seefahrtspsychologie (Psychology of navigation). Kasing, Bielefeld.

Guijt, W., 2004: Analyses of incident data show US, European pipelines becoming safer. *Oil and Gas Journal,* January 26, pp.68-73.

Hendriks, C.A., T. Wildenborg, P. Feron, and W. Graus, 2005: Capture and Storage, prepared for EC, DG-ENV, Ecofys Energy and Environment, report nr. M70066.

IEA GHG, 2002: Transmission of CO_2 and Energy, IEA Greenhouse Gas R&D Programme, Report PH4/6, IEA GHG, Cheltenham, UK (March).

IEA GHG, 2003a: Review of International Conventions having Implications for the Storage of Carbon Dioxide in the Ocean and Beneath the Seabed, Report PH4/16, IEA GHG, Cheltenham, UK, 1641 pp.

IEA GHG, 2003b: Barriers to Overcome in Implementation of CO_2 Capture and Storage (2): Rules and Standards for Transmission and Storage of CO_2, Report PH4/23, IEA GHG, Cheltenham, UK, 165 pp.

IEA GHG, 2004: Ship Transport of CO_2, Report PH4/30, IEA GHG, Cheltenham, UK, July 2004-11-16.

Katz, D.L., 1959: Handbook of natural gas engineering. McGraw-Hill, New York, 802 pp.

Lelieveld, J., S. Lechtenböhmer, S.S. Assonov, C.A.M. Brenninkmeijer, C. Dienst, M. Fischedick, and T. Hanke, 2005: Low methane leakage from gas pipelines. *Nature*, **434**, 841-842.

Morris, D. and K. Breaux, 1995: Proceedings of the International Workshop on Damage to Underwater Pipelines, New Orleans, LA, Minerals Management Service.

O&GJ, 2000: Pipeline Economics. *Oil and Gas Journal*, **98**(36), 68-86.

Ormerod, B., 1994: The disposal of carbon dioxide from fossil fuel fired power stations. IEA Greenhouse Gas R&D Programme, Cheltenham, Technical Rep. IEAGHG/SR3, June 1994.

Palmer, A.C. and R.A. King, 2004: Subsea pipeline engineering. Pennwell, Tulsa, OK.

Perrow, C., 1984: Normal accidents. Basic Books, 386 pp.

Rogers, G.F.C. and Y.R. Mayhew, 1980: Engineering thermodynamics and heat transfer. Longman, New York.

Sarv, H. and J. John, 2000: Deep ocean sequestration of captured CO_2. *Technology,* **7S**, 125-135.

Sarv, H., 2001a: Further Technological Evaluation of CO_2 Storage in Deep Oceans. Presented at the 26th International Technical Conference on Coal Utilisation & Fuel Systems, March 5-8, 2001, Clearwater, Florida.

Sarv, H., 2001b: Large-scale CO_2 transportation and deep ocean sequestration - Phase II final report. McDermott Technology Inc., Ohio. Technology Report DE-AC26-98FT40412, 2001.

Seiersten, M., 2001: Material selection for separation, transportation and disposal of CO_2. Proceedings Corrosion 2001, National Association of Corrosion Engineers, paper 01042.

Statoil, 2004: Written communication – O. Kaarstad, Trondheim, Norway, January.

UK Department of Trade and Industry, 2002: Carbon Capture and Storage, report of DTI International Technology Service Mission to the USA and Canada, Advanced Power Generation Technology Forum.

United Nations Environment Programme (UNEP), 2000: Text of the Basel Convention and Decisions of the Conference of the Parties (COP 1 to 5), United Nations Publications, Switzerland.

United Nations, 2001: Recommendations on the Transport of Dangerous Goods: Model Regulations, Twelfth Edition, United Nations Publications ST/SG/AC.10/Rev12, United Nations, New York and Geneva, 732 pp.

Van Bernem, C. and T. Lubbe, 1997: Ől im Meer (Oil in the sea) Wissenschaftliche Buchgesellschaft, Darmstadt.

Vendrig, M., J. Spouge, A. Bird, J. Daycock, and O. Johnsen, 2003: Risk analysis of the geological sequestration of carbon dioxide, Report no. R, Department of Trade and Industry, London, UK.

Veritec, 1988: On-bottom stability design of submarine pipelines. Recommended Practice E305.

West, J.M., 1974: Design and operation of a supercritical CO_2 pipeline-compression system, SACROC unit, Scurry County, Texas. Society of Petroleum Engineers Permian Basin Oil and Gas Recovery Conference, paper SPE 4804.

Energy & Environmental Science

PAPER

View Article Online
View Journal | View Issue

Cite this: *Energy Environ. Sci.*, 2019, **12**, 3567

The health and climate impacts of carbon capture and direct air capture

Mark Z. Jacobson

Data from a coal with carbon capture and use (CCU) plant and a synthetic direct air carbon capture and use (SDACCU) plant are analyzed for the equipment's ability, alone, to reduce CO_2. In both plants, natural gas turbines power the equipment. A net of only 10.8% of the CCU plant's CO_2-equivalent (CO_2e) emissions and 10.5% of the CO_2 removed from the air by the SDACCU plant are captured over 20 years, and only 20–31%, are captured over 100 years. The low net capture rates are due to uncaptured combustion emissions from natural gas used to power the equipment, uncaptured upstream emissions, and, in the case of CCU, uncaptured coal combustion emissions. Moreover, the CCU and SDACCU plants both increase air pollution and total social costs relative to no capture. Using wind to power the equipment reduces CO_2e relative to using natural gas but still allows air pollution emissions to continue and increases the total social cost relative to no carbon capture. Conversely, using wind to displace coal without capturing carbon reduces CO_2e, air pollution, and total social cost substantially. In sum, CCU and SDACCU increase or hold constant air pollution health damage and reduce little carbon before even considering sequestration or use leakages of carbon back to the air. Spending on capture rather than wind replacing either fossil fuels or bioenergy always increases total social cost substantially. No improvement in CCU or SDACCU equipment can change this conclusion while fossil fuel emissions exist, since carbon capture always incurs an equipment cost never incurred by wind, and carbon capture never reduces, instead mostly increases, air pollution and fuel mining, which wind eliminates. Once fossil fuel emissions end, CCU (for industry) and SDACCU social costs need to be evaluated against the social costs of natural reforestation and reducing nonenergy halogen, nitrous oxide, methane, and biomass burning emissions.

Received 24th August 2019,
Accepted 21st October 2019

DOI: 10.1039/c9ee02709b

rsc.li/ees

Broader context

The Intergovernmental Panel on Climate Change concludes that carbon capture and storage/use (CCS/U) and synthetic direct air carbon capture and storage/use (SDACCS/U) are helpful technologies for avoiding 1.5 °C global warming. However, no study has evaluated their performance or social cost compared with merely replacing fossil with renewable electricity. Here, data from CCU and SDACCU equipment powered by natural gas are evaluated. Only 10.8% of the CCU plant's CO_2-equivalent (CO_2e) emissions and 10.5% of the CO_2 removed from the air by SDACCU are captured over 20 years; only 20–31% are captured over 100 years. Moreover, both plants increase air pollution and social cost *versus* no capture. Powering the equipment with wind instead of gas reduces CO_2e but allows the same pollution as and increases the social cost *versus* no capture. Replacing coal with wind (without capture) reduces CO_2e, pollution, and social cost substantially. In sum, spending on capture rather than wind replacing fossil or bioenergy always increases social cost. No improvement in CCU or SDACCU equipment can change this conclusion while fossil emissions exist. Once fossil emissions end, CCU (for industry) and SDACCU social costs must be evaluated against those of reforestation and reducing nonenergy halogen, nitrous oxide, methane, and biomass burning emissions.

Introduction

Carbon capture and storage (CCS) and use (CCU) involve the installation of equipment in a coal, natural gas, oil, or biomass electric power or heat generating facility to remove carbon dioxide (CO_2) from the exhaust and either sequester it underground or in a material (CCS) or sell it for industrial use (CCU).

Synthetic direct air carbon capture and storage (SDACCS) or use (SDACCU) is the removal of CO_2 from the air by chemical reaction. Upon removal, the CO_2 is either sequestered (SDACCS) or sold (SDACCU). SDACCS differs from natural direct air carbon capture and storage (NDACCS), which is the natural removal of carbon from the air by either planting trees or reducing biomass burning.

Department of Civil & Environmental Engineering, Stanford University, Stanford, CA, USA. E-mail: jacobson@stanford.edu

Both CCS/U and SDACCS/U have been proposed as technologies to reduce atmospheric CO_2 and global warming. For example, IPCC[1] states that "capture, utilization, and storage" (CCS/U) can help reduce 75–90% of global CO_2 emissions and that it is "technically proven at various scales." They also identify SDACCS as a method to limit warming to 1.5 °C.

Historically, researchers have assumed CCS/U removes 85–90% of CO_2 exhaust with an energy penalty of ∼25%.[2–4] An energy penalty is the additional electricity required to run the carbon capture equipment per unit electricity produced by the power plant for normal electricity consumption. However, until recently,[5] no public data from a commercial power plant with CCU were available to test these numbers. Similarly, until recently,[6] no data were available to evaluate an operating SDACCU plant. Models have also not evaluated the social cost of air pollution that CCS/U and SDACCS/U increase due to their energy use. Air pollution already kills 4–9 million people worldwide annually.[7] Evaluating the emissions and social (energy plus health, plus climate) cost of any proposed technology is critical given the enormous cost of eliminating world emissions (∼\$100 trillion – Table S9 of ref. 8).

Prior studies have also not evaluated the opportunity cost of using renewable electricity to power CCS/U or SDACCS/U equipment instead of using the renewable electricity to displace fossil fuel power plants. Given limited national budgets, the enormous cost of reducing global air pollution and carbon emissions, and limitations in land areas available in each country to install renewables to replace fossil energy, it is essential to compare the air pollution and carbon emissions of using renewables to power carbon capture equipment with, instead, displacing fossil fuel electricity directly with renewables, thus avoiding emissions in the first place.

Coal-CCU plant

This study first quantifies the carbon dioxide equivalent (CO_2e) emissions from a retrofitted pulverized coal boiler connected to a steam turbine at the W. A. Parish coal power plant near Thompsons, Texas. The plant was retrofitted with carbon capture (CC) equipment as part of the Petra Nova project and began using the equipment during January 2017. The CC equipment (240 MW) receives 36.7 percent of the emissions from the 654 MW boiler. The equipment requires about 0.497 kWh of electricity to run per kWh produced by the coal plant (Table 2, footnote g). A natural gas turbine with a heat recovery boiler was installed to provide this electricity. A cooling tower and water treatment facility were also added. The retrofit cost \$1 billion (\$4200 per kW) beyond the coal plant cost.[9]

CO_2 from the gas turbine is not captured. Natural gas production also has upstream CO_2e emissions, including CH_4 leaks, which are not captured. Upstream CO_2 and CH_4 emissions from the coal plant are also uncaptured. Table 1 shows the January through June CO_2 coal combustion emission data[5] from the plant before (in 2016) and after (in 2017) the addition of the CC equipment. The table also shows the gas combustion emissions from powering the CC equipment. The table then

Table 1 Columns a–d: raw emissions for January through June 2016 and 2017 from the 654 MW (-all-coal) Petra Nova coal-CCU unit.[5] The 2016 data are before carbon capture was added. The 2017 data include combustion CO_2 from the coal plant and, separately, from the natural gas combined cycle turbine installed to run the CC equipment. Columns e–h: emissions (in units of kg-CO_2 per MWh) for the 240 MW (coal-CC) portion of the 654 MW coal unit subject to carbon capture in 2016 and 2017. Column e equals column (a) multiplied by K = 0.4536 kg lb^{-1}. Column f equals $[b - a(1 - F)]K/F$, where b and a are the CO_2 stack emission rates for each month in 2017 (column b) and 2016 (column a), respectively, and F = 0.367 = 240 MW/654 MW is the fraction of the coal unit subject to carbon capture. Column g equals column c multiplied by K/F

	(a) 2016 coal CO_2 no CC lb-CO_2 per MWh-all-coal[5]	(b) 2017 coal CO_2 with CC lb-CO_2 per MWh-all-coal[5]	(c) 2017 gas CO_2 with CC lb-CO_2 per MWh-all-coal[5]	(d) 2017 total CO_2 with CC lb-CO_2 per MWh-all-coal = $b + c$	(e) 2016 coal CO_2 no CC kg-CO_2 per MWh-coal-CC = aK	(f) 2017 coal CO_2 with CC kg-CO_2 per MWh-coal-CC = $[b - a(1 - F)]K/F$	(g) 2017 gas CO_2 with CC kg-CO_2 per MWh-coal-CC = cK/F	(h) 2017 total CO_2 with CC kg-CO_2 per MWh-coal-CC = f + g
Jan	2060	1500	220	1720	934.4	242.2	271.9	514.1
Feb	2110	1615	225	1840	957.1	345.2	278.1	623.3
Mar	2130	1950	60	2010	966.2	743.7	74.2	817.8
Apr	2050	1550	155	1705	929.9	311.8	191.6	503.4
May	2010	1640	160	1800	911.7	454.4	197.8	652.2
Jun	1950	1550	155	1705	884.5	390.1	191.6	581.7
Average	**2052**	**1634**	**163**	**1797**	**930.6**	**414.6**	**200.9**	**615.4**

translates the emissions from the full 654 MW coal unit to the 240 MW portion of the unit subject to CC. When upstream emissions are excluded, the CC equipment captures an average of only 55.4% (Table 2) of coal combustion CO_2 (rather than 90%) and only 33.9% of coal plus gas combustion CO_2.

Table 2 and Fig. 1 expand results from Table 1 to account for upstream emissions from the mining and processing of coal and natural gas. The CC equipment reduces coal and gas combustion plus upstream CO_2 a net of only 10.8% over 20 years (Fig. 1) and 20% over 100 years. 20 years is a relevant time frame to avoid 1.5° global warming and resulting climate feedbacks.[1]

When wind, instead of gas, is used to power the CC equipment, CO_2e decreases by 37.4% over 20 years and 44.2% over 100 years compared with no CC (Table 2 and Fig. 1). The CO_2e decrease exceeds that in the CCU-gas case because wind powering CC equipment case does not result in any combustion or upstream emissions from wind, as seen in Fig. 1.

However, using the wind electricity that powers the CC equipment instead to replace coal electricity directly at the same plant reduces CO_2e by 49.7% compared with no CC (Table 2 and Fig. 1). It is not 100% because only the wind used to run the capture equipment replaces coal. More wind would be needed to replace the whole coal plant. This third strategy is the best for reducing CO_2e among the three cases. Using solar PV to replace coal directly results in a similar benefit as using wind.

But, CO_2e is only part of the story. Because CCU equipment does not capture health-affecting air pollutants, air pollution emissions continue from coal and rise by about 25% compared with no capture from the use of natural gas to run the Petra Nova equipment (Table 2). Even when wind powers the CC equipment, air pollution from the coal plant continues as before (but not from using the new wind turbine). Only when wind partially replaces the use of coal itself does air pollution decrease by $\sim$50% (Table 2).

The equipment cost of new coal and wind electricity in the U.S. are a mean of \$102 per MWh and \$42.5 per MWh, respectively.[10] The capital cost of CC equipment, \$4200 per kW,[9] is about 74% the capital cost of a new coal plant (\$5700 per kW),[10] suggesting that new coal plus CCU is 1.74 × \$102 per MWh/\$42.5 per MWh = 4.2 times the equipment cost of new wind. Since CC equipment reduces only 10.8% of coal CO_2e over 20 year and 20% over 100 year, the equipment for coal-CCU powered by natural gas alone costs 39 and 21 times that of wind-replacing coal per mass-CO_2 removed over 20 and 100 years, respectively.

Major additional social costs associated with coal electricity generation are air pollution and climate costs. The health cost of coal emissions in the U.S. is calculated as a mean of \$80 per MWh, which is much lower than the world average (\$169 per MWh, Table 2, footnote m). Since the use of CC equipment requires 50% more electricity than the coal plant produces but the health cost of natural gas emissions are about half those of coal, the use of gas to run the CC equipment increases health costs by $\sim$25% compared with no capture (Table 2, row o). Mean climate costs of U.S. emissions are estimated as \$152 per MWh, close to the world mean of \$160 per MWh (Table 2, footnote m). CC equipment with natural gas is estimated to reduce this cost by only 10.8% and 20% over 20 and 100 years, respectively (Table 2, row n).

In sum, the total social cost (equipment plus health plus climate cost) of coal-CCU powered by natural gas is over twice that of wind replacing coal directly (Table 2 and Fig. 1). Moreover, the social cost of coal with CC powered by natural gas is 24% higher over 20 years and 19% higher over 100 years than coal without CC. Thus, no net social benefit exists of using CC equipment. In other words, from a social cost perspective, using CC equipment powered by natural gas causes more damage than does doing nothing at all.

When wind powers CC equipment, the social costs are still 6% and 2% higher over 20 and 100 years, respectively, than not using CC (Table 2 and Fig. 1). Although wind-powering-CC decreases CO_2e, thus climate cost, compared with coal without CC, wind-CC allows the same air pollution emissions from coal as no CC, and the cost of the wind plus CC equipment outweighs the CO_2e cost reduction (Fig. 1).

Only when wind replaces coal electricity production directly does the total social cost drop 43% compared with no CC (Table 2). This is the best scenario. A similar benefit occurs if wind replaces natural gas and no CC is used.

Some may argue that (a) the six months of data with *versus* without the CC equipment are insufficient for drawing conclusions about this plant and (b) future plants may improve upon the Petra Nova plant. Whereas both points are valid, in order for the social cost of using the CC equipment powered by natural gas to be less than that of doing nothing, the CO_2e reemitted by the Petra Nova plant would need to be 37% or less instead of 89.8% over 20 years. However, this is all but impossible, because 59.2% of the re-emissions is due to upstream coal and gas emissions and natural gas combustion emissions, so little to do with how effective the CC equipment is at capturing carbon. In other words, even if the CC equipment captured 100% of the stack CO_2, which no-one is proposing is feasible, the reemissions would still be 59.2%. This is because controlling 100% of the coal stack emissions can reduce only 40.8% of the total upstream plus stack coal emissions due to the additional upstream and combustion emissions of the gas plant over a 20 year time frame. As such, the data indicate that no technological improvement will result in the social cost of using CC equipment powered by natural gas being less than that of not using the equipment.

When CC is powered by wind, it is theoretically possible, albeit challenging, to reduce the total social cost below that of no CC. However, it is impossible to reduce the total social cost below that of wind replacing coal electricity directly because wind-powering-CC also incurs a CC equipment cost and never reduces air pollution or mining from coal, whereas wind replacing coal incurs no CC equipment cost and eliminates coal air pollution and mining.

SDACCU plant

This section evaluates the efficiency of CO_2 removal from the air by an SDACCU facility,[6] where electricity for the air capture

Table 2 Comparison of relative CO_2e emissions, electricity use, and electricity social costs among three scenarios related to the Petra Nova coal-CCU facility, each over a 20 year and 100 year time frame. The first scenario is using natural gas to power the carbon capture (CC) equipment. This is based on data from the Petra Nova facility (Table 1). The second scenario is running the CC equipment with onshore wind instead of natural gas. The third is using the same quantity of wind electricity required to run the CC equipment to instead replace coal electricity from the coal plant. In all cases, the additional energy required to run the CC equipment is equivalent to 49.7% of the energy output of the coal plant (footnote g). The coal plant has a nameplate capacity of 654 MW, but only 240 MW (36.7%) is subject to CC. The numbers in the table are all based on the portion subject to CC. All emission units (including of natural gas emissions) are g-CO_2e per kWh-coal-electricity-generation

	Coal with gas-powered CC 20 year	Coal with gas-powered CC 100 year	Coal with wind-powered CC 20 year	Coal with wind-powered CC 100 year	Wind used for CC replacing coal + remaining coal 20 year	Wind used for CC replacing coal + remaining coal 100 year
(a) Upstream CO_2 from coal[a]	97.2	97.2	97.2	97.2	48.9	48.9
(b) Upstream CO_2e of leaked CH_4 from coal[b]	353	140	353	140	177.6	70.4
(c) Coal stack CO_2 before capture[c]	930.6	930.6	930.6	930.6	468.1	468.1
(d) Total coal CO_2e before capture (a + b + c)	1381	1168	1381	1168	695	587
(e) Remaining stack CO_2 after capture[d]	414.6	414.6	414.6	414.6	—	—
(f) CO_2 captured from stack (c–e)	516.0	516	516	516	—	—
(g) Percent stack CO_2 captured (f/c)	55.4	55.4	55.4	55.4	—	—
(h) CO_2 emissions gas combustion[e]	200.9	200.9	0	0	0	0
(i) Upstream CO_2e of CH_4 from gas leaks[f]	139.2	55.03	0	0	0	0
(j) Upstream CO_2 from gas mining, transport[g]	26.85	26.85	0	0	0	0
(k) Total CO_2e emissions (a + b + e + h + i + j)	1,232	934.5	865	652	695	587
(l) Percent of coal CO_2e re-emitted (k/d)[h]	**89.2**	**80.0**	**62.6**	**55.8**	**50.3**	**50.3**
(m) Percent of coal CO_2e captured (100-l)	**10.8**	**20**	**37.4**	**44.2**	**49.7**	**49.7**
(n) Relative CO_2e to original (l/100)[i]	0.892	0.80	0.626	0.558	0.503	0.503
(o) Relative air pollution to original[j]	1.25	1.25	1.0	1.0	0.503	0.503
(p) Energy required relative to original[k]	1.497	1.497	1.497	1.497	1	1
(q) Private energy cost per kWh relative to original[l]	1.74	1.74	1.74	1.74	0.71	0.71
(r) Social cost before changes ($ per MWh)[m]	334	334	334	334	334	334
(s) Social cost after changes ($ per MWh)[n]	413	399	353	342	189	189
(t) Social cost ratio (s/r)	1.24	1.19	1.06	1.02	0.57	0.57

[a] Coal upstream emissions are estimated as 27 g-CO_2 per MJ = 97.2 g-CO_2 per kWh.[11] Upstream emissions include emissions from fuel extraction, fuel processing, and fuel transport. Upstream CO_2 emissions (from the portion of the coal plant not replaced) for the wind-replacing some coal cases (last two columns) are the same as in the other cases, but multiplied by 0.503, which equals 1 minus the fraction of coal electricity used to run the carbon capture equipment, which is derived in footnote g. Since the electricity used to run the CC equipment is used to replace coal in this case, upstream coal emissions are reduced accordingly. [b] For coal, the 100 year CO_2e from CH_4 leaks is estimated from (ref. 12, slide 17). The emission factor is derived from that number and the 100 year GWP of CH_4, 34 from ref. 13. The 20 year CO_2e is then derived from the resulting emission factor (4.1 g-CH_4 per kWh) and the 20 year GWP of CH_4, 86. Emissions in the wind cases are reduced as described under footnote a. [c] The average coal stack emission rate for the Petra Nova facility in 2016, prior to the addition of CC equipment, is from Table 1, column e. In the wind-replacing-coal cases (last two columns), the emission rate is reduced as described under footnote a. [d] The coal-stack CO_2 remaining after capture is from Table 1, column f. [e] The natural gas combustion emissions resulting from powering the CC equipment is from Table 1, column g. [f] Natural gas upstream leaks are obtained by dividing the raw emission rate of CO_2 from natural gas for each month January through June 2017 from Table 1 (in kg-CO_2 per MWh-coal-electricity) by the molecular weight of CO_2 (44.0098 g-CO_2 per mol) to give the moles of natural gas burned per MWh-coal-electricity. Multiplying the moles burned per MWh by the fractional number of moles burned that are methane (0.939)[14] and the molecular weight of methane (16.04276 g-CH_4 per mol) gives the mass intensity of methane in the natural gas burned each month (kg-CH_4-burned per MWh-coal-electricity). The upstream leakage rate of methane is then the kg-CH_4-burned per MWh-coal-electricity multiplied by $L/(1 - L)$, where $L = 0.023$ is the fraction of all methane produced (from conventional and shale rock sources) that leaks,[15] giving the methane leakage rate in kg-CH_4 per MWh-coal-electricity. This leakage rate is conservative based on a more recent full-lifecycle leakage rate estimate of methane from shale rock alone of $L = 0.035$.[16] Using the latter estimate would result in CCS/U with natural gas re-emitting even more CO_2e than calculated here. Multiplying the kg-CH_4 per MWh-coal-electricity by the 20- and 100 year GWPs of CH_4 (86 and 34, respectively)[13] gives the CO_2e emission rate of methane leaks each month. The monthly values are linearly averaged over January through June 2017. [g] The non-CH_4 upstream CO_2e emissions rate is estimated as 15 g-CO_2 per MJ-gas-electricity = 54 g-CO_2 per kWh-gas-electricity.[11] Multiplying that by 0.497 MWh-electricity from natural gas per MWh-coal-electricity produced gives 26.8 kg-CH_4 per MWh-coal-electricity. 0.497 MWh-electricity from natural gas per MWh-coal-electricity produced, or 49.7%, is calculated by dividing the average gas combustion emission from Petra Nova (200.9 g-CO_2 per kWh-coal from the present table) by the combustion emissions per unit electricity from a combined cycle gas plant (404 g-CO_2 per kWh-natural-gas). [h] The percent CO_2 reemitted for the wind cases (last two columns) equals row k for the wind cases divided by row d for either of the non-wind cases. [i] CO_2e emissions relative to coal with no CC equipment. [j] Air pollution emissions relative to coal with no CC equipment. In the natural gas cases, all air pollution from coal emissions still occurs. Although gas is required to produce 0.497 MWh of electricity for the CC equipment per MWh of coal electricity, gas is assumed to be 50% cleaner than coal, so the overall air pollution in this case increases only 25% relative to the no CC case. In the wind-CC cases, all upstream and combustion emissions from coal still occur. [k] The electricity required (for end-use consumption plus to run the CC equipment) in all CC cases is 49.7% higher than with no CC. In the wind-replacing coal case, no electricity is needed to run the CC equipment, but electricity is still needed for end use. [l] The private energy cost in all CC cases is assumed to be 74% higher than coal with no CC because the CC equipment (including the gas plant) costs $4200 per kW, which represents about 74% of the mean capital cost of a new coal plant ($5700 per kW) from.[10] For simplicity, it was assumed that the cost of a wind turbine running the CC equipment was the same as of a gas turbine running the equipment. In the wind-replacing-coal cases, the cost of coal was assumed to be a mean of c = $102 per MWh and of wind, w = $42.5 per MWh.[10] The final ratio was calculated as $(0.503c + 0.497w)/c$. [m] The social cost before changes is the private energy cost of new coal without CCU [$102 per MWh from ref. 10] plus air pollution mortality, morbidity, and non-health environmental costs of coal power plant emissions in the U.S. plus the global climate costs of U.S. emissions ($152 per MWh).[18] U.S. coal power plant emissions health costs are estimated as $80 per MWh, which is twice the background grid health cost of $40 per MWh.[17] In the worldwide average, from the same source, the health cost of background grid emissions is estimated as $169 per MWh, so use of the U.S. number here is likely to underestimate the health costs of using carbon capture outside the U.S. [n] The social cost after changes is the sum of the private energy cost multiplied by row q, the air pollution health cost multiplied by row o, and the climate cost multiplied by row n.

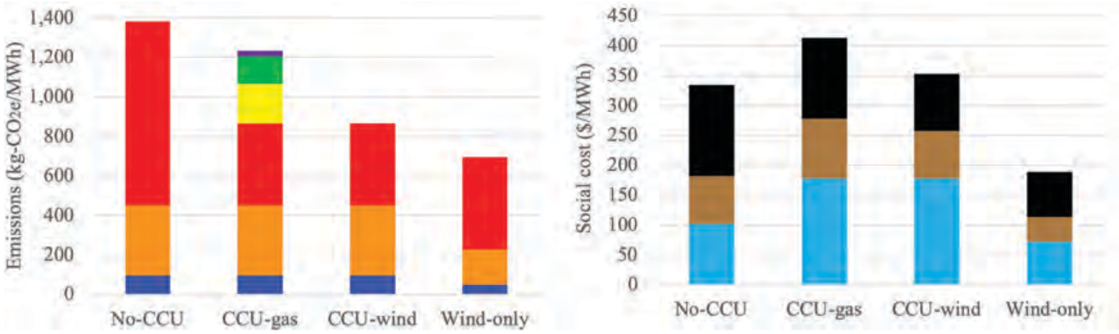


Fig. 1 Left: CO_2e emissions, averaged over 20 years, from the Petra-Nova coal plant before (No-CCU) and after (CCU-gas) the addition of CCU equipment powered by natural gas. Also shown are emissions when the CCU equipment is powered by wind energy (CCU-wind) and when the portion of wind energy used to power the CCU equipment is instead used only to replace a portion of the coal power (thus some power is generated by coal and some by wind). Blue is upstream CO_2e from coal mining and transport aside from CH_4 leaks; orange is upstream CO_2e from coal mining CH_4 leaks; red is coal combustion CO_2; yellow is natural gas combustion CO_2; green is CO_2e from natural gas mining and transport CH_4 leaks; and purple is natural gas mining and transport CO_2e aside from CH_4 leaks. Right: Mean estimate of social costs per unit electricity over 20 years generated by the coal plant (in the first three cases) or the residual coal plant plus replacement wind plant (fourth case) for each of the four cases shown on the left. Light blue is the cost of electricity generation plus CCU equipment; brown is air pollution health cost; and black is 20 year climate cost. All data are from Table 2.

(AC) equipment is provided by a natural gas combined cycle turbine.

Table 3 indicates that, averaged over 20 and 100 years, 89.5% and 69%, respectively, of all CO_2 captured by the AC equipment is returned to the air as CO_2e. The emissions come from mining, transporting, processing, and burning the natural gas used to power the equipment.

In comparison with taking no action, using SDACCU equipment powered by natural gas also increases air pollution due to the combustion and upstream emissions associated with natural gas. With no action, SDACCU further incurs an equipment cost. Thus, although SDACCU powered by natural gas reduces some CO_2e, the equipment cost and air pollution cost far outweigh that decrease, resulting in a near doubling of the total social cost per MWh of electricity use relative to the health and climate cost per MWh of coal power plant emissions (Fig. 2).

Even when zero re-emissions occur, such as when wind powers the SDACCU equipment, the mean social cost of using SDACCU still exceeds that of doing nothing (Fig. 2). On the other hand, using wind to replace coal electricity instead of to run the AC equipment eliminates CO_2e and air pollution emissions and their associated costs from the coal. The resulting social cost is ~15% of that from wind powering SDACCU equipment (Table 3 and Fig. 2). A similar result is found when wind replaces a natural gas plant instead of a coal plant. In fact, there is no case where wind powering an SDACCU plant has a social cost below that of wind replacing any fossil fuel or bioenergy power plant directly. The reasons are that wind-powering-SDACCU always incurs an SDACCU equipment cost that wind alone never incurs and SDACCU always allows air pollution and mining to continue whereas wind always eliminates air pollution and mining.

Discussion

Tables 1–3 suggest virtually no carbon benefit of and greater air pollution damage from CCS/U and SDACCS/U before considering the disposition of the captured CO_2.

Three reasons this result has not been identified previously, aside from the lack of data, are that previous studies and models did not consider upstream fossil emissions, the air pollution social cost resulting from the additional energy needs, or the higher fossil emissions due to using renewable electricity for CC or AC equipment instead of to displace fossil electricity. Air pollutants not captured by CC or AC equipment from fossil or bioenergy plants include CO, NO_x, SO_2, organic gases, mercury, toxins, black and brown carbon, fly ash, and other aerosol components.

Ref. 4 found that even after assuming 90% capture by equipment (and ignoring upstream and combustion emissions to run the capture equipment), renewables return better on investment than CC. The results here suggest that a specific coal-CCU plant reduces only 10.5% and 20% of the plant's overall CO_2e over 20 and 100 years, respectively, while increasing air pollution and land degradation (from additional mining). More than half the re-emissions are due to upstream coal and gas emissions and natural gas combustion emissions to run the CC equipment. In addition, CC always incurs an equipment cost and never reduces air pollution, whereas renewables have no such equipment costs and always reduce air pollution. For all these reasons, renewables replacing fossil fuels or bioenergy are a lower social-cost investment to address climate than even[4] found.

SDACCS/U powered by natural gas similarly increases air pollution by increasing fossil energy consumption and upstream mining. Clean electricity used to run SDACCS/U equipment does not increase air pollution but keeps it the same. However, the social cost of using that clean electricity to replace fossil fuels or bioenergy is always lower than the social cost of using the electricity to run SDACCS/U equipment. The reasons are that SDACCU equipment always incurs a cost that renewables never incur and SDACCU always allows air pollution and fuel mining to continue, whereas renewables eliminate air pollution and fuel mining.

The results here are independent of the fate of the CO_2 after it leaves the CC equipment, thus apply to CC with bioenergy (*e.g.*, BECCS/U) or cement manufacturing. The CC equipment

Table 3 Comparison of relative CO_2e emissions, electricity private costs, and electricity social costs among three scenarios related to the carbon engineering SDACCU plant, each over a 20 year and 100 year time frame. The first scenario is using an on-site natural gas (NG) combined cycle turbine to power the direct air capture (DAC) equipment. The DAC equipment does not capture the gas emissions; if it did, the results would be the same, since if the equipment captured turbine CO_2 emissions, it would not capture the equivalent CO_2 from the air. The third scenario involves using the same wind turbine electricity to instead replace coal power generation without using AC equipment. All emission units (rows a–f, i) are kg-CO_2e per MWh

	DAC with NG elec. 20 year	DAC with NG elec. 100 year	DAC with wind elec 20 year	DAC with wind elec. 100 year	Wind replacing coal 20 year	Wind replacing coal 100 year
(a) SDACCU removal from air[a]	825	825	825	825	—	—
(b) CO_2 emissions combined cycle gas turbine[b]	404	404	—	—	—	—
(c) Upstream CO_2e of CH_4 from gas leaks[c]	280	111	—	—	—	—
(d) Upstream CO_2 from gas mining, transport[d]	54	54	—	—	—	—
(e) Emission reduction due to replacing coal with wind[e]	0	0	0	0	−1381	−1168
(f) All emissions (b + c + d + e)	738	569	0	0	−1381	−1168
(g) Percent CO_2 returned (f/a)	**89.5**	**68.9**	**0**	**0**	—	—
(h) Percent CO_2 captured (100-g)	**10.5**	**31.1**	**100**	**100**	—	—
(i) Absolute emission reduction (a–f)	87	256	825	825	1381	1168
(j) Low SDACCU (\$ per tonne-CO_2-removed)[a]	94	94	94	94	—	—
(k) High SDACCU (\$ per tonne-CO_2-removed)[a]	232	232	232	232	—	—
(l) Low private electricity cost (aj/1000) (\$ per MWh)[f]	78	78	78	78	29	29
(m) High private electricity cost (ak/1000) (\$ per MWh)[f]	191	191	191	191	56	56
(n) Health cost of background grid (\$ per MWh)[g]	40	40	40	40	40	40
(o) Ratio health cost of scenario to of background grid[h]	3	3	2	2	0	0
(p) Health cost of scenario (no) (\$ per MWh)	120	120	80	80	0	0
(q) Climate cost of background grid (\$ per MWh)[i]	152	152	152	152	152	152
(r) Ratio climate cost of scenario to of background grid[j]	0.937	0.781	0.403	0.294	0	0
(s) Climate cost of scenario (qr) (\$ per MWh)	142	119	61.2	44.6	0	0
(t) Low social cost (\$ per MWh) (l + p + s)	340	316	219	202	29	29
(u) High social cost (\$ per MWh) (m + p + s)	454	430	333	316	56	56
(v) Low social cost ratio (row t-SDACCU/u-wind)	6.1	5.6	3.9	3.6	—	—
(w) High social cost ratio (row u-SDACCU/t-wind)	15.6	14.8	11.5	10.9	—	—

[a] Ref. 6. Assumes values for DAC with wind electricity are the same as DAC with natural gas electricity. [b] Ref. 19. [c] Same methodology as in Table 2, footnote f, but using the CO_2 combustion emissions from row (b) here. [d] Ref. 11. [e] Assumes wind that would otherwise be used to run the SDACCU equipment instead directly replaces coal electricity, its upstream CO_2 combustion, its upstream CH_4 leaks, and its stack combustion CO_2 emissions. The overall emission rates from coal are obtained from Table 2, row d. [f] Low and high wind electricity costs for wind-replacing coal are from.[10] Others are from the formula provided. [g] The U.S. health cost of \$40 per MWh for the background grid per MWh is from ref. 17. [h] The ratio of the health cost in the scenario to that of the background grid is defined as zero for the wind-replacing coal case, since wind produces zero emissions during its operation. In comparison, wind running SDACCU equipment allows those coal emissions, which are about twice background grid emissions per unit energy, to continue, so the factor in that scenario is 2. Natural gas running SDACCU equipment not only allows those coal emissions to continue, but it also produces 50% more emissions, assumed equal to background grid emissions per MWh, so the factor in that scenario is 3. [i] The U.S. climate cost of \$152 per MWh for the background grid is from ref. 17 and 18. [j] The ratio of the climate cost of the scenario to that of the background grid is defined as zero for the wind-replacing coal case, since wind produces zero emissions during its operation. For the other cases, it is simply the absolute CO_2e emission reduction in the case minus that in the wind case all divided by that in the wind case, where all values are from row i.

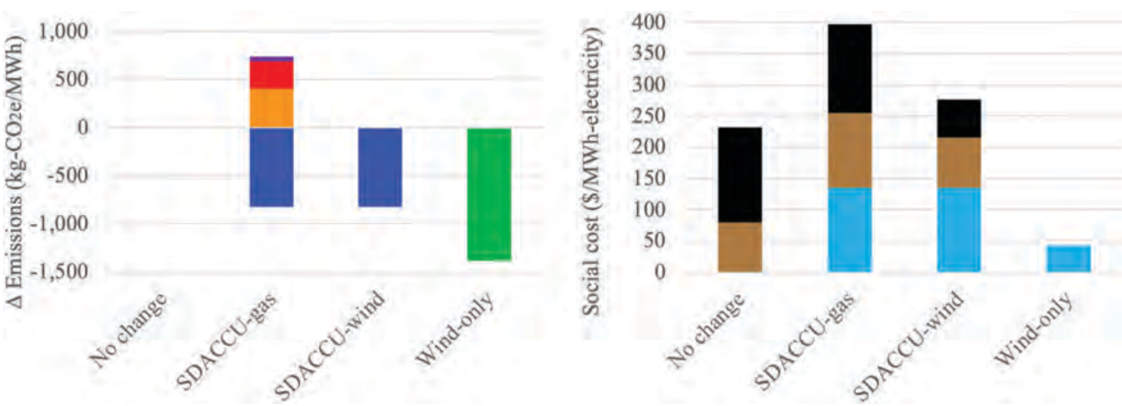


Fig. 2 Left: Change in CO_2e emissions, averaged over 20 years, per unit electricity needed to run SCACCU equipment resulting from either no action (no-change), using an SDACCU plant with equipment powered by natural gas (SDACCU-gas), using an SDACCU plant with equipment powered by wind (SDACCU-wind), and using the same quantity of wind required to run the SDACCU equipment but to replace coal power directly (wind-only). Blue is the removal of CO_2 from the air by the SDACCU equipment; orange is the natural gas turbine emissions; red is the CO_2e from natural gas mining and transport CH_4 leaks; purple is natural gas mining and transport CO_2e aside from CH_4 leaks; and green is the CO_2e emission reduction due to replacing coal power with wind power. Right: Mean estimate of social costs per unit electricity over 20 years for each of the four cases shown on the left. Light blue is the cost of equipment (either air capture equipment plus gas turbine, air capture equipment plus wind turbine, or wind turbine alone); brown is air pollution health cost; and black is 20-year climate cost. All data are from Table 3, except that the costs in the no-change case are the health and climate costs of coal power plant emissions (\$80 per MWh health cost and \$152 per MWh climate cost – Table 2, footnote m). Such emissions costs are used as the background because the wind-only case removes such emissions.

always requires energy. If the energy comes from a fossil fuel, mining and combustion emissions from the fuel cancel most CO_2 captured. If it comes from a renewable, total social costs are still always greater than using the renewable to replace fossil fuels or bioenergy directly.

When the fate of captured CO_2 is considered, the problem may deepen. If CO_2 is sealed underground without leaks, little added emissions occur. If the captured CO_2 is used to enhance oil recovery, its current major application, more oil is extracted and burned, increasing combustion CO_2, some leaked CO_2, and air pollution. If the captured CO_2 is used to create carbon-based fuel to replace gasoline and diesel, energy is still required to produce the fuel, the fuel is still burned in vehicles (creating pollution), and little CO_2 is captured to produce the fuel with. A third proposal is to use the CO_2 to produce carbonated drinks. However, along with the issues previously listed, most CO_2 in carbonated drinks is released to the air during consumption. In addition, the quantity of CO_2 needed for carbonated drinks is small compared with the CO_2 released by fossil fuels globally.

Another argument for using SDACCS/U is that it will be needed for removing CO_2 from the air once all fossil fuels are replaced with renewables. If renewables are then used to power SDACCS/U they can reduce CO_2 without incurring an air pollution cost. However, the question at that point is whether growing more trees, reducing biomass burning, or reducing halogen, nitrous oxide, and non-energy methane emissions is a more cost-effective method of limiting global warming.

In sum, SDACCS/U and CCS/U are opportunity costs, not close to zero-carbon technologies. For the same energy cost, wind turbines and solar panels reduce much more CO_2 while also reducing fossil air pollution and mining, pipelines, refineries, gas stations, tanker trucks, oil tankers, coal trains, oil spills, oil fires, gas leaks, gas explosions, and international conflicts over energy. CCS/U and SDACCS increase these by increasing energy use and always increase total social costs relative to using renewables to eliminate fossil fuel and bioenergy power generation directly.

Author contributions

M. Z. J. performed the research and wrote the paper.

Data and materials availability

Virtually all data are provided within the paper and references therein but any data not provided may be obtained from the author.

Conflicts of interest

Author declares no competing interests.

Acknowledgements

This paper was not funded by any entity.

Notes and references

1 IPCC (Intergovernmental Panel on Climate Change), Special report: Global warming of 1.5°, https://www.ipcc.ch/sr15/, 2018.
2 *IPCC (Intergovernmental Panel on Climate Change), IPCC special report on carbon dioxide capture and storage. Prepared by working group III*, ed. B. Metz, O. Davidson, H. C. de Coninck, M. Loos and L. A. Meyer, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2005, p. 442.
3 M. Z. Jacobson, Review of solutions to global warming, air pollution, and energy security, *Energy Environ. Sci.*, 2009, **2**, 148–173.
4 S. Sgouridis, M. Carbajales-Dale, D. Csala, M. Chiesa and U. Bardi, Comparative net energy analysis of renewable electricity and carbon capture and storage, *Nat. Energy*, 2019, **4**, 456–465.
5 EIA, (U.S. Energy Information Administration), https://www.eia.gov/todayinenergy/detail.php?id=33552, 2017.
6 D. W. Keith, G. Holmes, D. S. Angelo and K. Heidel, A process for capturing CO_2 from the atmosphere, *Joule*, 2018, **2**, 1573–1594.
7 WHO (World Health Organization), https://www.who.int/gho/phe/outdoor_air_pollution/en/, 2017.
8 M. Z. Jacobson, M. A. Delucchi, M. A. Cameron and B. V. Mathiesen, Matching demand with supply at low cost among 139 countries within 20 world regions with 100% intermittent wind, water, and sunlight (WWS) for all purposes, *Renewable Energy*, 2018, **123**, 236–248.
9 Scottmadden, https://www.scottmadden.com/insight/billion-dollar-petra-nova-coal-carbon-capture-project-financial-success-unclear-can-replicated/, 2017.
10 Lazard, https://www.lazard.com/media/450784/lazards-levelized-cost-of-energy-version-120-vfinal.pdf, 2018.
11 R. W. Howarth, A bridge to nowhere: methane emissions and the greenhouse gas footprint of natural gas, *Energy Sci. Eng.*, 2014, **2**, 47–60.
12 T. J. Skone, Lifecycle greenhouse gas emissions: Natural gas and power production. EIA Energy Conference, Washington DC, June 15, 2015, https://www.eia.gov/conference/2015/pdf/presentations/skone.pdf, 2015.
13 G. Myhre, D. Shindell and F.-M. Breon, *et al.*, Anthropogenic and Natural Radiative Forcing, in *Climate Change: The Physical Science Basis. Contribution of Working Group I to the Fifth-Assessment Report of the Intergovernmental Panel on Climate Change*, ed. T. F. Stocker, *et al.*, Cambridge University Press, Cambridge, UK and NY, USA, 2013.
14 Union Gas, https://www.uniongas.com/about-us/about-natural-gas/chemical-composition-of-natural-gas, 2018.
15 R. A. Alvarez, D. Zavalao-Araiza and D. R. Lyon, *et al.*, Assessment of methane emissions from the U.S. oil and gas supply chain, *Science*, 2018, **361**, 186–188.
16 R. W. Howarth, Is shale gas a major driver of recent increase in global atmospheric methane, *Biogeosciences*, 2019, **16**, 3033–3046.

17 M. Z. Jacobson, M. A. Delucchi and M. A. Cameron, *et al.*, Impacts of Green New Deal energy plans on grid stability, costs, jobs, health, and climate in 143 countries, *One Earth*, 2019.
18 M. Z. Jacobson, M. A. Delucchi and Z. A. F. Bauer, *et al.*, 100 percent clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for 139 countries of the world, *Joule*, 2017, **1**, 108–121.
19 J. A. De Gouw, D. D. Parrish, G. J. Frost and M. Trainer, Reduced emissions of CO_2, NO_x, and SO_2 from U.S. power plants owing to switch from coal to natural gas with combined cycle technology, *Earth's Future*, 2014, **2**, 75–82.

nature climate change

PERSPECTIVE

PUBLISHED ONLINE: 5 APRIL 2017 | DOI: 10.1038/NCLIMATE3231

The role of CO_2 capture and utilization in mitigating climate change

Niall Mac Dowell[1,2*], Paul S. Fennell[3], Nilay Shah[2,3] and Geoffrey C. Maitland[2,3]

To offset the cost associated with CO_2 capture and storage (CCS), there is growing interest in finding commercially viable end-use opportunities for the captured CO_2. In this Perspective, we discuss the potential contribution of carbon capture and utilization (CCU). Owing to the scale and rate of CO_2 production compared to that of utilization allowing long-term sequestration, it is highly improbable the chemical conversion of CO_2 will account for more than 1% of the mitigation challenge, and even a scaled-up enhanced oil recovery (EOR)-CCS industry will likely only account for 4–8%. Therefore, whilst CO_2-EOR may be an important economic incentive for some early CCS projects, CCU may prove to be a costly distraction, financially and politically, from the real task of mitigation.

The continued growth in anthropogenic CO_2 emissions would appear to be characterized by one word—inexorable. Despite a growing number of climate change mitigation policies, anthropogenic CO_2 emissions in the period 2000–2014 grew at an average rate of 2.6% per year, in contrast with an average rate of 1.72% per year in the period 1970–2000[1,2]. Indeed, in the period 2010–2014, emissions increased from approximately 31.9 to 35.5 Gt_{CO_2} per year; an average rate of 2.75% per year[2]. With the exception of a one-year reduction from 2008 to 2009, every year of this century has seen a year-on-year increase in anthropogenic CO_2 emissions.

It has become commonplace to discuss future emission trajectories in terms of scenarios from, for example, the International Energy Agency (IEA) or the IPCC. Both the IEA and IPCC project that a world commensurate with no more than 2 °C of warming above pre-industrial levels is one in which total anthropogenic CO_2 emissions are reduced to something less than 20 Gt_{CO_2} per year by 2050, with further reductions to near-zero or even net-negative emissions by the end of the century. This is typically referred to as the two-degree scenario or 2DS. At the other end of the spectrum, allowing anthropogenic emissions to increase to 60 Gt_{CO_2} per year by 2050 is commensurate with warming of approximately 6 °C above pre-industrial levels—this is the six degree scenario, 6DS[1,3].

The conclusion one can draw from the foregoing data is that if anthropogenic emissions of CO_2 continue along any of the recent growth trends, we are poised to very significantly overshoot the 6DS. To even meet the 6DS, we would need to reduce the annual rate of growth of emissions to 1.4% and to meet the 2DS, the rate of growth needs to be –1.5% if global emissions peak in the 2020s. If emissions peak later, the required rate of reduction similarly increases. For the remainder of this analysis, we hypothesize a world, inspired by recent success in Paris, that reduces emissions to a level commensurate with the 6DS by 2020 and aims thereafter to transition to a world commensurate with the 2DS, focusing on the period to 2050. This allows us to introduce the quantity mitigation challenge (MC), the amount of avoided CO_2 emissions (against a reference case) by a given date, t_f, in order to reduce emissions to a level commensurate with meeting the 2DS, E_{2DS}. E_{2DS} is a function of the year in which emissions peak, t_p, the emission rate in that year, E_{t_p}, and lastly the rate at which CO_2 would be emitted in t_f according to a low mitigation scenario (LMS) reference scenario, E_{LMS}. Therefore, MC can be expressed as equation (1):

$$MC = \frac{(t_f - t_p)(E_{LMS}(t_p) - E_{2DS})}{2}$$

In addition to being a function of t_f, E_{LMS} is also a function of t_p, and the average rate of growth of anthropogenic CO_2 associated with the LMS scenario in the period $(t_f – t_p)$. Therefore, $E_{LMS}t_p = E_{t_p}(1+r)^{(t_f-t_p)}$. Thus, in order to meet the IEA's 2DS with the 6DS as a baseline, it is necessary to avoid the cumulative emission of approximately 800 Gt_{CO_2} in the period to 2050 (Fig. 1).

Globally, despite an increasing emphasis on renewable energy, annual investment in fossil energy has more than doubled in real terms in the period 2000–2013, totalling more than US$950 billion at the end of this period[4]. It is therefore not unreasonable to suggest that fossil fuels will continue to be important to, if not dominate, the world's energy landscape for some time to come, with some estimates indicating that fossil fuels will still account for over 65% of the total energy mix in 2100[5], despite increasing penetration of renewable electricity generation[6]. For this energy mix to be coherent with the long-term ambition of substantially mitigating anthropogenic CO_2 emissions, the widespread deployment of CCS technology[7–9] will most likely be a vital part of the least-cost energy system of the future, working in conjunction with renewable energy to deliver energy which is low carbon, available, and affordable.

From one perspective, CCS is a readily deployable technology solution, relying on well-understood components[7–9]. Two leading options for decarbonizing both the power and industrial sectors are the oxy-combustion of fuel or post-combustion scrubbing of the exhaust gas arising from a conventional combustion process. Both of these technologies are highly mature. Alkanolamine gas scrubbing was first patented in the 1930s and has since been widely used for natural gas sweetening[10]. Oxy-combustion, which relies on the cryogenic separation of air, was developed by Linde in 1902 and was operating at 30,000 t_{oxygen} per day at the Shell Pearl gas to liquids project in Qatar in 2006. This is sufficient oxygen to supply a 2 GW oxy-combustion power plant. Similarly, CO_2 transport and injection has been practiced at scale for EOR since the 1950s. As of 2014, there are over 3,000 miles of high-pressure pipeline which transport

[1]Centre for Environmental Policy, Imperial College London, South Kensington Campus, London SW7 1NA, UK. [2]Centre for Process Systems Engineering, Imperial College London, South Kensington Campus, London SW7 2AZ, UK. [3]Department of Chemical Engineering, Imperial College London, South Kensington Campus, London SW7 2AZ, UK. *e-mail: niall@imperial.ac.uk

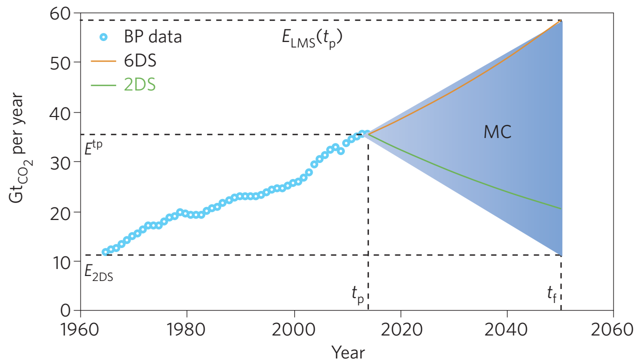


Figure 1 | Illustration of the calculation of the mitigation challenge. Here, historical data is sourced from BP data[2], the low-mitigation scenario chosen here is the IEA's 6DS, and the objective is to meet the IEA's 2DS for 2050[3]. In this example, the MC equates to approximately 800 Gt_{CO_2} in the period to 2050.

over 60 million tonnes of CO_2 per year for EOR in 113 projects in the US alone, with approximately 120 projects worldwide[11,12]. Similarly, the distribution and capacity of CO_2 storage locations are also reasonably well-characterized, with first order estimates of theoretical global CO_2 storage capacity of approximately 11,000 Gt_{CO_2} (ref. 13). Of this, approximately 1,000 Gt_{CO_2} capacity is provided by oil and gas reservoirs with approximately 9,000–10,000 Gt_{CO_2} capacity provided by deep saline aquifers[14–16]. Furthermore, there is also significant potential capacity in unmineable coal seams, with the additional economic benefit that this is may be accompanied by the recovery of coal-bed methane.

In order to stabilize atmospheric CO_2 concentrations at a level of 450 ppm, that is, a concentration consistent with a world with a high likelihood of not exceeding 2 °C of warming, it is expected that it will be necessary to store 120–160 Gt_{CO_2} via CCS in the period to 2050[17], with similar trends expected to the end of the century. Therefore we have more than enough CO_2 storage capacity to meet this target and, even without identification of further storage sinks, sufficient to meet even ambitious CO_2 sequestration needs for well beyond the next century, giving ample time for the likely lengthy transition from fossil fuels. Finally, the world's first commercial CCS-equipped power station has started operation at the Boundary Dam facility in Saskatchewan, Canada, with a second project also in operation in Alberta, where Shell are capturing the CO_2 arising from H_2 production[18]. CCS is inarguably a well-understood, mature technology that is deployable at commercial scale today.

However, despite CCS relying on well-known and well-understood technology components, the transition to its widespread deployment continues to be an uphill battle. The financing of this transition is a particular challenge, one which requires the combination of strong policy and price signals to ensure that low-carbon and energy efficiency investments offer a sufficiently attractive risk-adjusted return.

It is in this context that CCU is often mentioned. As a relatively benign material, it is possible to convert CO_2 into a wide variety of end products, in addition to its potential for enhanced hydrocarbon recovery. In this context, therefore, why should we not actively and favourably consider the reuse of captured CO_2?

Certainly it represents a beguiling opportunity—convert a waste product into high-value end products and kick-start a highly skilled regional manufacturing industry. Moreover, global demand for the potential products, such as methanol, appears healthy[19].

Therefore, it is easy to see why the prospect of CO_2 utilization is an attractive one for a wide variety of academic, industrial, and political stakeholders. However, serious questions arise when the narrative around CO_2 utilization becomes one of utilization in parallel with storage or utilization instead of storage. As will be discussed subsequently in this paper, from the perspective of mitigating anthropogenic climate change, CO_2 utilization is highly unlikely to ever be a realistic alternative to long-term, secure, geological sequestration.

The remainder of this paper is laid out as follows; we first discuss the scale at which various CCU options could be deployed, we then go on to discuss the rate at which they could be deployed before finally discussing how much of the CO_2 used in the various options corresponds to permanent storage. In all cases, this is contextualized with reference to the aforementioned mitigation challenge.

It's a matter of scale

To put this in some perspective, current total global anthropogenic emissions are about 35.5 Gt_{CO_2} per year. Typical CO_2 injection and storage conditions are approximately 10 MPa and 40 °C, corresponding to a CO_2 density of approximately 600 kg m^{-3}. This corresponds to approximately 1.64×10^8 m^3 per day, or more than 1,033 million barrels (MMbbl) of CO_2 per day. This is in contrast to current global oil production rates of approximately 87–91 MMbbl per day[20,21]. This means that global CO_2 production today is approximately a factor of 10 greater than global oil production today, and, at current rates of growth, may be as much as a factor of 20 greater in 2050[22].

Given that CCS is expected to account for the mitigation of approximately 14–20% of total anthropogenic CO_2 emissions, in 2050 the CCS industry will need to be larger by a factor of 2–4 in volume terms than the current global oil industry. In other words, we have 35 years to deploy an industry that is substantially larger than one which has been developed over approximately the last century, resulting in the sequestration of 8–10 Gt_{CO_2} per annum by 2050[22] with a cumulative CO_2 storage target of approximately 120–160 Gt_{CO_2} in the period to 2050[17] and between 1,200–3,300 Gt_{CO_2} over the course of the twenty-first century[13]. This is an exceptionally challenging task, similar in scale to wartime mobilization, but it is a task we should not be daunted by. Neither should we be distracted by focussing too much on the long-term solution without giving sufficient attention to the short-to-medium-term necessity of fossil-fuel decarbonization in a manner that allows them to operate in sympathy with intermittent generation from renewable sources[23].

It is important to note that when CO_2 utilization has traditionally been discussed, this has been in the context of CO_2-EOR in the United States. In this paper we include CO_2-EOR within a definition that considers any use of CO_2, physical or chemical, that prevents immediate release of CO_2 to the atmosphere as part of CCU. EOR is already a very mature technology with a history reaching back several decades, having well-defined techno-economic parameters, and is often considered to be an important part of the CCU landscape. In the early years of its development, CO_2-EOR faced the challenge of relatively low oil prices and relatively high CO_2 prices. Reservoir management was therefore optimized to maximize profit, not CO_2 sequestration. At the time of writing, CO_2-EOR provides approximately 5% of the total US crude oil production[24], and whilst it has the potential to be appreciably expanded[25], it is important to note the relationship between CO_2 price and oil price. At oil prices of approximately US$100 per bbl, CO_2 needs to be available at less than US$45 per tonne (ref. 12) for CO_2-EOR to be economically viable. This is the case in the US, where the business model is very mature and the CO_2-EOR capacity exists onshore, but this may not hold for the rest of the world. Thus, current oil prices in the range of US$40–60 per bbl and CO_2 costs of US$60–80 per tonne (refs 26,27) make CO_2-EOR less viable as a means of balancing the costs of large scale CCS operations, and separate economic or policy incentives are likely to be required.

Nevertheless, there is little question that CO_2-EOR offers a large, near-term option to store large quantities of CO_2 at lower net cost, with more than 90% of the world's oil reservoirs seemingly suitable for CO_2-EOR[12], if treated early enough, before the reservoir pressure drops below the minimum miscibility pressure. Thus, there exists the theoretical potential to produce 470 billion bbl of additional oil, corresponding to a cumulative theoretical CO_2 injection capacity in the range of 70–140 Gt (refs 12,28).

However, this may be a highly optimistic estimate of the total deployable CO_2-EOR capacity. As illustrated in Fig. 2, the majority of this capacity exists in the Middle East and North Africa and in the US at 50% and 13% respectively, whereas the estimated CO_2-EOR in South Asia is essentially zero and the Asia Pacific region accounts for only about 3%.

In other words, there appears to be an unfortunate disconnect between regions of substantial CO_2-EOR potential and those regions with the largest anticipated population growth, dependence on fossil fuels, and hence requirement to sequester CO_2 over the course of the next century. In fact, the only regions where it appears certain that there is sufficient CO_2-EOR capacity to meet the CO_2 storage requirements to 2050 are the Middle East and Africa—although the requirements are close in North America and the former Soviet Union. Given the size and rate of growth of the CO_2-EOR industry in the US, it is likely that the US will be a leader in the deployment of CO_2-EOR. If we accept the availability of a CCS-derived stream of CO_2 as a prerequisite for CO_2-EOR, it would make sense to estimate the scale of likely CO_2-EOR activities as matching regional CCS targets. Thus, a more realistic estimate is likely to be on the order of 40 Gt_{CO_2} cumulatively injected for CO_2-EOR. Thereafter, if we consider the average CO_2 footprint of a barrel of oil consumed, 0.43 t_{CO_2} per bbl (ref. 29), this results in revising the above estimate down to approximately 35 Gt_{CO_2}, or something in the range of 4.5% of the total CO_2 mitigation challenge.

It is, however, important to further note that, given the appropriate incentives and regulatory environment, it is possible to operate a CO_2-EOR operation so as to maximize the storage of CO_2 per bbl_{oil} recovered[30]. This can have the effect of reducing the amount of oil recovered per t_{CO_2} injected from approximately 3.33 bbl_{oil} per t_{CO_2} to 1.11 bbl_{oil} per t_{CO_2}. At the lower end, once the CO_2 emissions associated with the consumption of that oil are accounted for, this can result in the storage of up to 0.52 t_{CO_2} stored per t_{CO_2} injected, increasing the contribution of CO_2-EOR to something in the range of 8% of the total CO_2 mitigation challenge. A final point for consideration here is that oil derived from CO_2-EOR could well displace oil that would otherwise be derived from unconventional sources which are known to have a CO_2 intensity of 108–173% of conventional oil[31]. This displacement effect is estimated to be on the order of 80%, owing to market elasticities[30]. Therefore, assuming a constant demand, the deployment of CO_2-EOR could lead to the avoidance of CO_2 that would otherwise be emitted by the production of unconventional hydrocarbon resources, in addition to the reduced environmental and social risks of oil production via CO_2-EOR in mature fields relative to unconventional hydrocarbon production.

Obviously, CO_2-EOR is not the only route to CO_2 utilization—there are also CO_2 conversion options. There has been active interest in the chemical conversion of CO_2 into platform chemicals, plastics, and other materials and fuels since the 1850s[32–35] with the synthesis of salicylic acid, sodium carbonate via the Solvay process, and urea developed in 1869, 1882, and 1922 respectively[36–38]. It is therefore important to recognize that the focus on CO_2 utilization is not a recent phenomenon. Overall, current annual global CO_2 utilization is on the order of 200 Mt (ref. 35) and it has been suggested that this is likely capped at approximately 650–700 Mt in 2050 (ref. 33). Whilst this estimate was made in 2006, it is in line with current growth rates of the global chemical industry[39]. Further, of these conversion products, approximately 75% is accounted for by compounds which would not correspond to long-term sequestration of CO_2 as the incorporated CO_2 is released once the products are used.

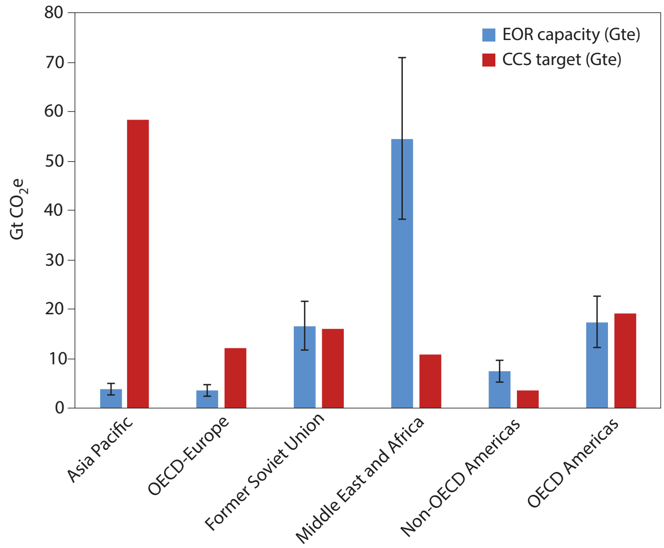


Figure 2 | Global CO_2-EOR capacity compared with regional CO_2 sequestration targets. Data from refs 13,17,22. The error bars included on this data indicate an average calculated variance of 30%. The reported variance is in the range 25–35%.

Therefore, given a 3% per year growth rate of CO_2 utilization and a sequestration rate of 25%, this corresponds to a cumulative total of 15.42 Gt_{CO_2} utilized by 2050 and 3.86 Gt_{CO_2} sequestered—about 0.49% of the 800 Gt_{CO_2} mitigation challenge.

Mineral carbonation is another process that is under consideration[40]. Whilst this process does correspond to the effectively permanent sequestration of CO_2 in a solid form, this is a reaction that happens naturally—albeit at an exceptionally slow rate. Accelerating the rate of these reactions requires mining (or other collection process), transporting, crushing, grinding and handling of vast quantities of material suitable for carbonation. This requires very large quantities of decarbonized electricity—which then begs the question: is there not a more profitable purpose to which we could put this decarbonized electricity—electrification of heating, or charging an electric vehicle, for example, and allow the carbonation of this material to take place naturally, noting that this may take an extremely long time?

Furthermore, whilst it is possible to convert CO_2 into liquid fuels such as methanol for use in ground transport[41], this would result in the near-immediate release of the CO_2 to the atmosphere, and, although potentially reducing emissions relative to a baseline, cannot be considered to contribute directly and significantly to the CO_2 mitigation challenge; capturing CO_2 directly from a vehicle is unlikely to be feasible in the medium term.

Leaving the toxicity of methanol to one side, at 43–44 GJ per $t_{methanol}$ (ref. 42), the energy required to convert CO_2 into methanol is substantial relative to the energy density of methanol (19.7 GJ per $t_{methanol}$). This corresponds to an energy return on energy invested (EROEI)[43] of approximately 0.45. More than 80% of this energy is associated with the generation of renewable electrolytic H_2, with approximately 10% required for the capture of CO_2 from a fossil-fired power station. If we were to consider the direct capture of CO_2 from the air as the CO_2 source, then one might expect the specific energy footprint of CO_2-derived methanol to increase to the order of 60 GJ per $t_{methanol}$, or an EROEI of approximately 0.33. This represents a substantial quantity of renewable energy, which compares extremely poorly with the methanol's energy density (lower heating value basis), and could arguably be put to better use elsewhere.

By way of comparison, conventional coal and oil–gas production processes have an EROEI of approximately 46 and 20 respectively[44,45],

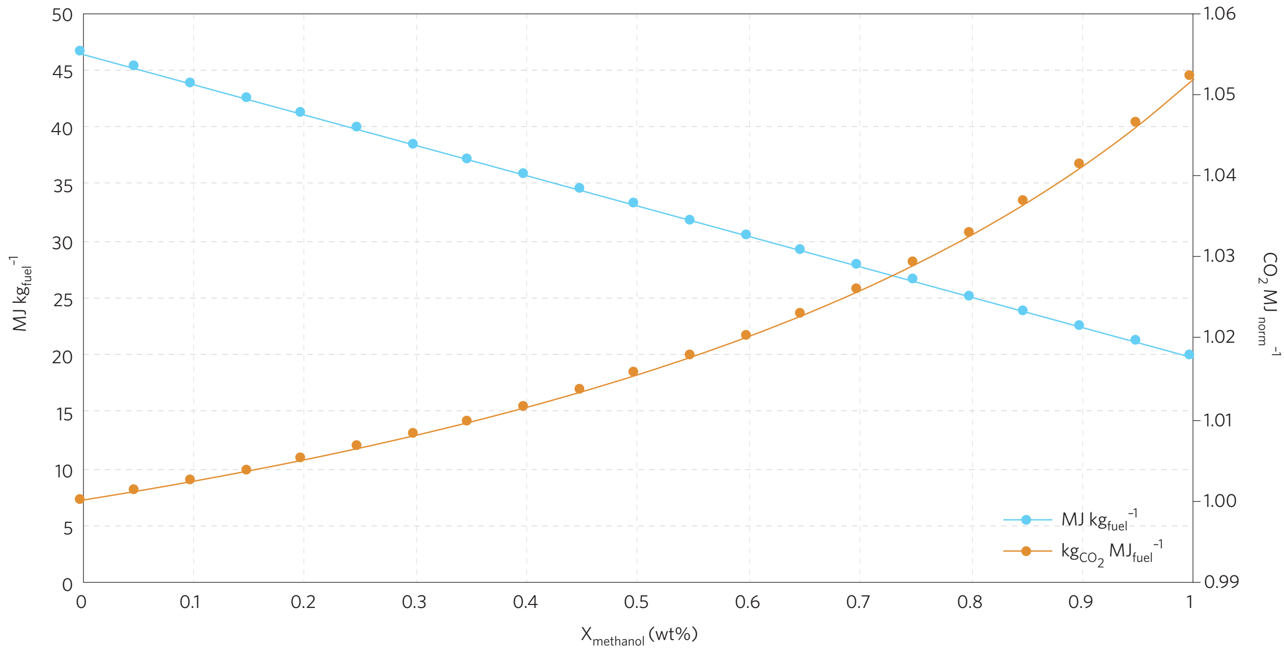


Figure 3 | The effect of blending methanol with gasoline. It can be observed that, as methanol is added to gasoline, the energy density of the fuel decreases, whilst the CO_2 footprint per unit of energy service delivered increases. Therefore, the substitution of methanol for gasoline will potentially increase the CO_2 emissions associated with delivering that energy service.

with wind, solar photovoltaic, geothermal, and biodiesel having an EROEI of approximately 18–20, 10, 9 and 2–5 respectively[44,46].

Given that a fuel or energy needs an EROEI of at least 3 to be considered useful to society[43,44], the energy required to produce methanol would have to be reduced by a factor of 6–10, depending on the source of the CO_2, in order to become viable: this is a substantial challenge.

The relatively low energy density of methanol also presents substantial challenges to its use as a fuel. Gasoline has an energy density of 46.4 MJ per kg and upon combustion produces 3.09 kg_{CO_2} per kg, whereas methanol has an energy density of 19.7 MJ per kg and upon combustion produces 1.38 kg_{CO_2} per kg.

As can be observed from Fig. 3, owing to the reduced energy density of methanol, its use as a fuel will result in the emission of approximately 5% more CO_2 than would have otherwise been the case.

Moreover, the processes for converting CO_2 to methanol do not have a perfect yield. There will be some fraction of CO_2 purged from the process—typical numbers are 0.08 t_{CO_2} purged and 0.67 $t_{methanol}$ produced per t_{CO_2} feedstock[42]. Consider, then, that 1 bbl_{oil} will yield 19 gallons of gasoline, and supply 2,469 MJ per bbl_{oil}, therefore emitting 164.46 kg_{CO_2} per bbl_{oil}. To deliver the same amount of energy requires 125.36 $kg_{methanol}$ per barrel of oil equivalent. When this methanol is combusted, and accounting for the CO_2 that was emitted in the initial production of the methanol, this corresponds to approximately 188 kg_{CO_2} per barrel of oil equivalent or approximately 14% more CO_2 than would have been produced had conventionally-sourced crude oil been used. This demonstrates the difficulty in using methanol production as a carbon sequestration process.

In order to compare CO_2-EOR and methanol production on the basis of energy service, we first recall that, depending on the version of EOR practiced[30], between 1.1–3.3 bbl_{oil} per t_{CO_2} are produced and that each bbl will produce 12 gallons of diesel and 19 gallons of gasoline, which delivers 4,284 MJ per bbl_{oil}. In the default CO_2-EOR case, 3.3 bbl_{oil} per t_{CO_2} are produced and where the EOR operation is optimized for storing CO_2, this is reduced to 1.1 bbl_{oil} per t_{CO_2}.

This leads to the net emission of 0.43 and −52 t_{CO_2} per t_{CO_2} injected, respectively and delivering 4,760–14,279 MJ per t_{CO_2} injected or between 0.03 and −0.11 kg_{CO_2} per MJ (Table 1). Displacing this service with CO_2-derived methanol would require the production of 242–725 $kg_{methanol}$, leading to the emission of approximately 0.08 kg_{CO_2} per MJ. Thus, from the perspective of both EROEI and a carbon balance, the utilization of CO_2 for EOR would appear to be preferable to the conversion of CO_2 to methanol. In all cases, CO_2-derived methanol would appear to increase the quantity of CO_2 emitted whilst delivering the same service and, under some circumstances, CO_2-EOR can result in the net sequestration of CO_2, whereas it does not appear that this is feasible with methanol.

It's a matter of time

A further point which must be taken into account is the period for which each utilization option actually stores the CO_2. It is well-accepted that in order to mitigate the effects arising from anthropogenic CO_2 emissions, it is necessary to permanently sequester the CO_2 that is excess to the earth's carbon cycle. Chemicals such as urea or methanol store CO_2 only until they are used; once urea is applied as fertilizer or methanol is used as a fuel, the CO_2 is immediately released to the atmosphere—corresponding to a storage duration of perhaps six months. The conversion of CO_2 into polymers might store the CO_2 for several decades, perhaps as much as 50 years. This is in contrast to geological sequestration, which can be considered permanent.

It's a matter of rate

In order to reduce global CO_2 emissions to 80% of 1990 levels by 2050, it will be necessary to reduce anthropogenic emissions by approximately 42 Gt_{CO_2} per year by 2050 compared to a 1990 baseline in line with the IEA and IPCC scenarios. To achieve this, it is anticipated that, amongst other things, it will be necessary to sequester a cumulative 120–160 Gt_{CO_2} in the period to 2050[3,15,22], or 16–20% of the cumulative mitigation challenge. This corresponds to a rate of CO_2 sequestration of approximately 2.5 Gt_{CO_2} per year by 2030, increasing to 8–10 Gt_{CO_2} per year by 2050[3,15,22], with further increases in the rate of sequestration in the period to 2100[1].

As discussed previously, CO_2-EOR is a potential sink for a substantial amount of CO_2. One of the major barriers—if not the

Table 1 | Comparison of the CO_2 footprint associated with CO_2-EOR and CO_2-derived methanol.

Oil recovered (bbl_{oil} per t_{CO_2})	Energy delivered (MJ per t_{CO_2} injected)	Net CO_2 emitted (kg_{CO_2} emitted per MJ)	Methanol required (kg)	Net CO_2 emitted (kg_{CO_2} emitted per MJ)
3.33	14,279	0.03	725	0.08
1.67	7,139	−0.04	362	0.08
1.11	4,760	−0.11	242	0.08

These calculations account for the energy service delivered by both the diesel and gasoline derived from the oil, and require the production of sufficient methanol to displace both fuels on an energy service basis. From left to right, the first column indicates the number of barrels of oil recovered per tonne of CO_2 injected, the second column indicates the energy service delivered by the gasoline derived from that oil and the third column indicates the CO_2 that is emitted as a result. The fourth column specifies the quantity of methanol required to provide the same service, and the fifth column specifies the quantity of CO_2 that is emitted as a result. It can be observed that converting CO_2 into methanol results in more CO_2 being emitted than for the CO_2-EOR case.

Table 2 | Present and short-term uses of CO_2 based on production data and forecasts from ref. 35.

Compound	2013 production (Mt per year)	CO_2 used in 2013 (Mt per year)	2016 production forecast (Mt per year)	2016 forecast CO_2 needed (Mt per year)	Rate of growth of production (% per year)	Rate of growth of CO_2 utilization (% per year)
Urea	155	114	180	132	5	5
Methanol	50	8	60	10	7	8
Carbonates	0.2	0.005	2	0.5	300	3,300
Polycarbonates	4	0.01	5	1	8	3,300
Carbamates	5.3	0	6	1	4	-
Polyurethanes	8	0	10	0.5	8	-
Acrylates	2.5	0	3	1.5	7	-
Formic acid	0.6	0	1	0.9	22	-
Inorganic carbonates	200	50	250	70	8	13
Technological		28		80	0	62
Algae for biodiesel	0.005	0.01	1	2	6,633	6,633
Total	**426**	**200**	**518**	**299**	**7.2**	**16.5**

The final two columns of this table contain figures calculated by the authors using data presented in ref. 35.

major barrier—to higher levels of CO_2-EOR on a global basis is an insufficient supply of affordable CO_2. In 2004, there was a supply shortfall of approximately 40 Mt_{CO_2} per year for CO_2-EOR in the Permian Basin. Subsequently, between 2007 and 2010, an additional supply of approximately 5 Mt_{CO_2} per year was sourced in response to this demand[28]. This is very possibly the world's first example of a demand pull on anthropogenic CO_2 capture. Recent years have seen a steadily increasing share of this CO_2 supply being provided by anthropogenic sources; as of 2010 this was 12 Mt per year[12]. This represents a very significant rate of increase in the size of this industry, and we would cautiously suggest that a global rate of increase in CO_2-EOR activity of 11% per year is feasible, given appropriate initial conditions such as secure supplies of CO_2. From a baseline of approximately 0.06 Gt_{CO_2} per year used for CO_2-EOR, this could grow to perhaps 26–27 Gt_{CO_2} per year in 2050. This could correspond to a cumulative total of approximately 40–60 Gt_{CO_2} injected, and 35–70 Gt_{CO_2} stored. As previously, this represents about 4–8% of the ~800 Gt_{CO_2} mitigation challenge by 2050.

Concerning other options for CO_2 conversion, data from some recent estimates of current and near-term market sizes is presented in Table 2. It should be noted that the two largest sinks for CO_2—urea and methanol—do not correspond to storing CO_2 for any significant period of time. Similarly, the technological category appears to be a catch-all for CO_2 utilization in food and drink manufacture, fire suppression, as an inerting agent and dry ice, and other miscellaneous activities. Again, these options do not correspond to long-term sequestration of CO_2.

It is worth considering for a moment the rates of growth implicit in the figures presented in Table 2. Given that the current rate of growth of the global chemical industry is approximately 3% per year[39], it is difficult to accept that this could, in any way, be indicative of a long-term trend. Furthermore, there appear to be significant assumptions in these data[35] surrounding the rate of displacement of CO_2-derived products in the market. Other, more conservative estimates of CO_2 utilization for the manufacture of chemicals place an upper limit of 650–700 Mt_{CO_2} per year on total global utilization[33]. This implies a growth rate of 3% year in the period 2010–2050, which is in line with the current rate of growth of the global chemical industry[39]. This would correspond to a cumulative total of 15.42 Gt_{CO_2} utilized in the period 2010–2050. As discussed previously, only about 25% of these products correspond to sequestering the CO_2 for any significant duration: therefore this total is reduced to 3.86 Gt_{CO_2}—or slightly less than 0.5% of the CO_2 mitigation challenge of 800 Gt_{CO_2} by 2050.

Putting it in perspective

When we take these data and then compare them for the period to 2050, it becomes clear how negligible the contribution of CCU will be to the global CO_2 mitigation challenge (Fig. 4).

This emphasizes the danger of reinforcing the narrative that CO_2 utilization is key to making CCS profitable in a simplistic commercial sense. If this narrative continues, it introduces the very real risk that emission mitigation targets will not be met and that CCS through geological storage will not be deployed in

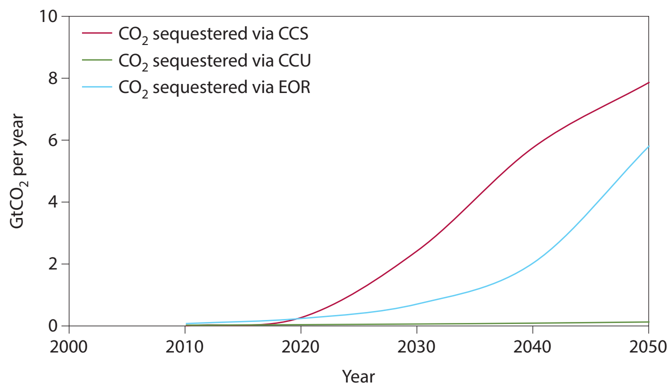


Figure 4 | CCS versus CCU—a perspective for the period 2010 to 2050. CO_2-EOR has the potential to materially contribute to the sequestration of CO_2 whereas the contribution of CCU is negligible.

any meaningful way. From a commercial and policy perspective, CCU should be encouraged when and only when CO_2 is useful as a cheap feedstock, or when it can robustly and reliably shown that the CO_2-derived product can reasonably displace the incumbent product, that is, deliver the same service at the same price, and also not result in an increase in the emission of CO_2 associated with delivering that service. The driver should be feedstock substitution and the production of materials at a lower cost and with lower fossil carbon content. The primary driver should not be locking up CO_2, as this can never happen at the required magnitude without geological storage.

Underpinning research into CO_2 conversion should continue in order to expand options and reduce costs. CO_2-EOR, whilst no panacea, can be deployed at a sufficient scale to facilitate the deployment of CO_2 transport infrastructure and potentially stacked CO_2 storage options. There is clearly a role for this technology to play in some early CCS demonstrations, as exemplified by the Sask Power Boundary Dam and the Air Products steam methane reformer projects in Canada and the United States, respectively. The key to climate change mitigation is scale, and it is generally accepted that the CCS cost reduction will be primarily achieved via deployment at scale[47,48]. Whilst CO_2-EOR projects can be deployed at a sufficient scale to facilitate learning, leading to material cost-reduction, the same is not true for the majority of CCU technologies. Thus, from the perspective of mitigating climate change, CCU can, at most, be seen as supplementing CCS to a small extent. Any proposals for its large-scale deployment should be accompanied by a careful and thorough analysis of associated primary and associated opportunity costs.

Received 25 August 2016; accepted 26 January 2017;
published online 5 April 2017

References

1. IPCC *Climate Change 2014: Mitigation of Climate Change* (eds Edenhofer, O. *et al.*) (Cambridge Univ. Press, 2014).
2. *BP Statistical Review of World Energy June 2015* (BP, 2015).
3. *Energy Technology Perspectives 2014—Harnessing Electricity's Potential* (IEA, 2014).
4. *World Energy Investment Outlook 2014 Factsheet* (IEA, 2014).
5. Jaccard, M. *Sustainable Fossil Fuels: The Unusual Suspect in the Quest for Clean and Enduring Energy* (Cambridge Univ. Press, 2006).
6. Brown, J. A. G., Eickhoff, C. & Hanstock, D. J. *Capacity and Balancing Options for the Design of Power Plant in the UK* (Institution of Chemical Engineers, 2014); http://go.nature.com/2lTDsAF
7. Mac Dowell, N. *et al.* An overview of CO_2 capture technologies. *Energy Environ. Sci.* **3,** 1645–1669 (2010).
8. Boot-Handford, M. E. *et al.* Carbon capture and storage update. *Energy Environ. Sci.* **7,** 130–189 (2014).
9. IPCC *IPCC Special Report on Carbon Dioxide Capture and Storage* (eds Metz, B. *et al.*) (Cambridge Univ. Press, 2005).
10. Rochelle, G. T. Amine scrubbing for CO_2 capture. *Science* **325,** 1652–1654 (2009).
11. Wallace, M. & Kuuskraa, V. *Near-Term Projections of CO_2 Utilization for Enhanced Oil Recovery* (NETL, 2014).
12. Godec, M. L. *Global Technolgogy Roadmap for CCS in Industry: Sectoral Assessment CO_2 Enhanced Oil Recovery* (United Nations Industrial Development Organisation, 2011).
13. Dooley, J. J. *et al. Carbon Dioxide Capture and Geologic Storage* (Global Energy Technology Strategy Program, 2006).
14. Blunt, M. *Carbon Dioxide Storage.* Briefing Paper No. 4 (Grantham Institute for Climate Change, 2010).
15. *CO_2 Capture and Storage: A Key Carbon Abatement Option* (IEA, 2008).
16. Gale, J. Geological storage of CO_2: what's known, where are the gaps, and what more needs to be done? *Greenhouse Gas Control Technol.* **1,** 201–206 (2003).
17. *Technology Roadmap: Carbon Capture and Storage* (IEA, 2013).
18. *The Global Status of CCS: 2015* (Global CCS Institute, 2015).
19. Driven by China, Global Methanol Demand to Rise Nearly 80 Percent by 2023; North America Marks Return as "Production Powerhouse". *IHS* (29 August 2014).
20. *The World Factbook* (CIA, accessed 18 August 2014); http://go.nature.com/2mbQZ7T
21. *Key World Energy Statistics* (IEA, 2012).
22. *Energy Technology Perspectives 2012—How to Secure a Clean Energy Future* (IEA, 2012).
23. Heuberger, C. *et al.* Quantifying the value of CCS for the future electricity system. *Energy Environ. Sci.* **9,** 2497–2510 (2016).
24. Dai, Z. *et al.* CO_2 accounting and risk analysis for CO_2 sequestration at enhanced oil recovery sites. *Environ. Sci. Technol.* **50,** 7546–7554 (2016).
25. Dai, Z. *et al.* An integrated framework for optimizing CO_2 sequestration and enhanced oil recovery. *Environ. Sci. Technol. Lett.* **1,** 49–54 (2014).
26. Charles, D. Stimulus gives DOE billions for carbon-capture projects. *Science* **323,** 1158 (2009).
27. Vora, S. D. *DOE/NETL Advanced Carbon Dioxide Capture R&D Program: Technology Update* (National Energy Technology Laboratory, 2013).
28. *Optimisation of CO_2 Storage in CO_2 Enhanced Oil Recovery Projects* (Advanced Resources International, 2010).
29. *GHG Equivalencies Calculator—Calculations and References* (EPA, 2016).
30. Lipponen, J. *Storing CO_2 Through Enhanced Oil Recovery: Combining EOR with CO_2 Storage (EOR+) For Profit* (IEA, 2015).
31. Mui, S. *et al. GHG Emission Factors for High Carbon Intensity Crude Oils* (Natural Resources Defense Council, 2010).
32. Inoue, S., Koinuma, H. & Tsuruta, T. Copolymerization of carbon dioxide and epoxide. *J. Polymer Sci. B Polymer Lett.* **7,** 287–292 (1969).
33. Song, C. Global challenges and strategies for control, conversion and utilization of CO_2 for sustainable development involving energy, catalysis, adsorption and chemical processing. *Catal. Today* **115,** 2–32 (2006).
34. Song, C. In *CO_2 Conversion and Utilization* (eds Song, C. *et al.*) 2–30 (ACS, 2002).
35. Aresta, M., Dibenedettoa, A. & Angeini, A. The changing paradigm in CO_2 utilization. *J. CO_2 Utilization* **3–4,** 65–73 (2013).
36. Kolbe, H. & Lautemann, E. Über die Constitution und Basicität der Salicylsäure. *Ann. Chem.* **113,** 125–127 (1869).
37. Solvay, E. Absorption of ammonia in soda ash production. US patent 263,981 A (1882).
38. Bosch, C. & Meiser, W. Process of manufacturing urea. US patent 1,429,483 A (1922).
39. Department, B. World chemical outlook 2017. *Chem. Eng. News* **91,** 11–19 (2013).
40. Kirchofer, A., Brandt, A., Krevor, S., Prigiobbe, V. & Wilcox, J. Impact of alkalinity sources on the life-cycle efficiency of mineral carbonation technologies. *Energy Environ. Sci.* **5,** 8631–8641 (2012).
41. Olah, G. A., Goeppert, A. & Surya Prakash, G. K. *Beyond Oil and Gas: The Methanol Economy.* (Wiley, 2009).
42. Van-Dal, E. S. & Bouallou, C. Design and simulation of a methanol production plant from CO_2 hydrogenation. *J. Cleaner Prod.* **57,** 38–45 (2013).
43. Hall, C., Balogh, S. & Murphy, D. What is the minimum EROI that a sustainable society must have? *Energies* **2,** 25–47 (2009).
44. Hall, C. A. S., Lambert, J. G. & Balogh, S. B. EROI of different fuels and the implications for society. *Energy Policy* **64,** 141–152 (2014).
45. Dale, M., Krumdieck, S. & Bodger, P. Global energy modeling: a biophysical approach (GEMBA) part 1: an overview of biophysical economics. *Ecol. Econ.* **73,** 152–157 (2012).

46. Kubiszewski, I., Cleveland, C. & Endres, P. Meta-analysis of net energy return for wind power systems. *Renew. Energy* **36,** 218–225 (2010).
47. Rubin, E. S. *et al.* Use of experience curves to estimate the future cost of power plants with CO_2 capture. *Int. J. Greenhouse Gas Control* **1,** 188–197 (2007).
48. van den Broek, M. *et al*. Effects of technological learning on future cost and performance of power plants with CO_2 capture. *Prog. Energy Combustion Sci.* **35,** 457–480 (2009).

Author contributions

All authors contributed to the planning of the paper. N.M.D. led the work, benefiting from discussions with all authors. All authors contributed to writing the paper, providing comments to the framework, and input in terms of numbers and references backing the analysis.

Additional information

Reprints and permissions information is available online at www.nature.com/reprints. Publisher's note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations. Correspondence and requests for materials should be addressed to N.M.D.

Competing financial interests

The authors declare no competing financial interests.

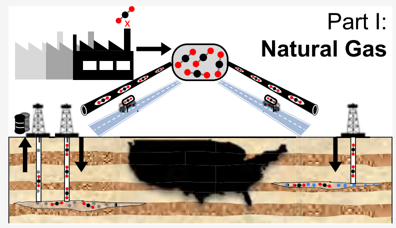
Environmental Science & Technology
pubs.acs.org/est
Article

Cost Analysis of Carbon Capture and Sequestration from U.S. Natural Gas-Fired Power Plants

Peter Psarras, Jiajun He, Hélène Pilorgé, Noah McQueen, Alexander Jensen-Fellows, Kourosh Kian, and Jennifer Wilcox*

Cite This: *Environ. Sci. Technol.* 2020, 54, 6272−6280
Read Online

ABSTRACT: Despite increasing efforts to decarbonize the power sector, the utilization of natural gas-fired power plants is anticipated to continue. This study models existing solvent-based carbon capture technologies on natural gas-fired power plants, using site-specific emissions and regionally defined cost parameters to calculate the cost of CO_2 avoided for two scenarios: delivery to and injection within reliable sequestration sites, and delivery and injection for the purpose of CO_2-enhanced oil recovery (EOR). Despite the application of credits from the existing federal tax code 45Q, a minimum incentive gap of roughly \$38/tCO_2 remains for the geologic sequestration of CO_2 and \$56/tCO_2 for CO_2-EOR (before consideration of revenue generated from delivered CO_2 contracts). At full escalation of 45Q, delivered CO_2 costs from this sector for geologic sequestration could reach as low as \$22/tCO_2. However, given the capital investment required in the near-term, it would be beneficial if the credit provided the greatest economic benefit early on and decreasing over time as deployment continues to ramp up. Additionally, due to the high qualifying limit of 45Q for the power sector, e.g., 500 ktCO_2/yr, the tax credit incentivizes the capture of roughly 397 MtCO_2/yr at a 90% capture efficiency or 75% of the emissions in this sector, with missed opportunities equating to roughly 118 MtCO_2. Advancing the scale of carbon capture and sequestration (CCS) will require both technological advances in the capture technology, cost reductions through the leveraging of existing infrastructure, and increased policy incentives in terms of cost along with the reduction of qualifying limits.



INTRODUCTION

Roughly 1500 million tonnes of CO_2 were generated from the combustion of natural gas in the United States in 2018, representing 33% of fossil-based emissions.[1] The technology exists today to avoid roughly half of these emissions through the direct installation of carbon capture and sequestration (CCS) at large (i.e., >100 000 tonnes CO_2/yr or 100 ktCO_2/yr) point sources consisting mostly of the industrial and electric power sectors (Figure 1). As demonstrated in Figure 2, of all natural gas-fired power plants in the United States, roughly 37% qualify for the federal tax credit 45Q,[2] provided they capture greater than 500 ktCO_2/yr. This represents 397 MtCO_2/yr or 26% of total emissions associated with natural gas and 75% of emissions of natural gas used for the power sector. Facilities that capture carbon and sequester it geologically or use it for CO_2-enhanced oil recovery (EOR) are eligible for 45Q. In the case of CO_2 used for EOR, the federal tax credit was \$15.29/tCO_2 in 2018 and grows linearly in value to \$35/tCO_2 by 2026. For geologic sequestration of CO_2, the credit was \$25.70 per ton in 2018 and similarly will grow to \$50/tCO_2 by 2026.

In fact, in many cases, emissions are much higher than 500 ktCO_2/yr. For example, in the Southeastern region of the United States, there are 28 natural gas plants that produce over 2 MtCO_2 annually, with the largest plant producing more than 7 MtCO_2/yr alone. Although the U.S. dependence on coal is still strong, representing 65% of U.S. electricity-related emissions in 2018, it has exhibited a decline in primary energy consumption of 8.0% from 2017 to 2018 and roughly 27% over the past 5 years.[3,4] Meanwhile, following an increase in production, the primary consumption of natural gas grew 6% from 2017 to 2018 and roughly 12% over the past 5 years.

Renewable energy such as solar and wind represents low-carbon opportunities that could replace some of these fossil-sourced emissions. Today, wind and solar comprise approximately 8.4% of the electric power sector (Figure 1), which is double that of 2008.[5] In 2018, 6.6 GW (wind) and 4.9 GW (solar) capacities were added in the U.S., while 12.9 GW of coal-generating capacity was retired.[6] Some municipalities have passed legislation encouraging a phase-out of coal power plants in favor of renewables. For example, in response to the Clean Air Clean Jobs Act (CACJA), which mandates the decommissioning of coal-generating power in Colorado, Xcel, the Public Service Company of Colorado closed two coal-fired units in Pueblo county in 2018.[7] Combined, the 2 plants

Received: October 11, 2019
Revised: April 24, 2020
Accepted: April 24, 2020
Published: April 24, 2020

https://dx.doi.org/10.1021/acs.est.9b06147
Environ. Sci. Technol. 2020, 54, 6272−6280

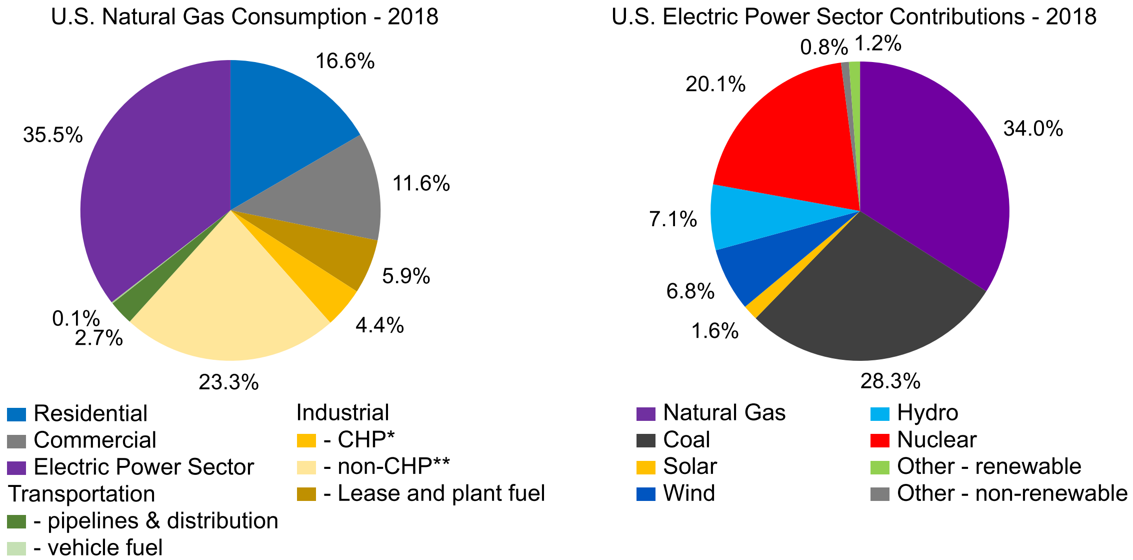


Figure 1. Distribution of natural gas usage across sectors (left) and breakdown of energy resources for the electricity power sector (right). * Industrial facilities that use combined heat and power (CHP), meaning that they have a single source of energy for generating both heat and electricity, and a small number of industrial electricity-only plants.[4] ** This category includes all industrial sector fuel use other than "lease and plant fuel" and "CHP".[4]

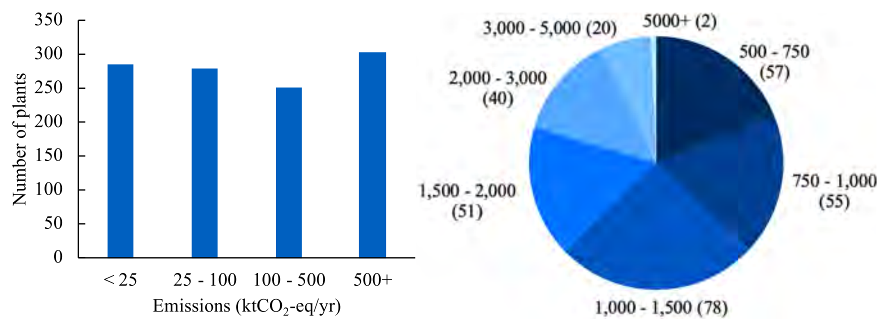


Figure 2. Distribution of the natural gas plants in the United States by emissions of CO_2 (ktCO_2/yr), for all plants (bar chart on the left) and detailed distribution for the plants emitting over 500 ktCO_2/yr (pie chart on the right).

produced 660 MW, and the wind and solar used to replace it will generate nearly three times this amount. Additionally, CAJCA endorses natural gas as a transition fuel.

Despite the U.S. closures of 4.7 GW of natural gas-generating capacity in 2018, 19.3 GW of new natural gas-generating capacity was added, the majority of which were efficient combined cycle units.[6] This is almost twice the combined additions of wind and solar capacities, signaling a continued, strong natural gas presence in the United States. Despite having a lower carbon intensity than coal-fired power plants, natural gas plants still emit on average 430 gCO_2/kWh. The IPCC identifies that in certain 1.5 and 2 °C pathways, natural gas utilization is likely to continue through and after coal phase-out, albeit with varying levels of CCS to curb emissions;[8] thus, it is important to examine CCS cost scenarios for natural gas power plants. Robust cost predictions for CCS are invaluable to the scientific community to inform research targets as well as for policymakers who are charged with developing mechanisms for increased CCS deployment. Other studies have examined the cost of CCS on natural gas plants, but assume a single value for transportation and sequestration costs, typically between \$7 and \$10/tCO_2.[9−11] This study identifies case-specific capture, compression, transport, and sequestration costs and considers recent tax code as a mechanism for cost reduction.

The most mature technologies used today for separating CO_2 from the exhaust streams of natural gas combustion are solvents based on chemical amines. However, the separation of CO_2 from NGCC exhaust using the conventional and mature amine technology monoethanolamine (MEA) is beset by several complications. First, the low CO_2 content in NGCC flue gas (i.e., 3−5 mol %) leads to a lower liquid-to-gas ratio when compared to separation from a pulverized coal (PC) power plant flue gas stream (compared at 12−15 mol %). This leads to a slightly higher plant energy penalty, which leads to higher relative costs of CO_2 capture. Second, excess air is required to drive the gas turbines, leading to a flue gas oxygen content of 15% v/v.[12] This can lead to oxidative degradation of the MEA solvent, which increases operating costs. Rubin et al. have carried out extensive research on the costs of implementing amine scrubbing for natural gas facilities. In their research, they consider many variables that could affect the cost of constructing and operating a plant, such as location and surrounding conditions, size, and efficiency. Using these variables, they produced low- and high-cost estimates. For a new plant, the capital cost is between 76 and 121% greater compared to a plant without any capture measures. By their

https://dx.doi.org/10.1021/acs.est.9b06147
Environ. Sci. Technol. 2020, 54, 6272−6280

Table 1. List of Relevant Economic Parameters Used in This Study[a]

plant type	NGCC retrofit	CRF	11.28%	45Q rate (2018) (use/sequestration)[2]	15.29/25.70 \$/tCO_2
retrofit factor	1.09	plant life	30 years	45Q rate (future) (use/sequestration)[2]	35/50 \$/tCO_2
capacity factor	75%	ref plant. emission rate	0.3615 kgCO_2/kWh	capital requirement	1556 \$/kW-net
cost NG	\$129.6/mscm	ref plant. LCOE	40.36−42.56 \$/MWh	turbine model	GE 7FB
cost year	2017 (constant)	capture rate	90%	number turbines	1−5
discount rate	7.09%	amine system	FG+	injection cost (incl. MRV)[18]	11 \$/tCO_2
CCS plant gross power	97−1484 MW	CCS plant net power output (1−5 turbines)	262−1309 MW	consumer price indices[19]	369.8 (2018) 361.0 (2017) 270.2 (2003)

[a]All values from the Integrated Environmental Control Module unless otherwise noted.

estimates, approximately 89% of the CO_2 produced by gas combustion would be captured. The incremental energy required for capture would range between 13 and 18% of a reference facility without capture. This results in an increase to the levelized cost of electricity (LCOE) between 27 and 61%.[10]

Further R&D of advanced solvents and process configurations for regeneration may lead to reduced costs of separation. For example, there has been significant research into the use of mixed solvents with monodiethanolamine and piperazine (MDEA/PZ). Frailie modeled several concentrations and combinations of MDEA and PZ and found that when capturing 99% of CO_2 as compared to 90%, the cost of capture only increased by 1% for an 8 molal PZ system as well as a blended system with 7 molal MDEA with 2 molal PZ.[13] Many recent studies have focused on levels of 90% removal. If CCS were used for avoiding emissions from the portion of the natural gas sector in the United States that is used for power generation, this additional 9% would be equivalent to roughly an additional 40 MtCO_2/yr. Assuming that CCS could be applied to all 284 natural gas power plants that qualify for 45Q, this would equate to roughly 397 MtCO_2/yr.

■ MATERIALS AND METHODS

Natural Gas Power Plant Cost Estimates. Cost estimates were calculated using the Integrated Environmental Control Model software (IECM, version 11.2).[14] In IECM, the size of the capture plant is mainly determined by the number of turbines in the power plant cycle. The 284 natural gas plants across the United States with annual CO_2 emissions over 500 kt were grouped according to their annual CO_2 emissions, i.e., the size of the plant was approximated by the number of turbines that yields the closest amount of CO_2 produced. The capture technology selected in this work involves chemical absorption using Fluor's Econamine FG Plus, with a solvent consisting of 30% w/w monoethanolamine (MEA) with an oxygen inhibitor.[15] FG+ has a lower regenerator heat requirement (174 kJ/mol CO_2) than traditional 30 wt % MEA (221 kJ/mol CO_2).[14] A simple stripper configuration was assumed, where a flash separator is installed to condense and recover the water and solvent vapors exiting the stripper, and a wet cooling tower was used as a cooling system. The plant locations were specified in the software to calculate region-specific cost factors relative to the Midwest (factor of 1.0): Northeast (1.012), Northwest (1.004), South Central (0.982), Southeast (0.985), and Southwest (1.004). Note that the states of RI and NH were not included in the software, which were assumed to follow the calculations associated with the Northeastern region of the United States. The natural gas cost was adapted from the 2018 U.S. average price for electric power,[16] i.e., \$129.6/mscm (\$3.67/mscf). Note that the regional variability in natural gas cost will impact the plant LCOE and in turn the cost of capture. A sensitivity analysis reveals that, as the cost of natural gas changes by ±\$1.0/mscf, the cost of capture changes by ±4−5%. Several plant parameters were selected as the default values set in the software, including capacity factor (75%), total CO_2 removal constraint (90%), and gas turbine model (GE 7FB).

The capture costs are reported as capital costs (CAPEX) and operating and maintenance costs (OPEX). The total capital cost is the sum of process facility capital, fees, interest, contingency, etc., where process facilities include direct contact cooler, flue gas blower, CO_2 stripper, heat exchangers, circulation pumps, solvent regenerator, reboiler, steam extractor, solvent reclaimer and processing unit, and drying and compression unit. The breakdowns of operating and maintenance costs include material replacement costs, electricity, water, CO_2 transport and sequestration, and total fixed costs. In addition, the annualized capital cost was calculated by the software, which took into account the levelized carrying charge factor, or fixed charge factor, over the entire life of the plant. A retrofit factor of 1.09 was applied to carbon capture CAPEX.[17] A list of parameters used in the economic analysis is provided in Table 1.

Cost Methodology. The calculation of the avoided cost of capture through IECM has been outlined elsewhere, whereby the incremental LCOE due to capture is divided by the net reduction in CO_2 emissions per unit energy.[9] In this study, the avoided cost of capture is reconstructed from the cost of capture obtained in IECM, the separately calculated (mode-specific) compression cost, the mode-specific transport cost, an injection cost of \$11/tCO_2,[18] and applicable tax credits via 45Q. This approach was necessary to (a) analyze an additional transport mode (trucking) and (b) use case-specific transportation distances and volumes to obtain less generalized transport cost estimations. Details on the individual cost components are provided below

Cost Estimate of CO_2 Capture. The levelized avoided cost of capture as defined by Rubin[20] is

$$C_{ca}' = \frac{(\mathrm{LCOE})_{\mathrm{CCS}} - (\mathrm{LCOE})_{\mathrm{REF}}}{\frac{\mathrm{tCO_2}}{\mathrm{kWh(REF)}} - \frac{\mathrm{tCO_2}}{\mathrm{kWh(CCS)}}} \quad (1)$$

where LCOE is the levelized cost of electricity for the CCS plant and reference (REF) plant, and the denominator takes into account CCS and reference plant emission rates. To calculate the cost of capture alone, compression and transportation must be decoupled from the IECM cost model. In this case, eq 1 yields the avoided cost of capture, excluding contributions from compression and transportation.

https://dx.doi.org/10.1021/acs.est.9b06147
Environ. Sci. Technol. 2020, 54, 6272−6280

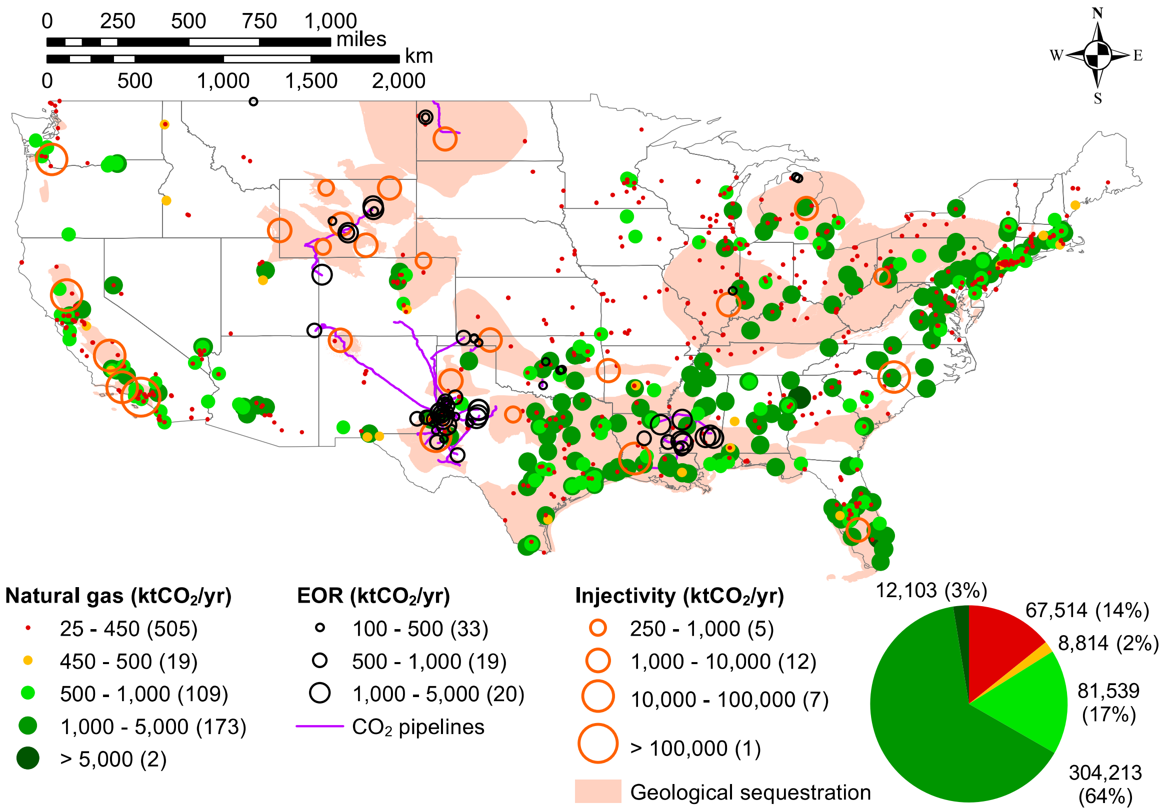


Figure 3. U.S. map of natural gas-fired power plants in the United States reporting emissions to EPA along with existing CO_2 pipelines with CO_2 sinks qualifying for federal tax credit 45Q, i.e., EOR and geologic sequestration. The pie chart demonstrates the share of CO_2 capture potential for each plant size category (matching colors) in $ktCO_2$/yr.

To avoid confusion with the full reconstructed cost of CO_2 avoided, eq 1 is renamed the levelized adjusted cost of capture (C_{ca}').

Cost Estimates of Compression and Transport via Trucking vs Pipeline. Compression is calculated based on the methodology outlined by McCollum and Ogden and others.[21,22] Liquefaction costs are calculated assuming conditions of 1.7 MPa and −30 °C.[21] Compression for pipeline is calculated assuming 10 MPa using five stages and interstage cooling, a compression ratio of 1.76, and an isentropic efficiency of 0.75. The approximate energies for compression (including cooling) are 111 and 140 kWh/tCO_2 for trucking and pipeline, respectively. Additional compression prior to injection (trucking case) results in an additional energy of 41 kWh/tCO_2. The levelized cost of compression is calculated by adding the levelized amortized capital payment, the purchased cost of electricity per tonne CO_2 compressed, and an

$$C_{co,i} = \frac{TCC_{comp,i} \times (CRF + O\&M)}{nCO_2} + w_{co,i} \times C_E \tag{2}$$

where $TCC_{comp,i}$ is the total capital cost of the compression/pumping system, CRF is the capital recovery factor (Table 1), O&M is an operation and maintenance factor applied to the total capital cost of compression (taken as 0.04 in this study), nCO_2 is the total amount of CO_2 compressed in tonnes per year, $w_{co,i}$ is the total work for compression and cooling, C_E is the cost of electricity, and the index i indicates a specific transport mode.

While large-scale CO_2 transport is dominated by pipeline, trucking transport becomes cost-competitive at less than 500 $ktCO_2$/yr and is favored for the transport of volumes of 200−300 $ktCO_2$/yr and lower.[23] The trucking model used in this work is based largely on the work of Berwick and Farooq,[24] using updated fuel emission rates, fuel costs, and labor costs. Source-end use distances were obtained by performing an origin−destination distance matrix over a U.S. street network data set. This set of distances together with the estimated CO_2 demand for each end use served as model inputs. Trucking transport costs are controlled mainly by two factors: hauling capacity and distance traveled. At very low volumes (~5 $ktCO_2$/yr and below), costs are dominated by trucking lease or purchasing as hauling remains well below the capacity. As delivery closes in on the maximum capacity per truck (here constrained to 100 000 miles of total travel per year), economies of scale are optimized, and costs are minimized. The levelized cost of transport via trucking is calculated from

$$C_{t\_tr} = c_T + w_T + f_T \tag{3}$$

where c_T is the levelized unit cost of capacity per tCO_2 delivered amortized over the useful equipment lifetime (here 5 years per truck and an annual cap of 100 000 miles), w_T is the time-averaged variable operating costs ($/$tCO_2$), including fuel, maintenance, tolls, and labor, and f_T is the time-averaged fixed operating costs ($/$tCO_2$), including permits, licenses, and insurance.

Pipeline costs were calculated using the FE/NETL CO_2 transport cost model[25] and the regression model of McCoy and Rubin.[26] Pipelines were assigned for single source−sink pairings where the geodesic source (NG plant)−sink (EOR or

https://dx.doi.org/10.1021/acs.est.9b06147
Environ. Sci. Technol. 2020, 54, 6272−6280

sequestration) distance and pipeline capacity served as model inputs. Pipeline transport costs change linearly for fixed volumes (variable distance) and nonlinearly for fixed distance hauls (variable load). This is due to the fact that the increased distance hauling requires a linear increase in pipeline infrastructure (piping and pumps), as well as fixed and variable operating expenses and maintenance, while variable load haul costs are more sensitive to the optimal pipeline diameter, which is determined from the desired pipeline capacity.[26] This study does not take into account escalation factors such as labor, elevation, and material costs. The levelized cost of transport for pipeline (C_{t_pi}) is taken as the first year breakeven cost as calculated in the FE/NETL CO_2 transport cost model.[25]

The cost of injection (C_s) is assumed as \$11/tCO_2 for both dedicated geologic sequestration[27] and CO_2-EOR[18] based on the average literature costs for injection and monitoring applied to geologic sequestration and EOR. There are several factors that could lead to discrepancies in injection costs such as differences in permeability, injection volume, injection rate, logistics in MRV fitting, and the length of time for postinjection site care. Future analyses on regional case studies should take into account the appropriate data resolution to convey site-specific injection costs.

The total cost of CO_2 avoided is calculated as

$$\text{cost of } CO_2 \text{ avoided } (\$/tCO_2) = C'_{ca} + \frac{C_{co,i} + C_{t\_i} + C_s}{(1 - x)} - C_q$$

where the index i represents either transport mode, C_q is any applicable tax credit, and x represents the total life cycle CO_2 emitted over the entire transport chain (excluding the capture where those emissions are embodied in C'_{ca}), on a tonne emitted per tonne captured basis. Due to uncertainties in inputs for each cost-modeling step, cost estimates are considered reliable to within ±12% for pipeline scenarios and ±19% in trucking scenarios.

GIS Mapping of Natural Gas Power Plants, EOR, and Geologic Sequestration Sites. The shapefiles for sedimentary basins were retrieved from the USGS website for the CO_2 geologic sequestration assessment[28] in addition to the national oil and gas assessment for sequestration potential in depleted oil and gas reservoirs.[29] The USGS has identified 186 sequestration assessment units (SAUs) in 34 basins.[28] Injectivity rates in the sedimentary basins were calculated using the USGS data[28] combined with a method developed by Baik et al.[30] using the radial form of Darcy's law for single-phase flow.[31] The 72 EOR injection locations over 100 ktCO_2/yr were selected out of 101 locations in total. Details about the EOR and geological sequestration sites are described further in the Supporting Information. The CO_2 pipeline data are sourced from Stanford University's Digital Repository.[32]

■ RESULTS AND DISCUSSION

EOR and Sequestration Opportunities. This study focuses on the cumulative cost of avoiding CO_2 emissions from power generation associated with natural gas combustion. In the United States, there are currently 808 natural gas facilities that generate power with emissions greater than or equal to 25 ktCO_2/yr. These facilities are mapped in Figure 3. Assuming 90% capture of CO_2 from these facilities, 284 or 35% qualify for the federal tax credit 45Q having the potential to capture at least 500 ktCO_2/yr. These qualifying facilities have the potential to capture 397 MtCO_2/yr assuming a 90% capture efficiency. The remaining 523 facilities are below the qualifying limit, with roughly 96% emitting less than 450 ktCO_2/yr. Missed opportunities at facilities not qualifying for the tax credit account for roughly 118 MtCO_2/yr.

Also mapped in Figure 3 are existing CO_2 pipelines with the primary function today of transporting CO_2 that is naturally stored in the earth to CO_2-EOR opportunities. Despite the approach by which EOR is conventionally carried out today in the United States, there are advanced EOR practices that may lead to maximum sequestration of CO_2. For instance, advanced EOR$^+$ (A-EOR) and maximum sequestration EOR$^+$ (MS-EOR)[33] exploit both business activities, i.e., oil recovery and CO_2 sequestration for profit and involve the injection of larger amounts of CO_2 than conventional EOR and ultimately lead to greater oil recovery. A recent study by Núñez-López shows that CO_2-EOR may result in more CO_2 stored than that generated through processing of and subsequent oxidation of the oil depending on strategic operational choices associated with its production.[34] It is important to note that if the CO_2 is sourced from avoided emissions, i.e., exhaust streams of natural gas power plants, then the oil recovered through CO_2-EOR may not be considered neutral, but rather may have a reduced carbon footprint depending on the amount of CO_2 sequestered. The CO_2 would have to be removed directly from the atmosphere to result in neutral or potential negative emissions, and the atmospheric concentrations of CO_2 are roughly 100 times more dilute than the exhaust streams of natural gas power plants, making that route more costly.

According to IEA,[33] A-EOR, and MS-EOR have global sequestration potentials of roughly 250 and 350 GtCO_2, respectively, while the cumulative sequestration required for preventing 2 °C warming by 2100 requires approximately 250 Gt of sequestration between 2015 and 2050. The work of Hovorka[35] has shown that enhanced sequestration with EOR may be possible by using CO_2 in a once-through system rather than recycling it, which is similar to the "stacked sequestration" approach. Although the costs that CO_2-EOR producers typically pay for CO_2 are proprietary, it has been well established that it is tied to oil prices and are generally found to be in the range of several dollars per thousand standard cubic feet (mscf). At oil prices of \$70/bbl, it has been reported that contracts were priced at \$27−40/tCO_2.[36−39] Also, the CO_2-EOR producers who own the geologic formations that naturally store CO_2 (e.g., Denbury Resources, Kinder Morgan, and Occidental Petroleum) pay significantly less for the CO_2, i.e., several U.S. dollars per tonne at comparable oil prices.[40] This makes it difficult to assign a static value to CO_2 resold for use in EOR. In their analysis, Skone et al. use a range of \$20−50/tCO_2 for CO_2 provided for the purpose of EOR.[11] While this study does not include within the cost model revenue generated from the sale of CO_2 for the purpose of EOR, the reader can infer cost adjustments using this cost range as a guide.

In addition to CO_2-EOR opportunities, Figure 3 also includes geological sequestration in sedimentary basins in the contiguous United States. Basins suitable for CO_2 injection have capacities ranging from 0.74 to 1800 GtCO_2, with a total sequestration resource of 2740 GtCO_2. The sequestration potential is large enough to offset all U.S. CO_2 emissions and potentially significant enough to sequester the 2035 ± 205 GtCO_2 emitted globally from 1870 to 2015.[41] The feasibility of

https://dx.doi.org/10.1021/acs.est.9b06147
Environ. Sci. Technol. 2020, 54, 6272−6280

CO_2 sequestration also relies on the injectivity of CO_2 in the appropriate sandstone and limestone formations. Injectivities range from 254 to 138 000 ktCO_2/yr, with the average weighted by a basin capacity of 22 500 ktCO_2/yr. This is true when considering a single injection point at the centroid of each basin. In reality, basins will have multiple injection points with injection projects localized according to various parameters, including the geology, the need for CO_2 injection, the ownership of the land, in addition to public acceptance.

Avoided Cost of Capture. Figure 4 illustrates the emission-weighted average avoided cost of capture, including separation, on-site compression, delivery (via trucking or pipeline), and injection of CO_2 to dedicated geologic sequestration or CO_2-EOR sites. These average costs are reported before consideration of the federal tax credit 45Q and do not include revenue from CO_2 resale to EOR. The cost of capture is invariant to the delivery mode and assumes an average value of \$53/tCO_2, with a low value of \$42/tCO_2 pointing to a high capacity (>6 MtCO_2/yr) NGCC plant in the Southeast and high value of \$66/tCO_2, assigned to a borderline case (ca. 500 ktCO_2/yr) in the Southwest. Compression costs are similar for each mode, as power requirements are similar when considering the higher compression ratio and overall pressure for pipeline and the cooling power required in liquefaction. Additional small discrepancies exist in the equipment capital between the two approaches (i.e., for the additional refrigeration requirement). Hence, the major differentiating factor in these configurations is the cost of CO_2 transport. Spatial analysis shows that the average trucking route from NG facilities to the nearest EOR facility is approximately 660 miles, with values ranging from 7 to 1500 miles. Of the 284 cases considered, only 4 yielded trucking as the least cost option. However, these are all cases where the volume of transport is very low (approaching 500 ktCO_2/yr) and the delivery distance great, resulting in average transport costs of \$150/tCO_2. While pipeline is considered more economical, due to the average distances reported here, pipeline transport incurs a cost of ca. \$40/tCO_2 avoided or roughly 25% of the total supply chain cost. Comparatively, geologic sequestration is, in general, more well distributed than EOR opportunities (Figure 3), which results in a lower average transport requirement of ca. 250 miles. Here, the cost for trucking and pipeline is more comparable, yet in the 284 cases studied, pipeline is more economical in every case, with an average transport cost of \$15/tCO_2.

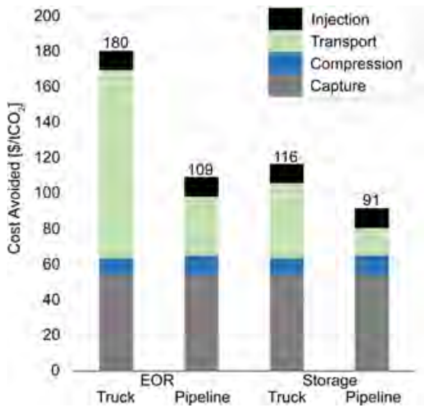


Figure 4. Avoided cost breakdown of CO_2 capture from natural gas-fired U.S. power plants, compression, transport, and injection. All costs reflect average values.

The implication of geographical opportunity distribution and application of federal tax credit 45Q is illustrated in Figure 5. Application of 45Q (a \$26 tax credit for delivery to geologic sequestration and \$15 tax credit for delivery to CO_2-EOR, for qualifying facilities) effectively absorbs the cost of compression and injection; thus, given the relatively flat cost of capture, the total avoided cost is most sensitive to transport. The broad span of costs for delivery to EOR sites is due to the range of proximity to natural gas CO_2 capture sites (i.e., 7−1500 miles), where the more distributed sequestration sites lead to a smaller cost range. The low-end values for geologic sequestration (\$38 and \$42/tCO_2) could be viewed as conservative values based on the current 45Q tax credit values. Taking these projections to the full escalated value (\$50/tCO_2) by 2026 and accounting for a flat 2.1% rate of inflation over that same time period lead to a low cost of \$22−26/tCO_2. The low-end pipeline configuration for EOR (\$56/tCO_2) could realize a value of \$46/tCO_2 by 2026 using these assumptions.

Pathways for Further Cost Reductions. As indicated previously, the federal tax credit falls short of offsetting the cost of CO_2 avoided, even at full escalation. If one assumes optimistic revenue from CO_2 resale for EOR (i.e., \$40/tCO_2), the incentive gap is roughly \$6/tCO_2 for the low-cost case and \$46/tCO_2 for the average NGCC/CO_2-EOR configuration. In addition, further R&D toward advanced solvents that may require less heat for regeneration has the potential to reduce costs up to 10% as previously noted, leading to a reduced

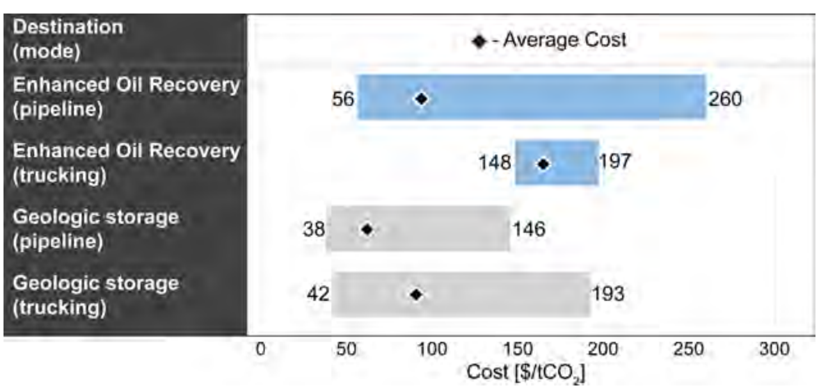


Figure 5. Costs of CO_2 capture from natural gas-fired U.S. power plants coupled to EOR or geologic sequestration via trucking or pipeline. In the plants where 90% removal results in <500 ktCO_2 avoided per year, the federal tax credit 45Q has been applied.

https://dx.doi.org/10.1021/acs.est.9b06147
Environ. Sci. Technol. 2020, 54, 6272−6280

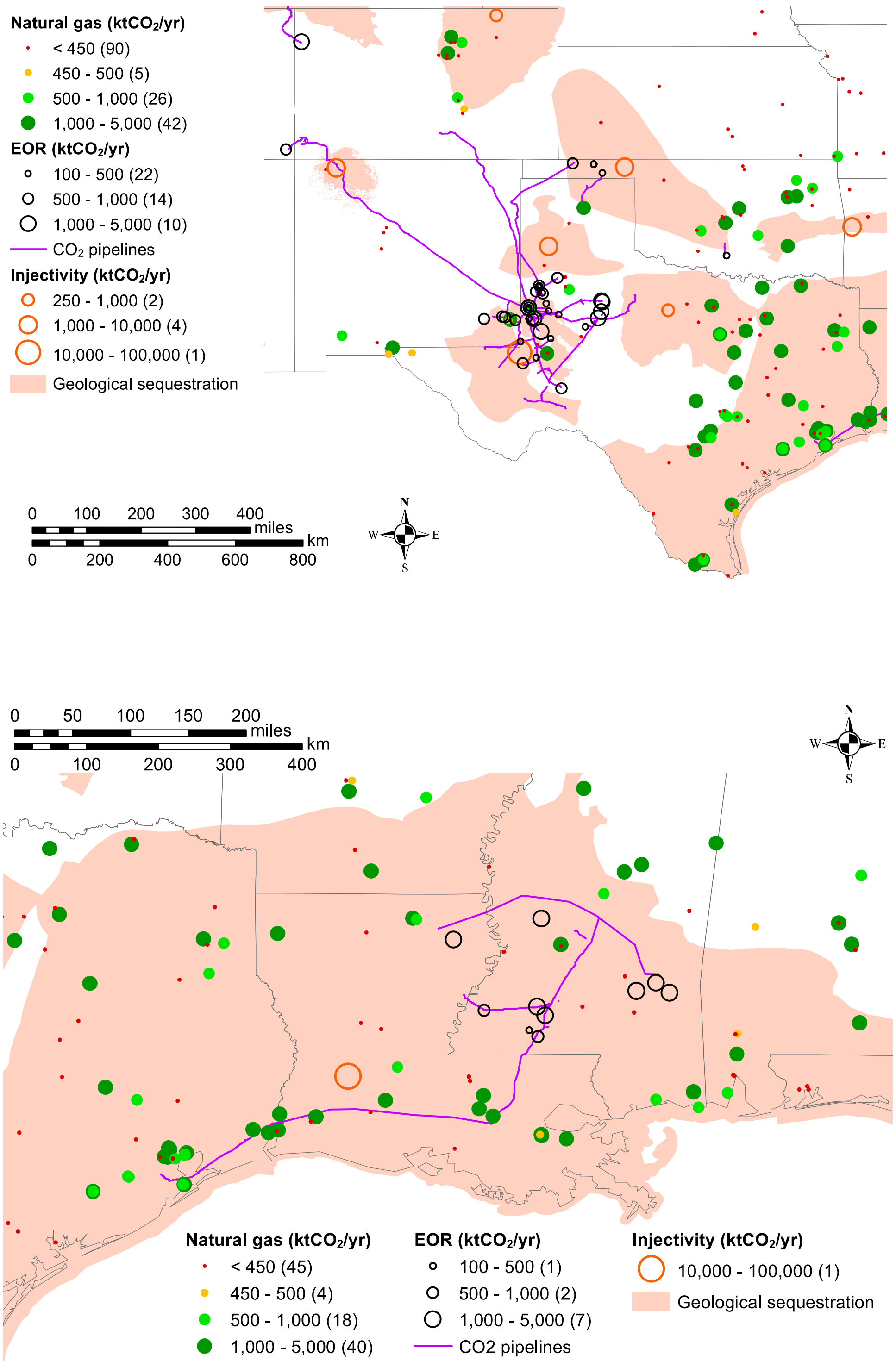


Figure 6. Regions of carbon "hub" potential surrounding the existing CO_2 pipelines and neighboring sinks, including both EOR and geologic sequestration in the Permian Basin (top) and Gulf Coast (bottom).

average cost of the capture of \$45/tCO_2. The addition of compression, transport, and sequestration reveals that increased policy incentives in terms of cost along with the reduction of qualifying limits are necessary to maximize impact.

One limitation of the transport model used in this study is the exclusion of hubs or feeder-trunk optimized pipeline systems in favor of single source−sink pairings. It is shown that the avoided cost of capture is largely dependent on the cost of transport, and the cost of transport is dependent on the volume moved. Transport cost reductions may be realized through the optimization of hub transportation networks where CO_2 at several, lower volume facilities is collected to exploit economies of scale. Figure 6 shows two regions that may be considered carbon hubs where significant anthropogenic CO_2 may be produced to replace the natural CO_2 that is currently used today for EOR. In fact, 13% of the U.S. natural gas-fired power plants having the potential to capture more than 25 ktCO_2/yr are located less than 100 miles from these two carbon hubs. The capture potential around the Louisiana−Mississippi and Texas−New Mexico pipelines is roughly 66 and 17 MtCO_2/yr, respectively, with a total capture potential of nearly 84 MtCO_2/yr, corresponding to nearly 18% of the CO_2 capture potential from natural gas-fired power plants in the United States. Roughly 74 MtCO_2/yr of the total potential CO_2 captured are from plants emitting more than 500 ktCO_2/yr, which are currently eligible for the 45Q tax credit.

In the vicinity of the Louisiana−Mississippi hub and the Texas−New Mexico pipelines, 22 and 5 natural gas plants qualifying for 45Q are located less than 20 miles from a CO_2 pipeline, having the opportunity to capture 34 and 4.6 MtCO_2/yr, respectively. Another potential 11 and 24 MtCO_2/yr captured qualifying for 45Q are located between 20 and 50 miles and between 50 and 100 miles from the pipelines, respectively. Missed opportunities (i.e., those not qualifying for the 45Q tax credit) would have the potential to capture additional 2.6, 4.7, and 2.6 MtCO_2/yr by natural gas power plants located within 20 miles, between 20 and 50 miles, and between 50 and 100 miles of CO_2 pipeline, respectively. These carbon hubs surrounding the existing CO_2 pipelines may serve as low-hanging fruit to EOR operators to source CO_2 while minimizing transport costs through the leverage of existing infrastructure.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.9b06147.

Cost model with baseline assumptions; learning through CO_2-EOR; geological sequestration methodology; trucking transportation analysis (PDF)

■ AUTHOR INFORMATION

Corresponding Author

Jennifer Wilcox − *Department of Chemical Engineering, Worcester Polytechnic Institute, Worcester, Massachusetts 01609, United States;* orcid.org/0000-0001-8241-727X; Email: jlwilcox@wpi.edu

Authors

Peter Psarras − *Department of Chemical Engineering, Worcester Polytechnic Institute, Worcester, Massachusetts 01609, United States;* orcid.org/0000-0002-5302-3412

Jiajun He − *Department of Mechanical Science and Engineering, University of Illinois, Urbana, Illinois 61801, United States*

Hélène Pilorgé − *Department of Chemical Engineering, Worcester Polytechnic Institute, Worcester, Massachusetts 01609, United States*

Noah McQueen − *Department of Chemical Engineering, Worcester Polytechnic Institute, Worcester, Massachusetts 01609, United States*

Alexander Jensen-Fellows − *Department of Chemical Engineering, Worcester Polytechnic Institute, Worcester, Massachusetts 01609, United States*

Kourosh Kian − *Department of Chemical Engineering, Worcester Polytechnic Institute, Worcester, Massachusetts 01609, United States;* orcid.org/0000-0002-0240-0089

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.est.9b06147

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

The authors would like to acknowledge the Executive Director of WPI's IT team, Siamak Najafi, for his support and guidance in assisting them with accessing the ArcGIS software required for carrying out this study. In addition, the authors would like to thank the Hewlett Foundation for their financial support toward the completion of this project.

■ REFERENCES

(1) U.S. Energy Information Administration (EIA). FAQ: How much of U.S. Carbon dioxide Emissions are Associated with Electricity Generation?. https://www.eia.gov/tools/faqs/faq.php?id=77&t=11 (accessed April 15, 2020).

(2) U.S. House of Representatives. H.R.1892-Bipartisan Budget Act of 2018: Division D395 Revenue Measures: Title II 689 Miscellaneous Provisions-Sec. 41119. https://www.congress.gov/bill/115th-congress/house-bill/1892/text (accessed April 15, 2020).

(3) U.S. Energy Information Administration (EIA). Coal Explained: Use of Coal, 2019. https://www.eia.gov/energyexplained/index.php?page=coal_use (accessed April 15, 2020).

(4) U.S. Department of Energy (DOE). Monthly Energy Review, 2019. https://www.eia.gov/totalenergy/data/monthly/previous.php (accessed April 15, 2020).

(5) Marcy, C. U.S. Renewable Electricity Generation Has Doubled since 2008, 2019, Vol. March, https://www.eia.gov/todayinenergy/detail.php?id=38752 (accessed April 15, 2020).

(6) U.S. Energy Information Administration (EIA). Today in Energy: More than 60% of Electric Generating Capacity Installed in 2018 Was Fuel by Natural Gas, 2019. https://www.eia.gov/todayinenergy/detail.php?id=38632 (accessed April 15, 2020).

(7) Pyper, J. *Xcel to Replace 2 Colorado Coal Units with Renewables and Storage*; Green Tech Media, 2018. https://www.greentechmedia.com/articles/read/xcel-retire-coal-renewable-energy-storage (accessed April 15, 2020).

(8) IPCC. *Global Warming of 1.5 °C. An IPCC Special Report on the Impacts of Global Warming of 1.5 °C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*; Delmotte, V.; Zhai, P.; Pörtner, H.-O.; Roberts, D.; Skea, J.; Shukla, P. R.; Pirani, A.; Moufouma-Okia, W.; Péan, C.; Pidcock, R.; Connors, S.; Matthews, J. B. R.; Chen, Y.; Zhou, X.; Gomis, M. I.; Lonnoy, E.; Maycock, T.; Tignor, M.; Waterfield, T., Eds.; Intergovernmental Panel on Climate Change, 2018.

(9) Rubin, E. S.; Zhai, H. The Cost of Carbon Capture and Storage for Natural Gas Combined Cycle Power Plants. *Environ. Sci. Technol.* **2012**, *46*, 3076−3084.

(10) Rubin, E. S.; Davison, J. E.; Herzog, H. J. The Cost of CO_2 Capture and Storage. *Int. J. Greenhouse Gas Control* **2015**, *40*, 378−400.

(11) Skone, T. J.; Schivley, G.; Jamieson, M.; Marriott, J.; Cooney, G.; Littlefield, J.; Mutchek, M.; Krynock, M. *Life Cycle Analysis: Natural Gas Combined Cycle (NGCC) Power Plant*, DOE/NETL-2018/1890, 2018.

(12) Jiang, L.; Gonzalez-Diaz, A.; Ling-Chin, J.; Roskilly, A. P.; Smallbone, A. J. Post-Combustion CO_2 Capture from a Natural Gas Combined Cycle Power Plant Using Activated Carbon Adsorption. *Appl. Energy* **2019**, *245*, 1−15.

(13) Frailie, P. Modeling of Carbon Dioxide Absorption/Stripping by Methydiethanolamine/Piperazine. https://repositories.lib.utexas.edu/handle/2152/25019 (accessed April 15, 2020).

(14) *Integrated Environmental Control Model (IECM)*; Carnegie Mellon University. https://www.cmu.edu/epp/iecm/ (accessed April 15, 2020).

https://dx.doi.org/10.1021/acs.est.9b06147
Environ. Sci. Technol. 2020, 54, 6272−6280

(15) Reddy, S.; Gilmartin, J. Fluor's Econamine FG PlusSM Technology for Post-Combustion CO2 Capture. 2008, https://www.fluor.com/about-fluor/corporate-information/technologies/fluor-econamine-fg-plus (accessed Aug 15, 2019).
(16) U.S. Energy Information Administration (EIA). Natural Gas Prices, 2019. https://www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PEU_DMcf_a.htm (accessed Aug 15, 2019).
(17) Matuszewski, M. *Estimating Plant Costs Using Retrofit Difficulty Factors - Quality Guidelines for Energy System Studies,* DOE/NETL-341/082313, 2013.
(18) Godec, M. L.; Riestenberg, D.; Cyphers, S. Potential Issues and Costs Associated with Verifying CO_2 Storage during and after CO_2-EOR. *Energy Procedia* **2017**, *114*, 7399−7414.
(19) U.S. Bureau of Labor and Statistics. Consumer Price Index. CPI Research Series Using447 Current Methods (CPI-U-RS). https://www.bls.gov/cpi/research-series/home.htm (accessed Feb 27, 2020).
(20) Rubin, E. S. Understanding the Pitfalls of CCS Cost Estimates. *Int. J. Greenhouse Gas Control* **2012**, *10*, 181−190.
(21) Wilcox, J. *Carbon Capture*; Springer Science & Business Media: New York, New York, USA, 2012.
(22) McCollum, D. L.; Ogden, J. M. *Techno-Economic Models for Carbon Dioxide Compression, Transport, and Storage & Correlations for Estimating Carbon Dioxide Density and Viscosity*; Research Report, UC Davis, Institute of Transportation Studies: Davis, California, USA, 2006. https://escholarship.org/uc/item/1zg00532 (accessed April 15, 2020).
(23) Psarras, P. C.; Comello, S.; Bains, P.; Charoensawadpong, P.; Reichelstein, S.; Wilcox, J. Carbon Capture and Utilization in the Industrial Sector. *Environ. Sci. Technol.* **2017**, *51*, 11440−11449.
(24) Berwick, M.; Farooq, M. *Truck Costing Model for Transportation Managers*, MPC Report, 2003.
(25) Grant, T.; Morgan, D. *FE/NETL CO2 Transport Cost Model*, DOE/NETL-2018/1876, 2018.
(26) McCoy, S. T.; Rubin, E. S. An egineering-economic model of pipeline transport of CO_2 with application to carbon capture and storage. *Int. J. Greenhouse Gas Control* **2008**, *2* (2), 219−229.
(27) National Academies of Sciences Engineering and Medicine (NASEM). *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*; The National Academies Press: Washington, DC, 2019.
(28) U.S. Geological Survey (USGS). National Assessment of Geologic Carbon Dioxide Storage Resources. https://pubs.usgs.gov/ds/774/ (accessed Feb 20, 2019).
(29) U.S. Geological Survey (USGS). National Oil and Gas Assessments. https://certmapper.cr.usgs.gov/data/apps/noga-drupal/ (accessed July 12, 2019).
(30) Baik, E.; Sanchez, D. L.; Turner, P. A.; Mach, K. J.; Field, C. B.; Benson, S. M. Geospatial Analysis of Near-Term Potential for Carbon-Negative Bioenergy in the United States. *Proc. Natl. Acad. Sci. U.S.A.* **2018**, *115*, 3290−3295.
(31) Nicot, J.-P.; Hosseini, S. A.; Solano, S. V. Are Single-Phase Flow Numerical Models Sufficient to Estimate Pressure Distribution in CO_2 Sequestration Projects? *Energy Procedia* **2011**, *4*, 3919−3926.
(32) Hart Energy Publishing. Carbon dioxide (CO2) pipelines in the United States. purl.stanford.edu/yf510bb3744 (accessed March 21, 2015).
(33) International Energy Agency (IEA).Storing CO2 through Enhanced Oil Recovery: Combining EOR with CO2 Storage (EOR+) for Profit; Paris, 2015. https://webstore.iea.org/insights-series-2015-storing-co2-through-enhanced-oil-recovery (accessed April 15, 2020).
(34) Núñez-López, V.; Gil-Egui, R.; Hosseini, S. A. Environmental and Operational Performance of CO_2-EOR as a CCUS Technology: A Cranfield Example with Dynamic LCA Considerations. *Energies* **2019**, *12*, 448−15.
(35) Hovorka, S. D. CCU&S via Stacked Storage - Case Studies from CO_2-EOR Basins of the United States. *Energy Procedia* **2013**, *37*, 5166−5171.
(36) Bliss, K.; Eugene, D.; Harms, R.; Carillo, V.; Coddington, K.; Moore, M.; Harju, J.; Jensen, M.; Botnen, L.; Marston, P.; Louis, D.; Melzer, S.; Drechsel, C.; Moody, J.; Whitman, L. *A Policy, Legal, and Regulatory Evaluation of the Feasibility of a National Pipeline Infrastructure for the Transport and Storage of Carbon Dioxide*, 2010. https://www.sseb.org/downloads/pipeline.pdf (accessed April 15, 2020).
(37) Martin, D.; Johnson, K.; Stolberg, A.; Zhang, X.; De Young, C. *Carbon Dioxide Removal Options: A Literature Review Identifying Carbon Removal Potentials and Costs*; University of Michigan, 2017.
(38) Middleton, R. S. A New Optimization Approach to Energy Network Modeling: Anthropogenic CO_2 Capture Coupled with Enhanced Oil Recovery. *Int. J. Energy Res.* **2013**, *37*, 1794−1810.
(39) Kuuskraa, V. A.; Van Leeuwen, T.; Wallace, M.; DiPietro, P. *Improving Domestic Energy Security and Lowering CO_2 Emissions with "next Generation" CO_2-Enhanced Oil Recovery (CO_2-EOR)*, DOE/NETL-2011/1504, National Energy Technology Laboratory: Pittsburgh, PA, USA, 2011.
(40) International Energy Agency (IEA). World Energy Outlook, 2015. https://www.iea.org/reports/world-energy-outlook-2015 (accessed April 15, 2020).
(41) Le Quéré, C.; Moriarty, R.; Andrew, R. M.; Canadell, J. G.; Sitch, S.; Korsbakken, J. I.; Friedlingstein, P.; Peters, G. P.; Andres, R. J.; Boden, T. A.; Houghton, R. A.; House, J. I.; Keeling, R. F.; Tans, P.; Arneth, A.; Bakker, D. C. E.; Barbero, L.; Bopp, L.; Chang, J.; Chevallier, F.; Chini, L. P.; Ciais, P.; Fader, M.; Feely, R. A.; Gkritzalis, T.; Harris, I.; Hauck, J.; Ilyina, T.; Jain, A. K.; Kato, E.; Kitidis, V.; Klein Goldewijk, K.; Koven, C.; Landschützer, P.; Lauvset, S. K.; Lefèvre, N.; Lenton, A.; Lima, I. D.; Metzl, N.; Millero, F.; Munro, D. R.; Murata, A.; Nabel, J. E. M. S.; Nakaoka, S.; Nojiri, Y.; O'Brien, K.; Olsen, A.; Ono, T.; Perez, F. F.; Pfeil, B.; Pierrot, D.; Poulter, B.; Rehder, G.; Rödenbeck, C.; Saito, S.; Schuster, U.; Schwinger, J.; Séférian, R.; Steinhoff, T.; Stocker, B. D.; Sutton, A. J.; Takahashi, T.; Tilbrook, B.; van der Laan-Luijkx, I. T.; van der Werf, G. R.; van Heuven, S.; Vandemark, D.; Viovy, N.; Wiltshire, A.; Zaehle, S.; Zeng, N. Global Carbon Budget 2015. *Earth Syst. Sci. Data* **2015**, *7*, 349−396.

https://dx.doi.org/10.1021/acs.est.9b06147
Environ. Sci. Technol. 2020, 54, 6272−6280

nature COMMUNICATIONS

COMMENT

DOI: 10.1038/s41467-018-06175-4 OPEN

Europe's renewable energy directive poised to harm global forests

Timothy D. Searchinger[1], Tim Beringer[2], Bjart Holtsmark[3], Daniel M. Kammen[4], Eric F. Lambin[5,6], Wolfgang Lucht[7,8], Peter Raven[9] & Jean-Pascal van Ypersele[6]

This comment raises concerns regarding the way in which a new European directive, aimed at reaching higher renewable energy targets, treats wood harvested directly for bioenergy use as a carbon-free fuel. The result could consume quantities of wood equal to all Europe's wood harvests, greatly increase carbon in the air for decades, and set a dangerous global example.

In January of this year, even as the Parliament of the European Union admirably voted to double Europe's 2015 renewable energy levels by 2030, it also voted to allow countries, power plants and factories to claim that cutting down trees just to burn them for energy fully qualifies as low-carbon, renewable energy. It did so against the written advice of almost 800 scientists that this policy would accelerate climate change[1]. This Renewable Energy Directive (RED) is now finalized. Because meeting a small quantity of Europe's energy use requires a large quantity of wood, and because of the example it sets for the world, the RED profoundly threatens the world's forests.

Makers of wood products have for decades generated electricity and heat from wood process wastes, which still supply the bulk of Europe's forest-based bioenergy[2,3]. Although burning these wastes emits carbon dioxide, it benefits the climate because the wastes would quickly decompose and release their carbon anyway. Yet nearly all such wastes have long been used[4].

Over the last decade, however, due to similar flaws in the 2008 RED, Europe has expanded its use of wood harvested to burn directly for energy, much from U.S. and Canadian forests in the form of wood pellets. Contrary to repeated claims, almost 90% of these wood pellets come from the main stems of trees, mostly of pulpwood quality, or from sawdust otherwise used for wood products[5].

Greenhouse gas effects of burning wood

Unlike wood wastes, harvesting additional wood just for burning is likely to increase carbon in the atmosphere for decades to centuries[6–16]. This effect results from the fact that wood is a carbon-based fuel whose harvest and use are inefficient from a greenhouse gas (GHG) perspective. Typically, around one third or more of each harvested tree is contained in roots and small branches that are properly left in the forest to protect soils but that decompose and release

[1]Woodrow Wilson School of Public and International Affairs, Princeton University, Princeton 08544, New Jersey, USA. [2]Integrative Research Institute on Transformations of Human Environment Systems (IRI THESys), Humboldt-Universität zu Berlin, Berlin 10099, Germany. [3]Statistics Norway, Oslo N-0131, Norway. [4]Energy and Resources Group, Renewable and Appropriate Energy Laboratory, and Goldman School of Public Policy, UC Berkeley, Berkeley 94720, California, USA. [5]School of Earth, Energy & Environmental Sciences and Woods Institute for the Environment, Stanford University, Stanford 94305, California, USA. [6]Earth and Life Institute, Université catholique de Louvain, B-1348, Louvain-la-Neuve, Belgium. [7]Potsdam Institute for Climate Impact Research, Potsdam 14473, Germany. [8]Humboldt-Universität zu Berlin, 100998 Berlin, Germany. [9]Missouri Botanical Garden, St. Louis 63110, Missouri, USA. Correspondence and requests for materials should be addressed to T.D.S. (email: tsearchi@princeton.edu)

Table 1 Wood harvest energy and potential demands

Region	Roundwood production	Harvest volume 2015 (10^6 m^3)	Energy content of harvested wood (EJ)	Total primary energy consumption 2015 (EJ)[a]	Potential % of present primary energy supplied by 2015 roundwood harvests	Plausible primary wood biomass energy required by new directive (EJ)[b]	% of 2015 wood harvest plausibly required for expanded bioenergy in 2030[c]
Europe	Industrial	333	3	70	4.3%	3.9	130%
	Total	428	3.85	70	5.6%	3.9	101%
World	Industrial	1826	17.9	571	2.1%		
	Total	3688	36.1	571	4.2%		

[a]Based on estimate of 0.49 tDM/m^3 for the World and 0.45 tDM/m^3 for Europe and 20 GJ/tDM (Supplementary Methods)
[b]Assumes roundwood supplies 40% of mandated increase in Europe's final renewable energy from 2015–2030, which would be mandated by RED, 35% used for bioelectricity at 25% efficiency and 65% for heat at 85% efficiency (Supplementary Note 3)
[c]Also assumes Europe meets 32% target increase in European economy-wide energy efficiency from 2007 levels by 2030 (Supplementary Note 3)

carbon. Wood that reaches a power plant can displace fossil emissions but per kWh of electricity typically emits 1.5x the CO_2 of coal and 3x the CO_2 of natural gas because of wood's carbon bonds, water content (Table 2.2 of ref. 17) and lower burning temperature (and pelletizing wood provides no net advantages) (Supplementary Note 1)[6,16].

Allowing trees to regrow can reabsorb the carbon, but for some years a regrowing forest typically absorbs less carbon than if the forest were left unharvested, increasing the carbon debt. Eventually, the regrowing forest grows faster and the additional carbon it then absorbs plus the reduction in fossil fuels can together pay back the carbon debt on the first stand harvested. But even then, carbon debt remains on the additional stands harvested in succeeding years, and it takes more years for more stands to regrow before there is just carbon parity between use of wood and fossil fuels. It then takes many more years of forest regrowth to achieve substantial GHG reductions.

The renewability of trees, unlike fossil fuels, helps explain why biomass can eventually reduce GHGs but only over long periods. The amount of increase in GHGs by 2050 depends on which and how forests are ultimately harvested, how the energy is used and whether wood replaces coal, oil or natural gas. Yet overall, replacing fossil fuels with wood will likely result in 2-3x more carbon in the atmosphere in 2050 per gigajoule of final energy (Supplementary Note 2). Because the likely renewable alternative would be truly low carbon solar or wind, the plausible, net effect of the biomass provisions could be to turn a ~5% decrease in energy emissions by 2050 into increases of ~5–10% or even more (Supplementary Note 2).

Consequences for forests

The implications for forests and carbon are large because even though Europe harvests almost as much wood as the US and Canada combined, these harvests could only supply ~5.5% of its primary energy and ~4% of its final energy. If wood were to supply 40% of the additional renewable energy—an uncertain but plausible level—the wood volumes required would equal all of Europe's wood harvest (Supplementary Note 3). In fact, the RED sets a goal to increase by 10% renewable energy for heat, sourced overwhelmingly from wood, which would likely by itself use ~50% of Europe's present annual wood harvest[18,19]. European Commission planning documents projected somewhat smaller roles for bioenergy based on lower renewable energy targets, but they scale up to ~55–85% of Europe's wood harvest at the larger target ultimately adopted (Supplementary Note 4). Supplying this level of wood will probably require expanding harvests in forests all over the world.

The global signal may have even greater effects on climate and biodiversity. At the last global climate conference (UNFCCC-COP 23, Bonn 2017), tropical forest countries and others, including Indonesia and Brazil, jointly declared goals "to increase the use of wood … to generate energy as part of efforts to limit climate change"[20,21]. Once countries and powerful private companies become invested in such efforts, further expansion will become harder to stop. The effect can already be seen in the United States, where Congress in both 2017 and 2018 added provisions to annual spending bills declaring nearly all forest biomass carbon free—although environmentalists have so far fought to limit the legal effects to a single year[22,23]. If the world met just an additional 2% of global primary energy with wood, it would need to double its industrial wood harvests (Table 1).

Why the RED sustainability criteria are insufficient

Unfortunately, various sustainability conditions in the RED would have little consequence. For example, one repeated instruction is that harvesting trees should occur sustainably, but sustainable does not equal low carbon (Supplementary Note 5). Perhaps the strictest version of sustainability, often defended as a landscape approach, claims GHG reductions so long as harvest of trees in a country (or just one forest) does not exceed the forest's incremental growth[24–27]. Yet, by definition, this incremental growth would otherwise add biomass, and therefore carbon storage to the forest, holding down climate change[28]. This carbon sink, in large part due to climate change itself, is already factored into climate projections and is not disposable. Harvesting and burning this biomass reduces the sink and adds carbon to the air just like burning any other carbon fuel. The directive only requires forests to maintain existing carbon stocks in limited circumstances, but given the size of the global forest sink, even applying such a rule everywhere would still allow global industrial wood harvests to more than triple (Supplementary Note 6)[29,30].

The directive also repeatedly cites a goal to preserve biodiversity, but its provisions will afford little protection. Prohibitions on harvesting wood directly for bioenergy apply only to primary forests—a small share of global forests (Supplementary Note 5). In addition, any forests could be cut to replace the vast quantities of wood diverted from existing managed forests to bioenergy.

Some argue that increasing carbon in the atmosphere for decades is fine so long as reductions eventually occur, but timely mitigation matters. More carbon in the atmosphere for decades means more damages for decades, and more permanent damages due to more rapid melting of permafrost, glaciers and ice-sheets, and more packing of heat and acidity into the world's oceans. Recognizing this need, the EU otherwise requires that GHG reductions occur over 20-years, but that timing does not apply to forest biomass (Supplementary Note 5).

Instead, the directive incorporates the view that forest biomass is inherently carbon neutral if harvested sustainably (Supplementary Note 5). Although the RED requires that bioenergy generate large greenhouse gas reductions, its accounting rules ignore the carbon emitted by burning biomass itself (Annex VI, section C, par 13 in ref. 31). They only count GHGs from trace gases and use of fossil fuels to produce the bioenergy, which is like counting the GHGs from coal-mining machinery but not from burning the coal.

The main new Commission thinking, reflected in the sustainability provisions, is that bioenergy rules do not need to count plant carbon so long as countries that supply the wood have commitments related to land use emissions under European rules or the Paris accord (RED, Article 26, point (6)(1)(ii)) (Supplementary Note 5). But this thinking repeats the confusion that occurred at the time of the Kyoto Protocol between rules designed only to count global emissions and laws designed to shape national or private incentives[32]. Under accounting rules for the UN Framework Convention on Climate Change (UNFCCC), countries that burn biomass can ignore the resulting energy emissions because the countries that cut down the trees used for the biomass must count the carbon lost from the forest. Switching from coal to biomass allows a country to ignore real energy emissions that physically occur there, but the country supplying the wood must report higher land use emissions (at least compared to the no-bioenergy alternative). The combination does not make bioenergy carbon free because it balances out global accounting, the limited goal of national reporting.

But this accounting system does not work for national energy laws. If a country's laws give its power plants strong financial incentives to switch from coal to wood on the theory that wood is carbon-neutral, those power plants have incentives to burn wood regardless of the real carbon consequences. Even if a country supplying the wood reports higher land use emissions through the UNFCCC, that carbon is not the power plant's problem. Only if all potential wood-supplying countries imposed a carbon fee on the harvest of wood, and this fee equaled Europe's financial incentive to burn it, would European power plants have a financial reason to properly factor the carbon into their decisions. No country has done that or seems likely to do so.

In fact, few countries have any obligation to compensate for reduced carbon in their forests because few countries have adopted quantitative goals in the land use sector as part of the Paris accord[33]. Even if countries did try to make up for reduced forest carbon due to bioenergy with additional mitigation of some kind, all Europe would achieve is a requirement that its consumers pay more to do something harmful for the climate so that other countries could then spend additional money to compensate.

Europe has also created a kind of reverse REDD + strategy by treating forest and all other biomass as carbon neutral in its Emissions Trading System, which limits emissions from power plants and factories. While the not yet realized hope behind REDD + is to reward countries for preserving carbon in forests, this bioenergy policy means forest owners can be rewarded for the carbon in their trees—so long as they cut them down and sell them for energy. The higher the price of carbon rises, the more valuable cutting down trees will become. Strangely, this policy also undermines years of efforts to save trees by recycling used paper instead of burning it for energy. Even as recycling polices push consumers to save trees, this policy will encourage others to burn them.

Alternative low carbon energy sources

Alternatives include various forms of solar power, which typically generate at least 100 times more useable energy per hectare than bioenergy even on good land—and even more on dry lands and rooftops[34,35]. Possible future limits on solar if storage does not evolve cannot justify bioenergy today. With solar costs already dropping below \$US 0.02/kWh in some world locations, and offshore wind in Europe below \$US0.06, solar and wind have many economic advantages over bioenergy, particularly for electricity, even with bioenergy's incorrect GHG accounting[36]. Unfortunately, these advantages are unlikely to fully negate the political and occasional economic benefits enabled by flawed climate accounting of simply replacing fossil fuels with wood.

Although some scientists support this use of forests[24,26,27], and the IPCC has found it difficult to speak clearly about biomass in the face of different views (see Appendix 11.13 in ref. 37), the fact that ~800 scientists came forward provides hope of a clearer and stronger message from the scientific community. The fate of the biosphere appears at stake. Individual European countries still have discretion to pursue alternatives to forest biomass. Whatever their fields, all scientists who care should educate themselves, overcome a natural reluctance to venture into a separate and controversial field, speak with great clarity and hold public institutions to account.

Data availability

All data used or calculated for this comment are presented in tables in the main text or supplement or are available from publicly available sources cited.

Received: 18 April 2018 Accepted: 24 August 2018
Published online: 12 September 2018

References

1. Beddington, J. et al. *Letter from scientists to the EU parliament regarding forest biomass*. Available at: http://empowerplants.files.wordpress.com/2018/01/scientist-letter-on-eu-forest-biomass-796-signatories-as-of-january-16-2018.pdf (2018).
2. European Commission. *IMPACT ASSESSMENT Sustainability of Bioenergy* (European Commission, Brussels, 2016).
3. PricewaterhouseCoopers EU Services EESV's consortium. *Sustainable and optimal use of biomass for energy in the EU beyond 2020* (2017).
4. IEA. *Tracking Clean Energy Progress 2017* (IEA, Paris, 2017).
5. Walker, S., Lyddan, C., Perritt, W. & Pilla, L. *An Analysis of UK Biomass Power Policy, US South Pellet Production and Impacts on Wood Fiber Markets* (RISI, 2015).
6. Laganière, J., Paré, D., Thiffault, E. & Bernier, P. Y. Range and uncertainties in estimating delays in greenhouse gas mitigation potential of forest bioenergy sourced from Canadian forests. *GCB Bioenergy* **9**, 358–369 (2017).
7. Mitchell, S. R., Harmon, M. E. & O'Connell, K. E. B. Carbon debt and carbon sequestration parity in forest bioenergy production. *GCB Bioenergy* **4**, 818–827 (2012).
8. Stephenson, A. L. & MacKay, D. J. C. Life cycle impacts of biomass electricity in 2020 (Department of Energy & Climate Change, London, 2014).
9. Bernier, P. & Paré, D. Using ecosystem CO_2 measurements to estimate the timing and magnitude of greenhouse gas mitigation potential of forest bioenergy. *GCB Bioenergy* **5**, 67–72 (2013).
10. Holtsmark, B. Harvesting in boreal forests and the biofuel carbon debt. *Clim. Change* **112**, 415–428 (2012).
11. Hudiburg, T. W., Law, B. E., Wirth, C. & Luyssaert, S. Regional carbon dioxide implications of forest bioenergy production. *Nat. Clim. Change* **1**, 419–423 (2011).
12. McKechnie, J., Colombo, S., Chen, J., Mabee, W. & MacLean, H. L. Forest bioenergy or forest carbon? Assessing trade-offs in greenhouse gas mitigation with wood-based fuels. *Environ. Sci. Technol.* **45**, 789–795 (2011).
13. Manomet Center for Conservation Sciences. *Massachusetts Biomass Sustainability and Carbon Policy Study: Report to the Commonwealth of Massachusetts Department of Energy Resources* (2010).
14. Zanchi, G., Pena, N. & Bird, N. Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel. *GCB Bioenergy* **4**, 761–772 (2012).
15. Holtsmark, B. The outcome is in the assumptions: analyzing the effects on atmospheric CO_2 levels of increased use of bioenergy from forest biomass. *GCB Bioenergy* **5**, 467–473 (2013).
16. Booth, M. S. Not carbon neutral: assessing the net emissions impact of residues burned for bioenergy. *Environ. Res. Lett.* **13**, 035001 (2018).
17. IPCC. *IPCC Guidelines for National Greenhouse Gas Inventories* (IGES, Kitakyushu, 2006).

18. Hennenberg, K., Böttcher, H., Fehrenbach, H. & Bischoff, M. *Short analysis of the RED 2009, the iLUC Directive 2015 and the 2016 RED proposal regarding implications for nature protection* (Oeko-Institute and IFEU, Berlin, Darmstadt, Heidelberg, 2017).
19. European Environment Agency. *Renewable energy in Europe – 2017 Update. Recent growth and knock-on effects* (European Environment Agency, Copenhagen, 2017).
20. Biofuture Platform. Biofuture@COP23: Major countries agree to scale up the low carbon bioeconomy and develop sustainable biofuels targets. Available at: http://biofutureplatform.org/major-countries-agree-scale-low-carbon-bioeconomy-develop-sustainable-biofuels-targets/ (2017).
21. Doyle, A. & Roche, A. Nineteen nations say they'll use more bioenergy to slow climate change. *Reuters*. Available at: http://www.reuters.com/article/us-climatechange-accord-biofuels/nineteen-nations-say-theyll-use-more-bioenergy-to-slow-climate-change-idUSKBN1DG2DO (2017).
22. Consolidated Appropriations Act, 2017, Sec. 428, Pub. L. 115-31 (115th Cong), 131 Stat. 500. Available at: https://www.congress.gov/115/plaws/publ31/PLAW-115publ31.pdf (2017).
23. Consolidated Appropriations Act, 2018, Sec. 431, Pub. L. 115-141 (115th Cong). Available at: https://www.aila.org/infonet/house-bill-consolidated-appropriations-act-2018 (2018).
24. Smeets, E. M. W. & Faaij, A. P. C. Bioenergy potentials from forestry in 2050. *Clim. Change* **81**, 353–390 (2006).
25. Searchinger, T. & Lucht, W. Why 'sustainable forest management' does not make wood a good climate alternative to fossil fuels. *euractiv.com* Available at: http://www.euractiv.com/section/climate-environment/opinion/why-sustainable-forest-management-does-not-make-wood-a-good-climate-alternative-to-fossil-fuels/ (2018).
26. Cowie, A., Berndes, G., Junginger, M. & Ximenes, F. *Response to Chatham House report "Woody Biomass for Power and Heat: Impacts on the Global Climate"* (2018).
27. Berndes, G. et al. *Forest Biomass, Carbon Neutrality and Climate Change Mitigation*. (European Forest Institute, Vienna, 2016).
28. Ter-Mikaelian, M. T., Colombo, S. J. & Chen, J. The Burning Question: Does Forest Bioenergy Reduce Carbon Emissions? A Review of Common Misconceptions about Forest Carbon Accounting. *J. For.* **113**, 57–68 (2015).
29. Pan, Y. et al. A Large and Persistent Carbon Sink in the World's Forests. *Science* **333**, 988–993 (2011).
30. Krausmann, F. et al. Global human appropriation of net primary production doubled in the 20th century. *Proc. Natl. Acad. Sci.* **110**, 10324–10329 (2013).
31. European Commission. *Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the promotion of the use of energy from renewable sources (recast)*. (2016).
32. Searchinger, T. D. et al. Fixing a critical climate accounting error. *Science* **326**, 527–528 (2009).
33. FAO. *The agriculture sectors in the intended nationally determined contributions: analysis*. (Rome, 2016).
34. Searchinger, T. D., Beringer, T. & Strong, A. Does the world have low-carbon bioenergy potential from the dedicated use of land? *Energy Policy* **110**, 434–446 (2017).
35. Kammen, D. M. & Sunter, D. A. City-integrated renewable energy for urban sustainability. *Science* **352**, 922–928 (2016).
36. Natural Resources Defense Council. Money to Burn II: Solar and Wind Can Reliably Supply the United Kingdom's New Electricity Needs More Cost-Effectively Than Biomass (2017).
37. P. Smith et al. Agriculture, Forestry and Other Land Use (AFOLU). In *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate* Change (eds. O. Edenhofer et al.) (Cambridge University Press, Oxford, 2014).

Acknowledgements

We wish to thank the David & Lucille Packard Foundation for financial support for this research and the European Climate Foundation for organizing a meeting of several of the authors.

Author contributions

T.D.S. led the writing. T.D.S., T.B., and B.H. performed calculations. T.B., B.H., D.M.K., E.F.L., W.L., P.R., and J.-P.v.Y. contributed to writing and analysis.

Additional information

Supplementary Information accompanies this paper at https://doi.org/10.1038/s41467-018-06175-4.

Competing interests: The authors declare no competing interests.

An Action Plan for Carbon Capture and Storage in California: Opportunities, Challenges, and Solutions

Stanford | SCHOOL OF EARTH, ENERGY & ENVIRONMENTAL SCIENCES | Stanford Center for Carbon Storage

ENERGY FUTURES — INITIATIVE —

Stanford | ENERGY
Precourt Institute for Energy

A Presentation on the Study Results by the Project Executives
Professor Sally Benson, Stanford University
Melanie Kenderdine, Energy Futures Initiative

October 22, 2020

Study Approach and Framing

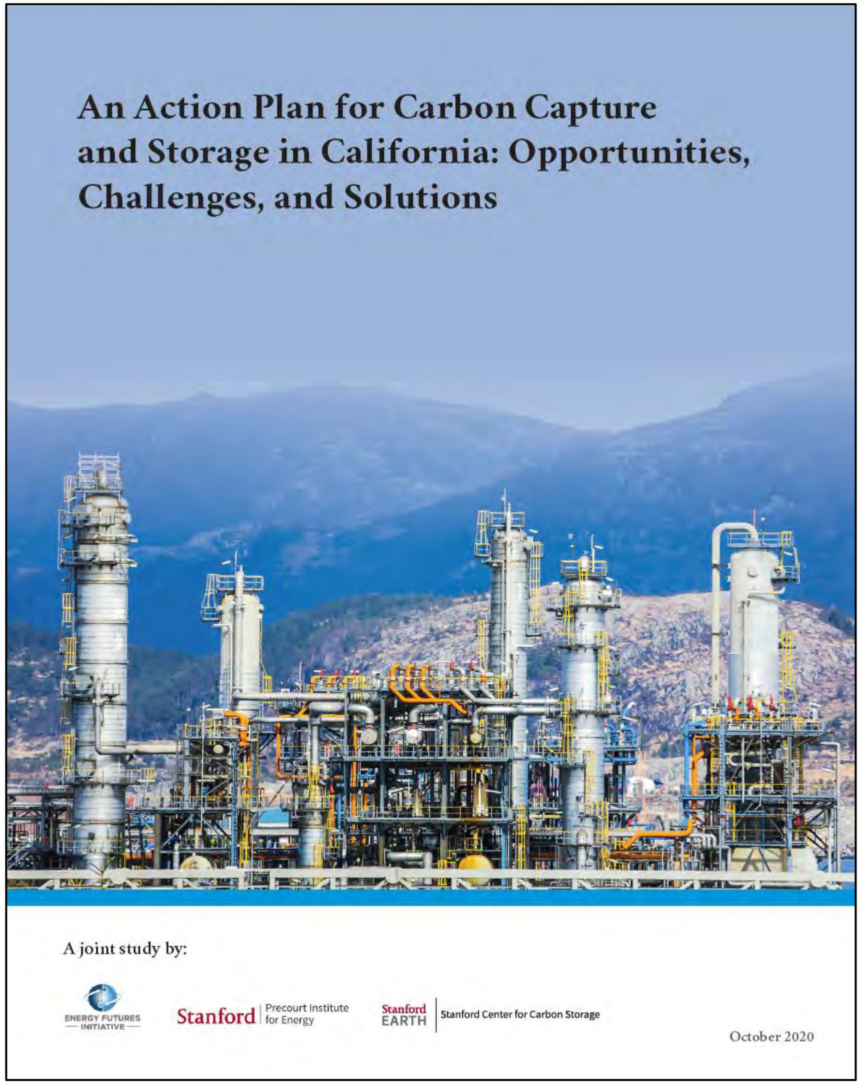
Analysis focused on five key areas

- Meeting California's Decarbonization Targets: The Critical Role of CCS in Carbon Dioxide Removal
- The Status of CCS in California
- The CCS Opportunity in California
- The Challenges for CCS Project Development in California
- A Policy Action Plan for Maximizing the Value of CCS in California

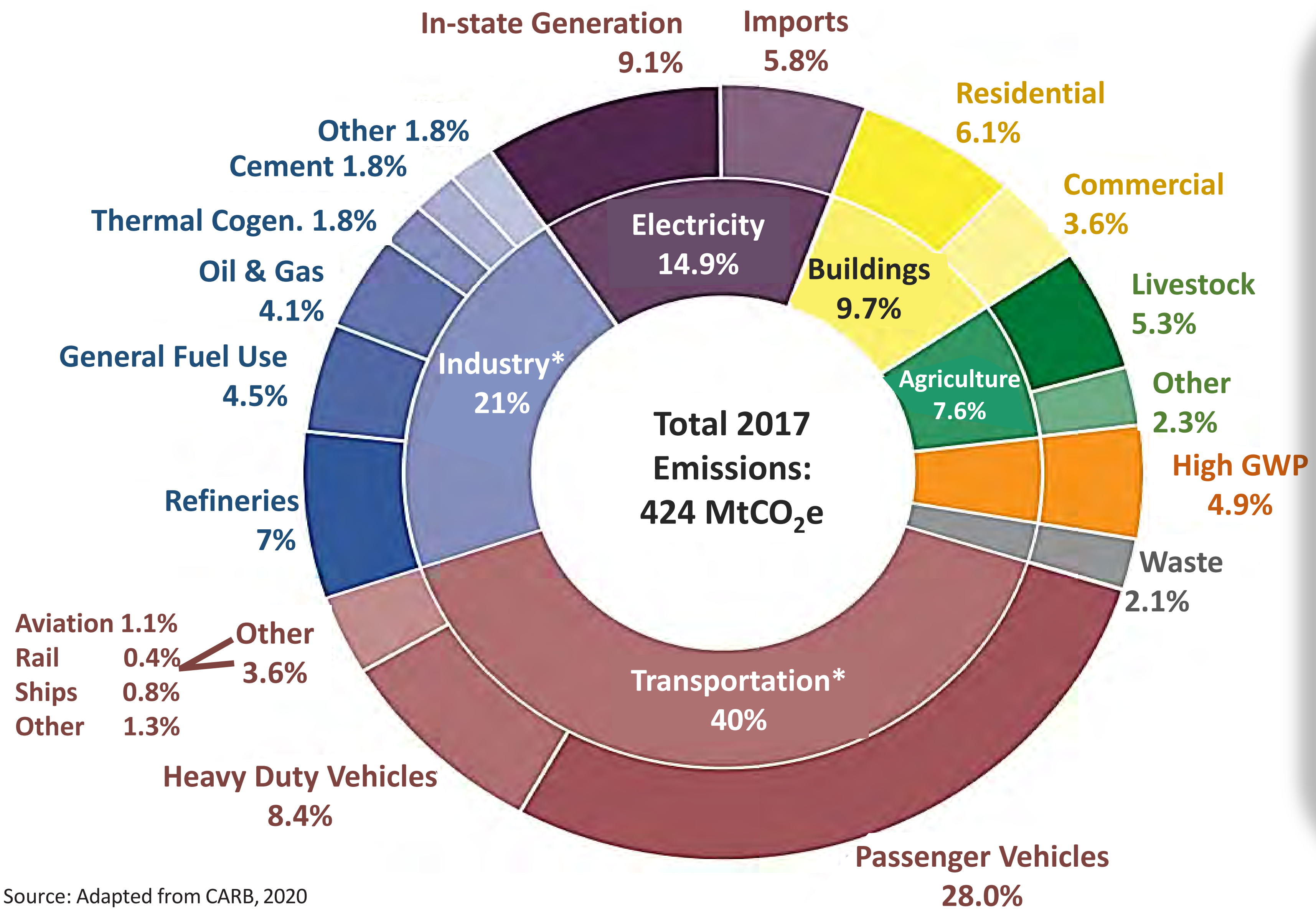
Bottom line up front

An Action Plan for Policymakers was developed to fulfill California's CCS potential, supporting the report's high-level goals of:

✓ Maximizing the value of CCS for meeting the state's economywide decarbonization goals affordably and equitably
✓ Motivating the private sector to decarbonize
✓ Enabling economic and reliability benefits from existing industries and power generation, and --
✓ Unlocking new clean energy industries and jobs



What CCS Can Do for California: Emissions Reductions



Source: Adapted from CARB, 2020

Emissions Reduction Potential from CCS in California

- Approx. 15% of state's total CO_2 emissions can be captured and stored with CCS
- This is 65% greater than emissions from in-state power generation in 2017
- 44% greater than emissions from the entire buildings sector
- 84% greater than all emissions from the entire agriculture sector
- 66% greater than emissions from all heavy-duty vehicles

ENERGY FUTURES INITIATIVE

Stanford SCHOOL OF EARTH, ENERGY & ENVIRONMENTAL SCIENCES | Stanford Center for Carbon Storage

Stanford | ENERGY Precourt Institute for Energy

What CCS Can Do For California: Meet Climate Targets While Supporting Economic Base/Jobs

Maximize options for meeting 2030 and 2045 GHG targets to reduce associated costs, improve the likelihood of achieving the targets, and foster innovation.

2020 Goal: Equal to 1990 Emissions Level of 427 $MtCO_2e$ → **2030 Goal: 40% Reduction from 1990 Emissions Level, 256.2 $MtCO_2e$** → **2045 Goal: Carbon Neutrality and Net-negative Emissions Thereafter**

Motivate the private sector to deeply decarbonize its operations.

	California	
	Cement	Cement & Related
# Employees	1,449	16,774
Payroll ($)	101 million	924 million
Contribution to State Taxes Revenues ($)	35.6 million	412 million
Economic Contribution ($)	2.4 billion	12.1 billion

Source: Adapted from Portland Cement Association, 2017

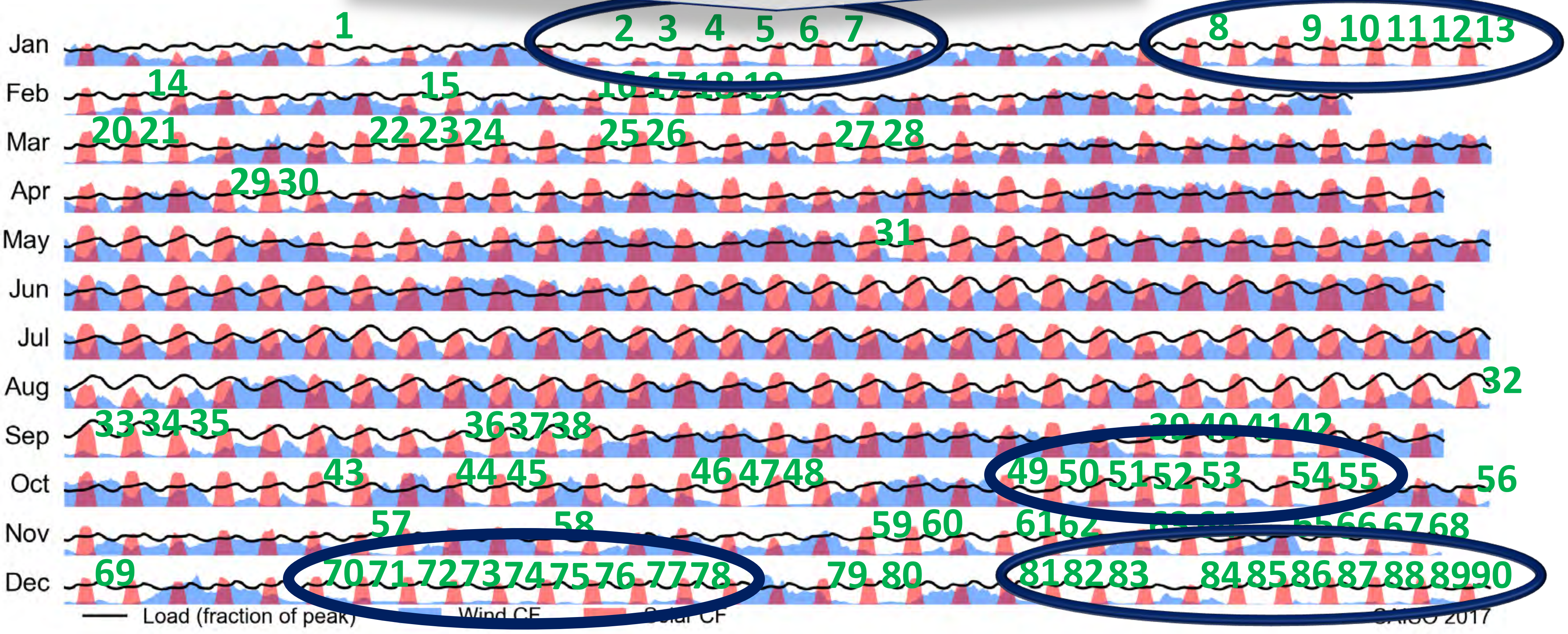
California

- ✓ Industry 21% of total emissions
- ✓ Largest manufacturing state in the country
- ✓ Few technology options for decarbonization

"California's manufacturing accounted for roughly $315 billion in economic output in 2018 -- 11 percent of gross state product-- with more than 35,000 firms employing 1.3 million employees... **The use of CCS could enable difficult-to-decarbonize industries to stay in business and continue making large contributions to California's economy while dramatically reducing their GHG emissions."** *-National Association of Manufacturers, "2019 California Manufacturing Facts."*

What CCS Can Do For California: Support for Grid Reliability, Variable Renewable and Climate Targets

Enable continued reliability benefits from clean firm power generation ...



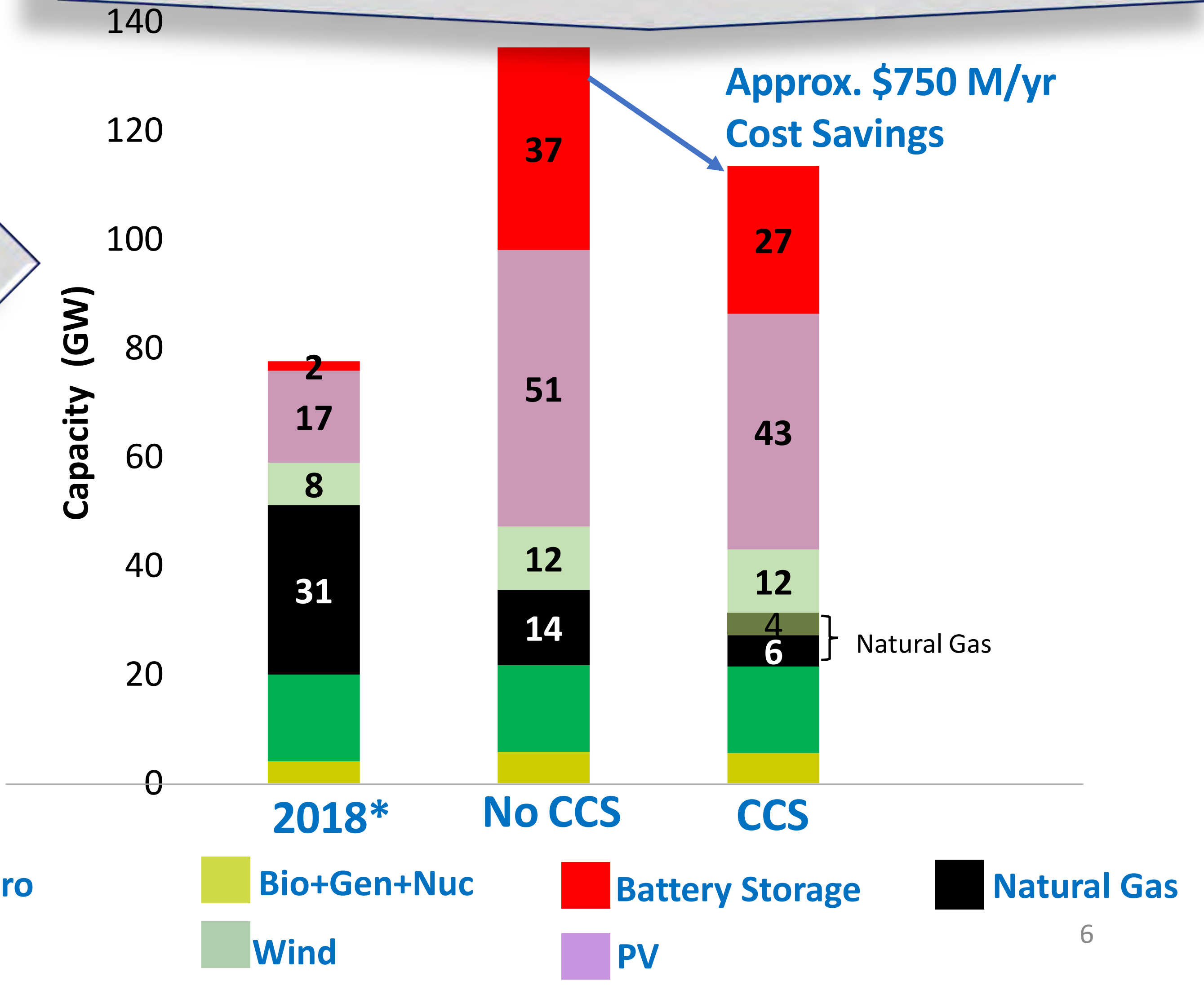
Source: Energy Futures Initiative, 2019. Compiled using data from CAISO, 2017

Hourly trends in solar and wind capacity factors in CA for 2017 aligned to normalized variation in hourly load relative to peak daily load

What CCS Can Do for California: Enable Affordable Clean Firm Power and Renewable

System capacity in 2018 and 2030 for a scenario with and without NGCC-CCS. The scenario with **CCS shows approx. 4 GW of CCS in the system, and overall lower capacity needs than a system without CCS.** The annual generation system cost for a scenario with CCS is approximately $750 million/year lower as well.

...and enable continued reliability benefits from clean firm power generation at lower cost



Note: *Capacities include in-state generation capacity and out-of-state generation capacity dedicated to California. *2018 Baseline is California's generating capacity based on 2018 eGRID database including planned natural gas and nuclear retirements, as well as planned capacity additions for PV and wind.*

Note: figure updated 10/25/20 to reflect final results

Source: Energy Futures Initiative and Stanford University, 2020.

What CCS Can Do for California: Enabling New Clean Energy Industries and Jobs

ENERGY FUTURES INITIATIVE

Stanford SCHOOL OF EARTH, ENERGY & ENVIRONMENTAL SCIENCES | Stanford Center for Carbon Storage

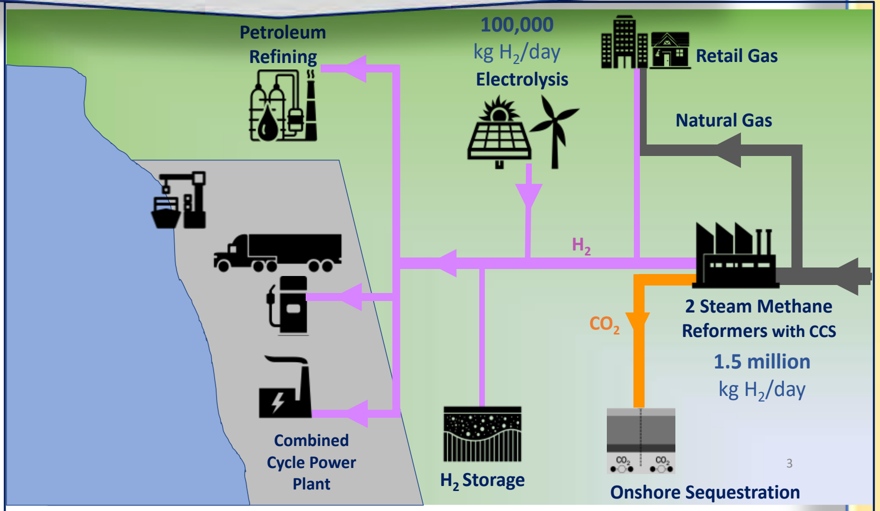
Stanford | ENERGY Precourt Institute for Energy

... Unlock new, potentially multi-billion-dollar clean energy industries, creating new jobs in the process.

Enable Carbon Dioxide Removal/Direct Air Capture Industry

Similarities with CCS

- Improved process energy efficiency
- Lifecycle analyses
- Low-carbon capture requirements/ systems
- Low-carbon heat
- **Geologic storage**
- Material manufacturing & scale-up
- Novel: catalysts; membranes; solvents; sorbents
- Simulation
- Sensors and controls



Support Development of A Hydrogen Economy

- Half of ports' drayage fleet (5,000 trucks)
- Entire ports' electricity requirement (50MW/h)
- 80% of SCG's petroleum refiner demand
- 10% of SCG's residential gas demand (as blend)
- CO_2 sequestration equivalent to half an average coal plant emissions

Translate Oil and Gas Skillsets to CCS Industry Job

Opportunities for Using Existing Carbon Infrastructure for Decarbonization

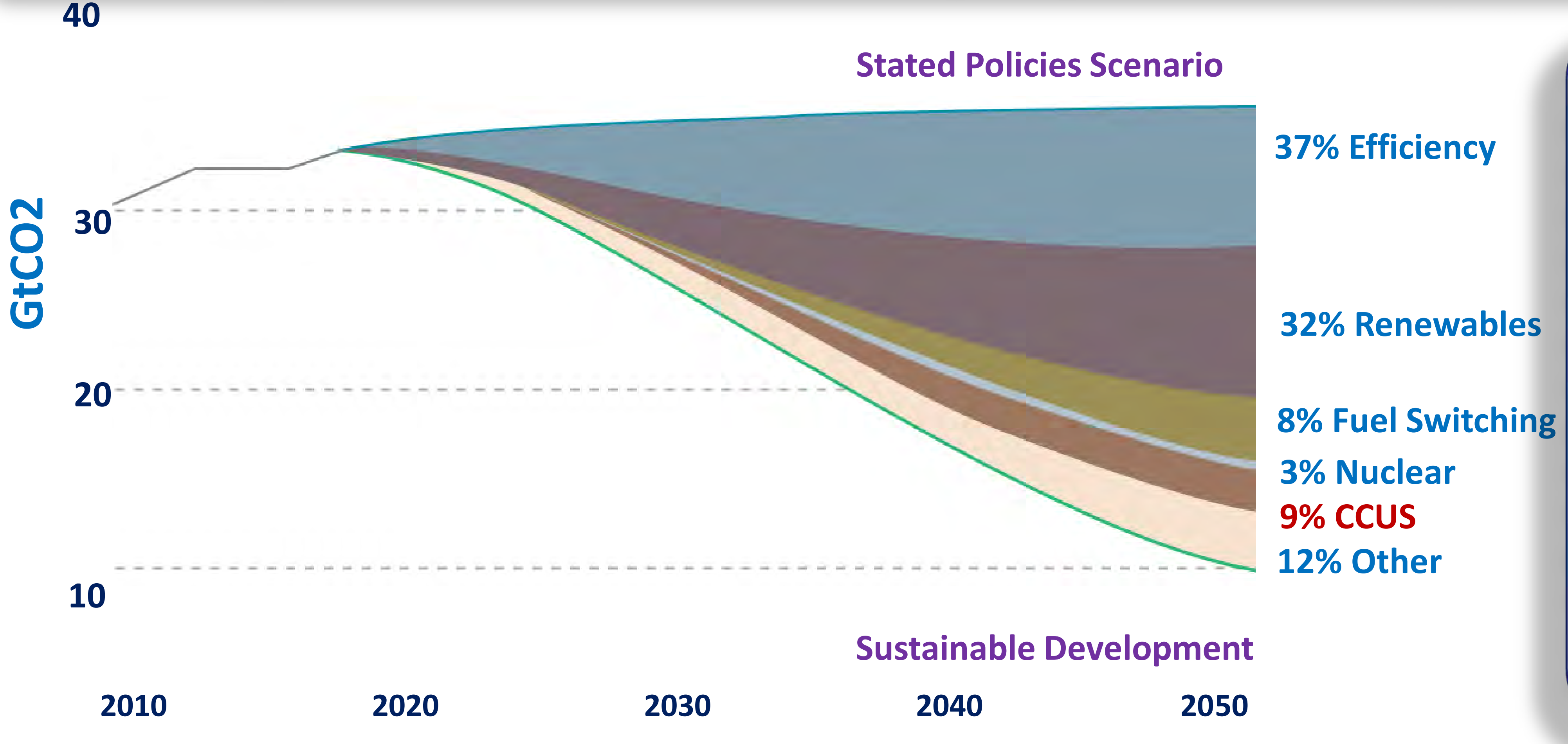
	Oil Refineries & Gas Processing	Natural Gas Generation	Oil & Gas Pipelines	Waterborne Transportation & Ports	Storage
Negative Emissions Technologies /Carbon Capture, Utilization, and Storage (CCUS)	• Applying industry expertise to CCUS technologies for direct-air capture (DAC) and bioenergy with carbon capture and storage (BECCS)	• Applying industry expertise: CCUS technologies for DAC and BECCS	• Using compression technologies similar to those in NG infra-structure for CO_2 • Rail and roadway = existing infrastructure • Leveraging pipeline rights-of-way	• Using industry expertise in lique-faction and trans-port of LPG/LNG for liquid CO_2 • Marine vessels for CO_2 using the same technology as existing LPG or LNG tankers • Port infrastructure for loading • Offshore facilities for subsea injection	• Using saline formations, depleted O&G reservoirs, un-mineable coal seams, basalt formations • Using industry expertise in large-scale CO_2 separ[illegible] and sequest[illegible] • Applying tec[illegible] drilling and inje[illegible] subsurface characteriza[illegible] and site monitoring, same as in the O&G sector • Leveraging similarities with NG storage, acid gas disposal, and CO_2-EOR

"The oil and gas industry…[w]as a major employer and leading economic drive in California responsible for 368,100 jobs in 2015, or 1.6 percent of California's employment, with almost $66 billion in total value-added, contributing 2.7 percent of California's state product." *-LA County Economic Development Corporation*

Source: Energy Futures Initiative and Stanford University, 2020.

CCS: An Important Technology for Meeting Global Sustainable Development Targets

“Reaching net zero will be virtually impossible without CCUS” IEA, 02/20



“Our collective failure to act early and hard on climate change means we now must deliver deep cuts to emissions... We need quick wins to reduce emissions as much as possible in 2020... We need to catch up on the years in which we procrastinated... If we don’t do this, the 1.5°C goal will be out of reach before 2030.”
UNEP Executive Director, 0919

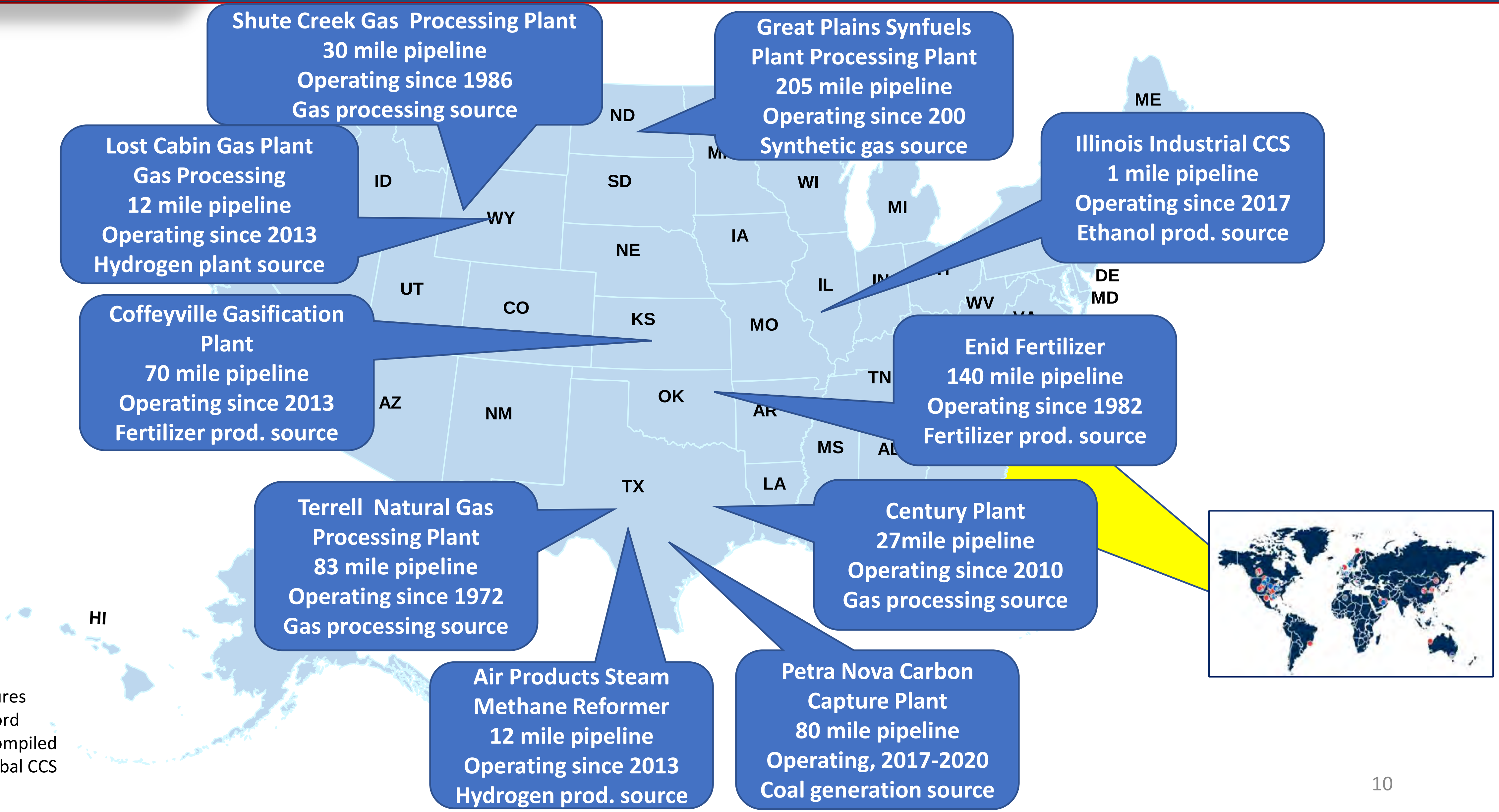
Source: Adapted from IEA, 2019

Global CCS Projects, 2019

Large scale CCS facilities in operation or under construction
Large scale CCS facilities in advanced development
Large scale CCS facilities completed
Pilot and demo in operation or under construction
Pilot & demo scale facility in advanced dev.
Pilot & demo scale facility completed
Test center

Source: Global Status of CCS, 2019, Global CCS Institute

US CO_2 Project, Emissions Sources, Age



Source: Energy Futures Initiative and Stanford University, 2020. Compiled using data from Global CCS Institute, 2020.

CCS in CA: Agencies of Jurisdiction, Projects Seeking LCFS Incentives

Application Process for Projects Seeking LCFS Credits, and Project Dependent Requirements

Agencies of Jurisdiction	Electricity	Industry	Agencies of Jurisdiction
CEC	Authority to Construct **and** Permit to Operate		Local Air District
EPA Region 9 CEC, CALGEM	Class VI permit **or** Class II permit		EPA Region 9 CALGEM
CEC CEC, Federal Lead Agency	CEQA Process **or** Joint CEQA/NEPA Process		State/Local Lead Agency Federal Lead Agency, State/ Local Lead Agency
CARB	LCFS Permanence Certification & Credit Generation Application		CARB

Project Dependent Permitting Requirements

Coastal	**Federal land**	**Federal Waters**	**Attainment Area**	**CA Lake, Stream, River**	**Municipal Zones**	**Endangered Species**
State Development Permits	Right of Way	404, NPDES Permits	New Source Review: PSD	Alteration Agreement	Conditional Use Permits	State, Fed Permits

Source: Energy Futures Initiative and Stanford University, 2020.

Four In-Development CCS Projects Pursuing LCFS, as of October 2020

Clean Energy System. Existing, mothballed biomass facility in California with new technologies to produce hydrogen through gasification of biomass and capture of CO_2. Onsite geologic storage into saline reservoir via short pipeline.

California Resources Corporation. Existing and operating NGCC used for combined heat and power (CHP) located within an oilfield in California paired with post-combustion carbon capture facility. Captured CO_2 is transported onsite via pipeline to injection well(s) for EOR.

Interseqt LLC (White Energy and Oxy Low Carbon Ventures). Two existing ethanol plants in Texas which sell bioethanol into California for fuel blending, each paired with carbon capture equipment. Captured CO_2 will be injected for EOR.

1PointFive (Oxy Low Carbon Ventures and Rusheen Capital Management) and Carbon Engineering. DAC facility located in Texas. Captured CO_2 will be injected for EOR.

ENERGY FUTURES INITIATIVE

Stanford SCHOOL OF EARTH, ENERGY & ENVIRONMENTAL SCIENCES | Stanford Center for Carbon Storage

Stanford | ENERGY Precourt Institute for Energy

Assessment of Opportunities for CCS in California

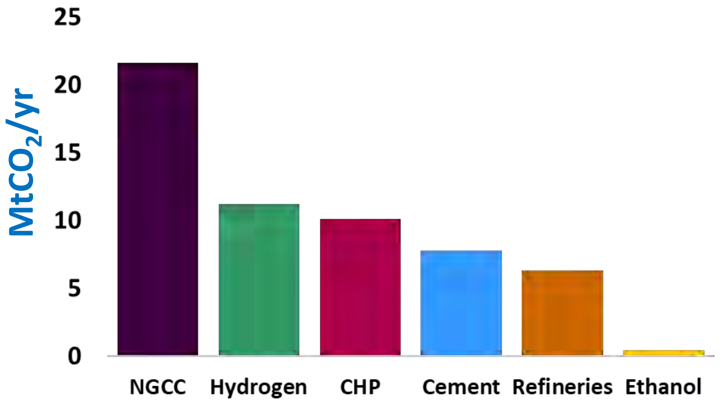
CO_2 Source Identification
- Industry
- Electricity

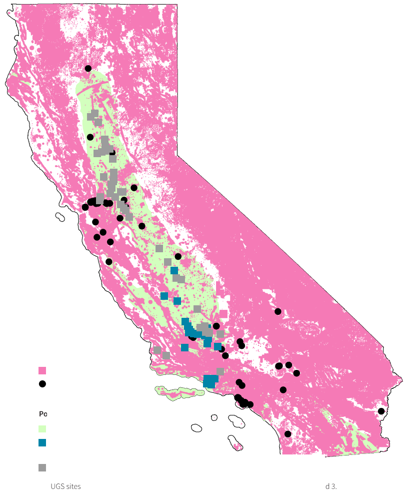
Assessment of Storage Potential
- Oil and gas reservoirs
- Saline Formations

Technoeconomic Analysis
- SB100 2030 goals
- Source/Sink Matching
- Cash flow analysis

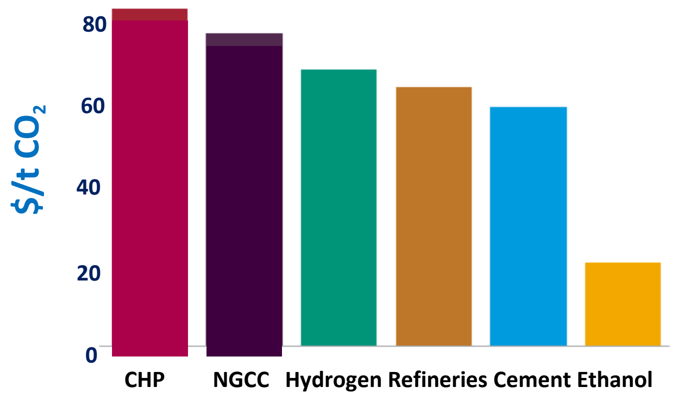
Social Equity & Community Benefits
- Local Air Quality
- Jobs

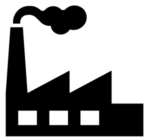
Current CO_2 Emissions





Capture Costs



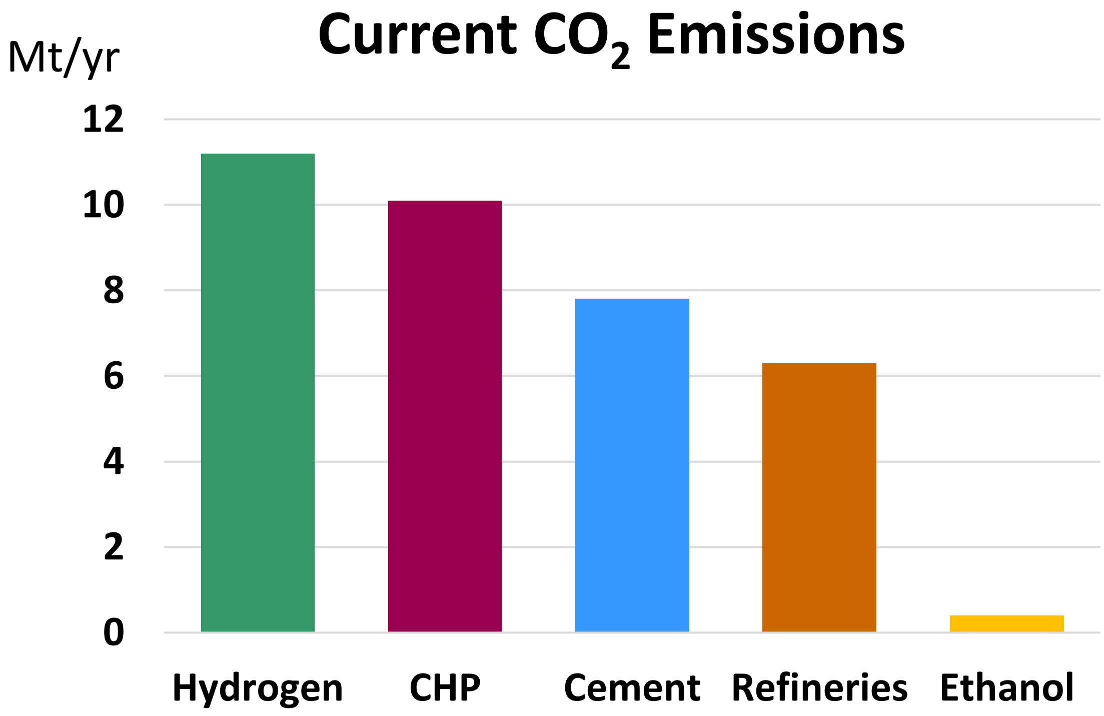


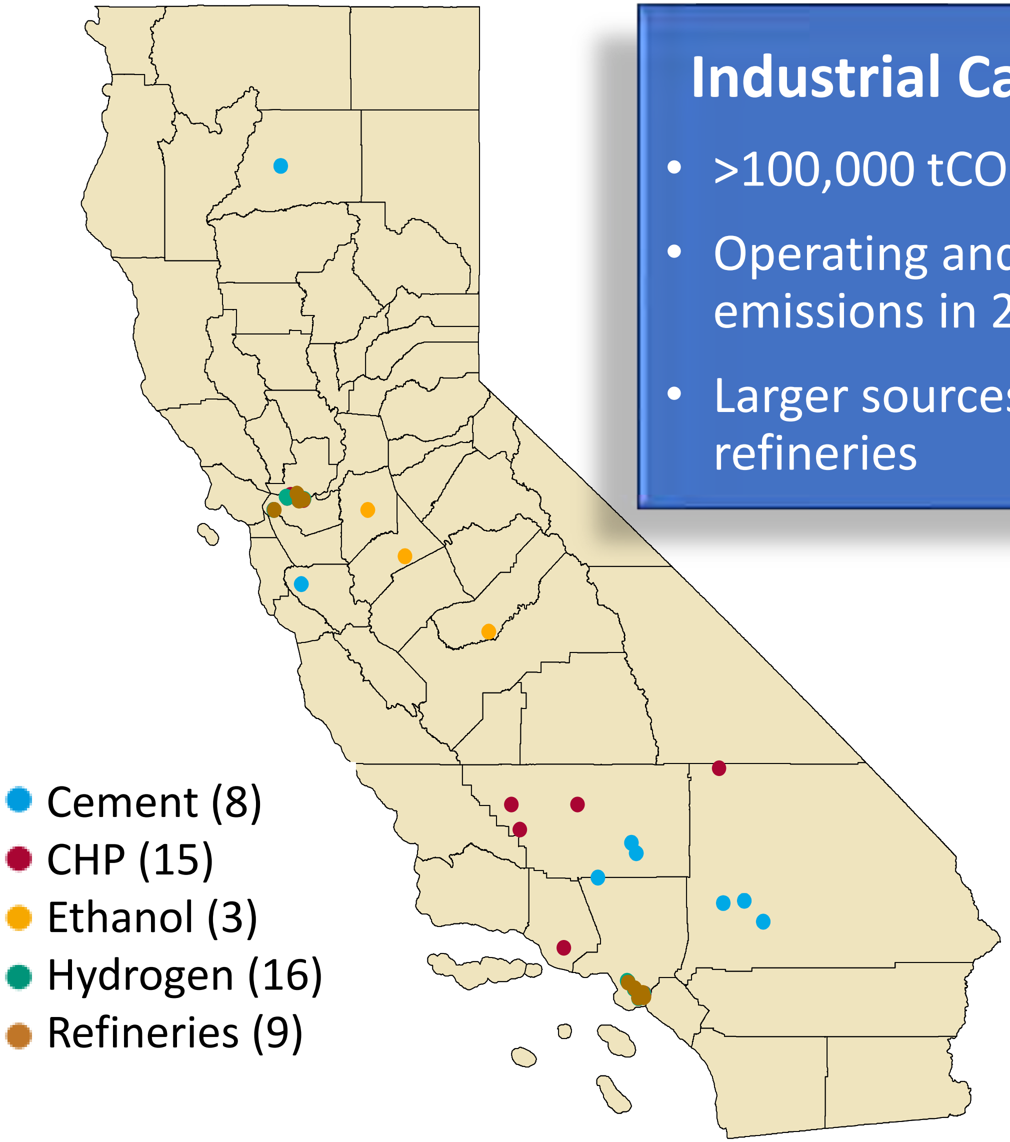
Source: Energy Futures Initiative and Stanford University, 2020.

Opportunities for CCS in the Industrial Sector

Industry Sources

- 35.8 $MtCO_2$/yr current emissions
- 31.8 $MtCO_2$ /yr capturable emissions
- 51 Facilities





Industrial Candidates

- >100,000 tCO_2/yr
- Operating and reporting emissions in 2018
- Larger sources at refineries

Source: Energy Futures Initiative and Stanford University, 2020.

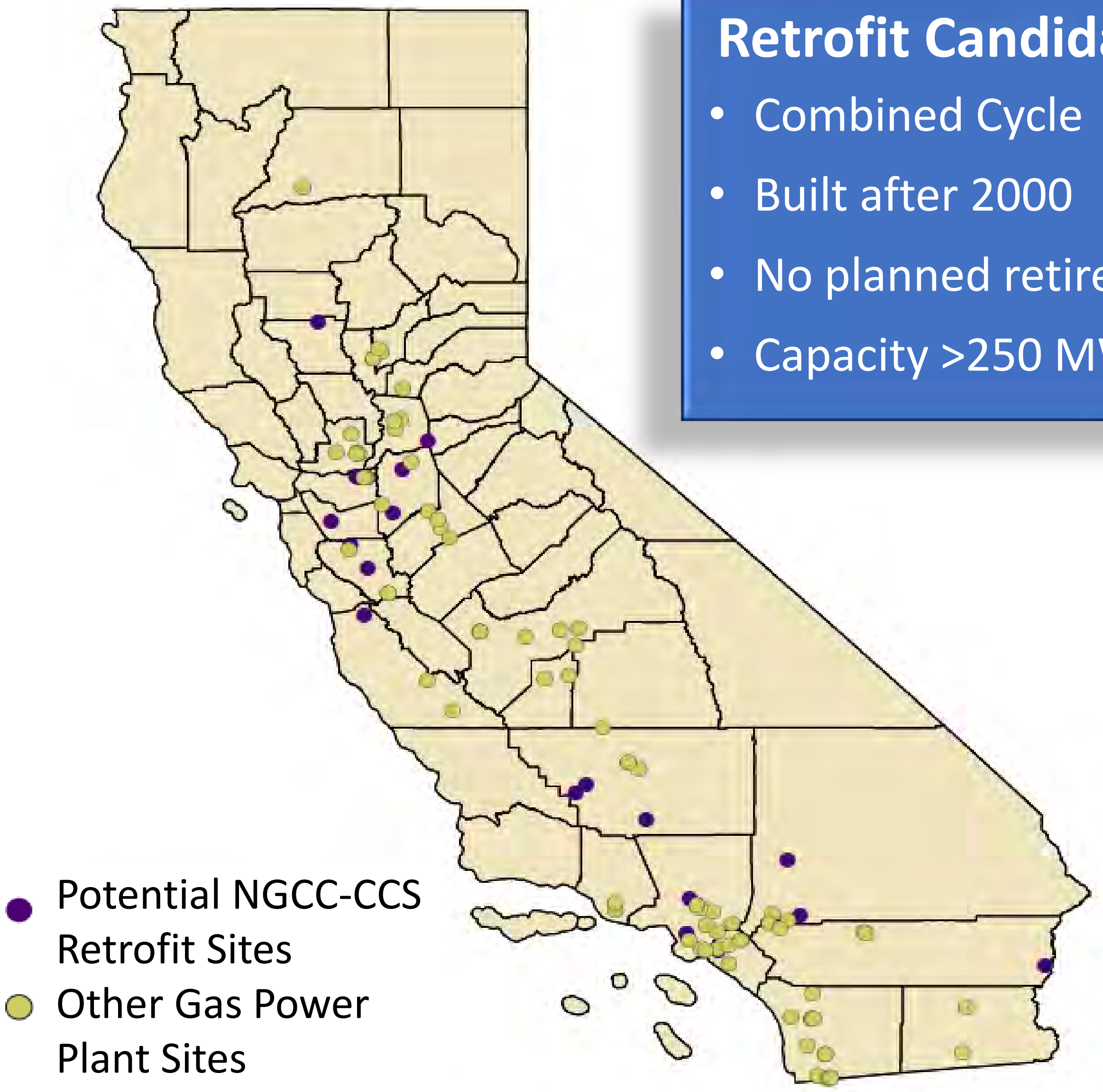
Opportunities for CCS Electricity Sector in California

- 25 natural gas combined cycle (NGCC) power plants meet CCS retrofit criteria
- 14 GW total capacity
- 21.6 $MtCO_2$/yr current emissions
- 27.5 capturable emissions $MtCO_2$/yr*

* Capacity factor to increase to 60%

Retrofit Candidates

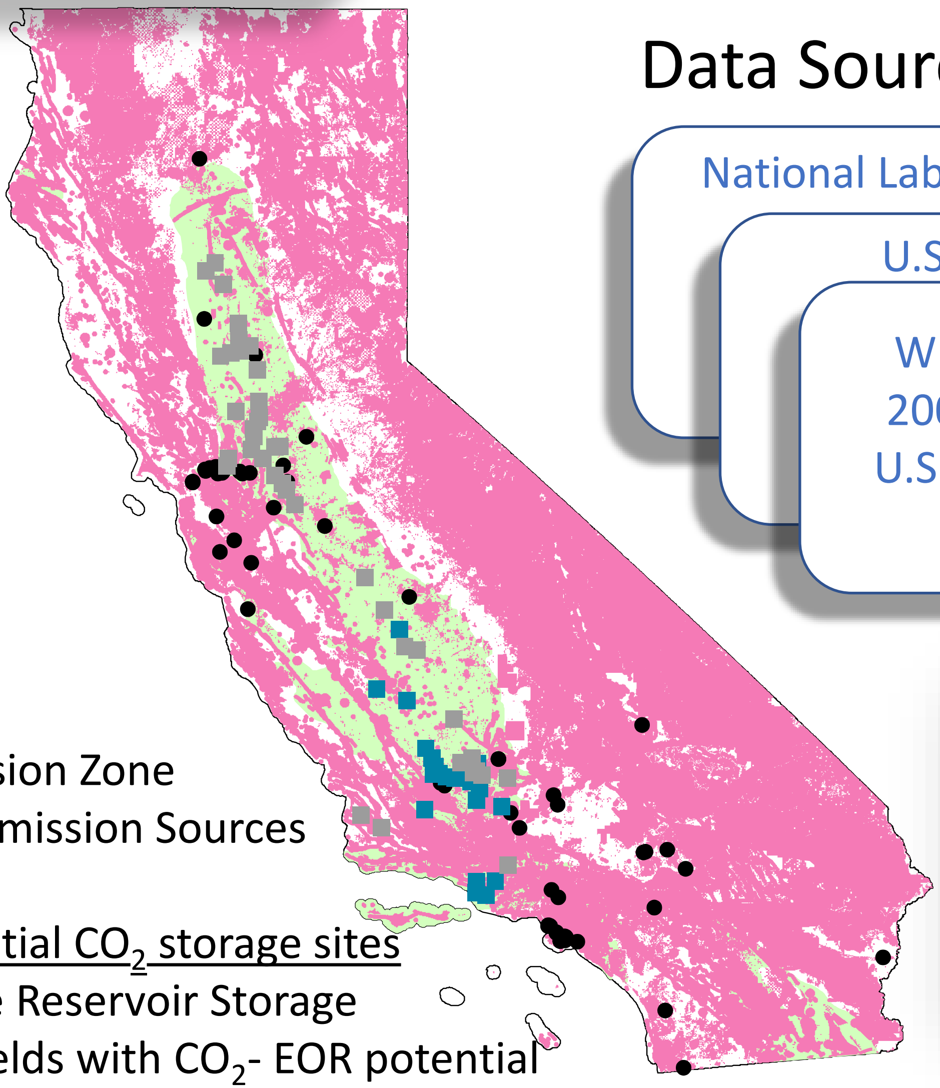
- Combined Cycle
- Built after 2000
- No planned retirement
- Capacity >250 MW



Source: Energy Futures Initiative and Stanford University, 2020.

California Has Abundant and High-Quality CO_2 Storage Resources

ENERGY FUTURES INITIATIVE
Stanford SCHOOL OF EARTH, ENERGY & ENVIRONMENTAL SCIENCES | Stanford Center for Carbon Storage
Stanford | ENERGY Precourt Institute for Energy



- Exclusion Zone
- CO_2 Emission Sources

<u>Potential CO_2 storage sites</u>
- Saline Reservoir Storage
- Oil Fields with CO_2- EOR potential
- Other Oil & Gas Fields

Data Sources

- National Labs
- U.S.G.S.
- WESTCARB 2003 - 2013 U.S. DOE and CEC

Screening Criteria

STAGE 1 + **STAGE 2** = **STAGE 3**

STAGE 1: **Qualify** sites and saline reservoirs
- Apply LCFS and EPA Class 6 minimum criteria
- Apply additonal "disallowed" conditions

STAGE 2: **Develop Exclusion Layer** consisting of geographic information (e.g. faulting, seismicity, population density, sensitive habitats, restricted lands)

STAGE 3: **Storage Opportunity Identification** by merging qualified sites with exclusion layer.

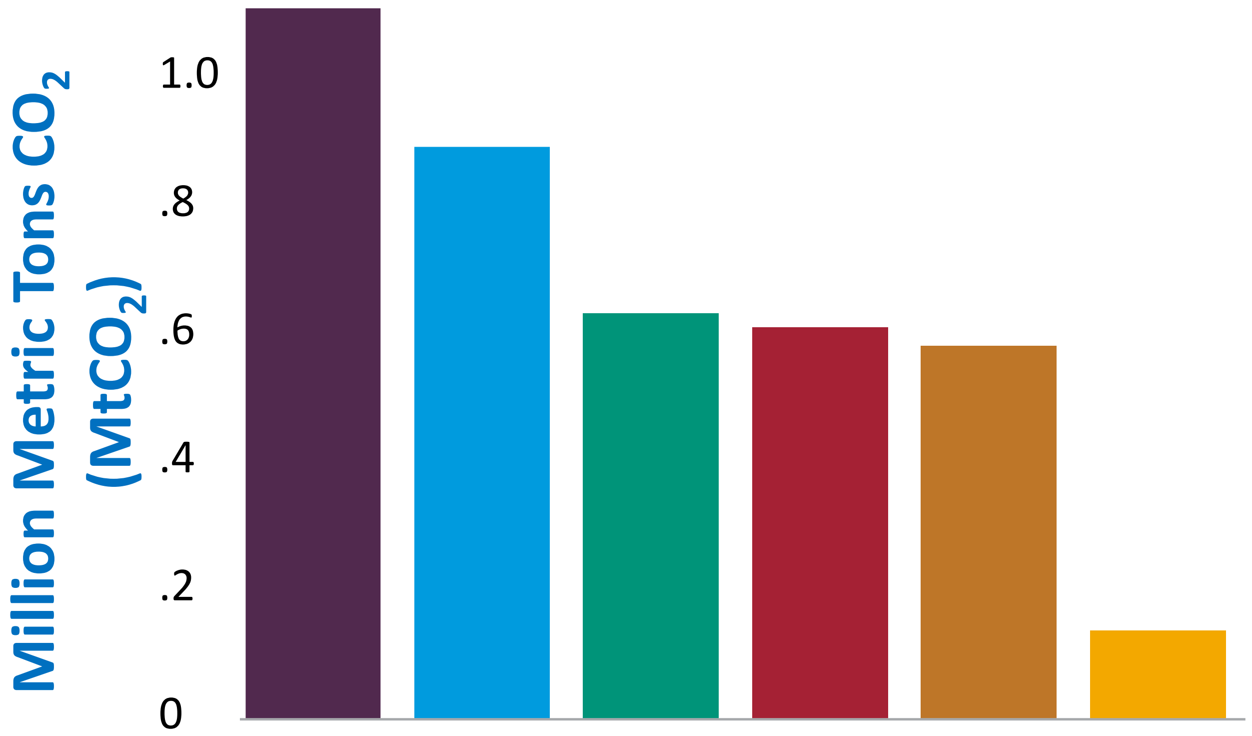
	Storage Capacity (GT CO_2)	
Saline Formations	70	
Oil and Gas	Low	High
	1.1	2.1

California could store 60 Mt/year for more than 1000 years.

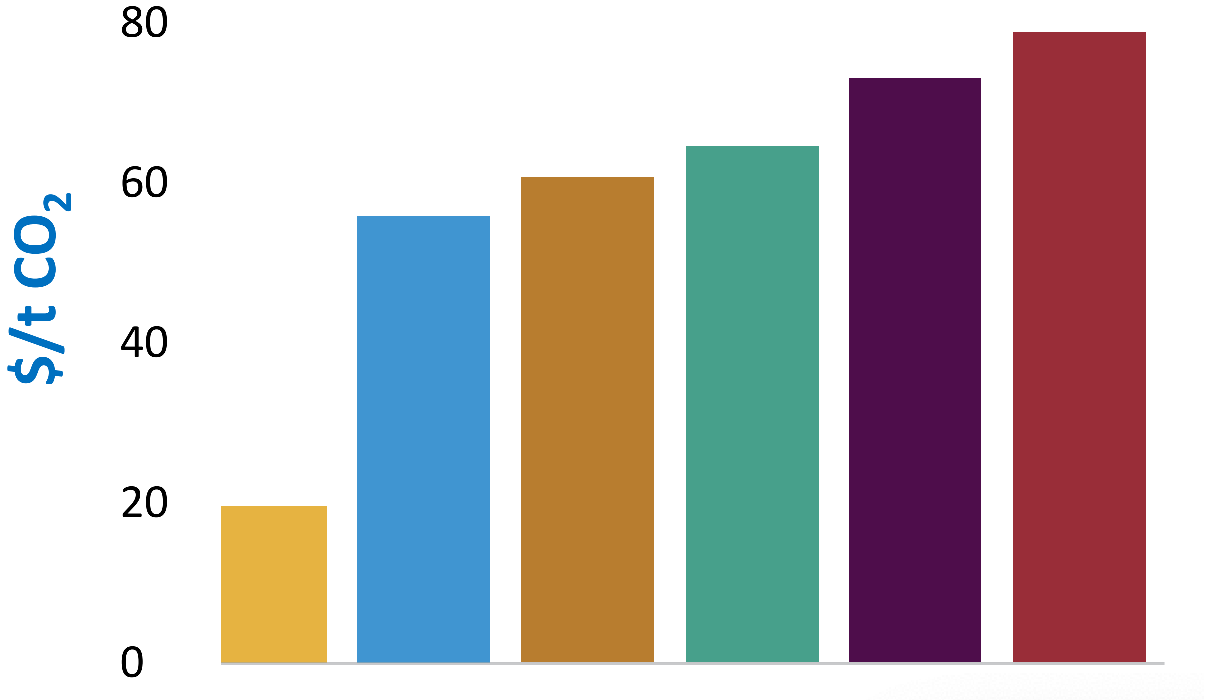
Source: Energy Futures Initiative and Stanford University, 2020.

Comparison of Emissions and Capture Costs by Subsector

Average Emissions for Different CO_2 Capture Sources



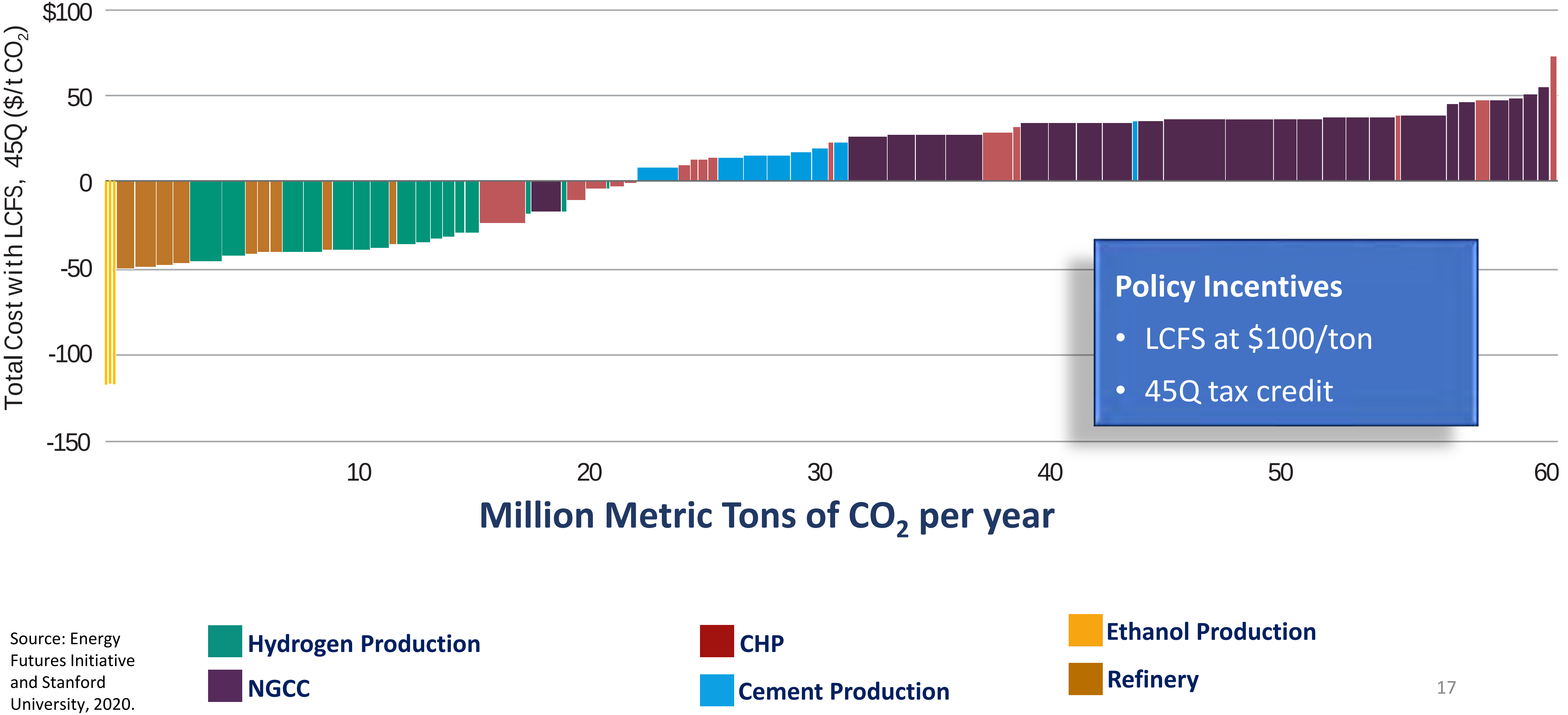
Average Cost for Capture for Different CO_2 Sources



Hydrogen Production
NGCC
CHP
Cement Production
Ethanol Production
Refinery

Source: Energy Futures Initiative and Stanford University, 2020.

With Current Incentives About 20 $MtCO_2$/yr Could Be Captured Cost Effectively



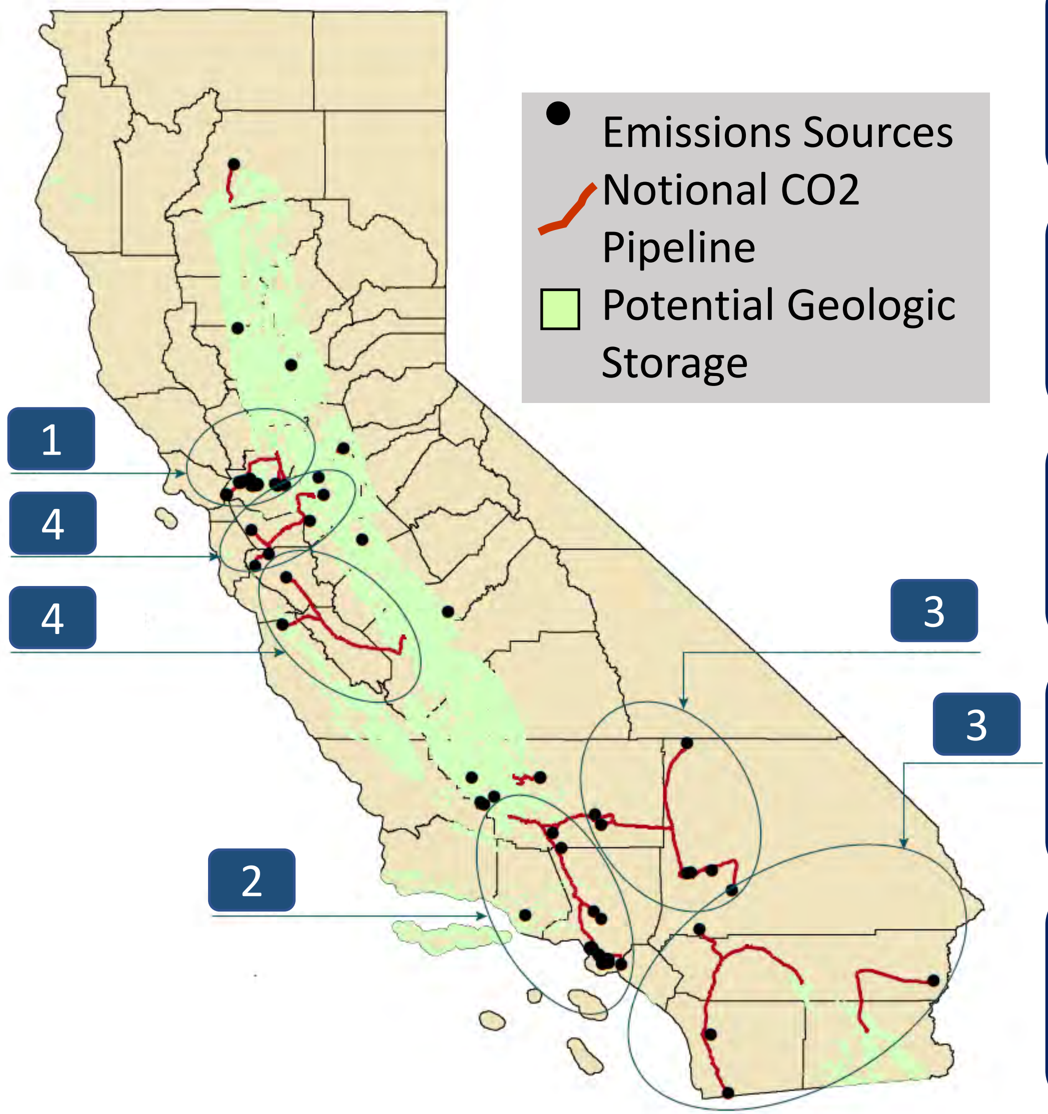
Source: Energy Futures Initiative and Stanford University, 2020.

ENERGY FUTURES INITIATIVE

Stanford SCHOOL OF EARTH, ENERGY & ENVIRONMENTAL SCIENCES | Stanford Center for Carbon Storage

Stanford | ENERGY Precourt Institute for Energy

Infrastructure Buildout for 60 $MtCO_2$/yr CCS

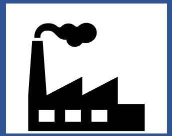


Co-located capture and storage	• 3 ethanol plants, 6 NGCC, 6 CHPs and 1 cement plant
1. Northern California Gathering System and Storage Hub	• 8 hydrogen 4 refineries, 5 CHPs, and 3 NGCC
2. Southern California Gathering System and Storage Hub	• 8 hydrogen, 5 refineries, 4 CHPs, 1 cement, and 5 NGCC
3. Desert and Salton Sea Gathering Systems	• 5 cement, 1 CHP, 6 NGCC
4. Central California and S. Bay Gathering System	• 1 cement, 5 NGCC

Source: Energy Futures Initiative and Stanford University, 2020.

Social Equity and Community Benefits

Local Air Quality Improvements



- Some industrial facilities with high CO_2 emissions also emit high levels of criteria air pollutants such as sulfur dioxide (SO_2), nitrous dioxide (NO_2), and particulates
- **Post-combustion carbon capture requires reduction of these other pollutants creating local air quality benefits**

Local Economic Activity

- CCS projects can **stimulate local economic activity**, including new construction, operations, and maintenance jobs
- **Multiplier effects across the supply chain can drive additional economic benefits**

Job Creation and Preservation

- The economic benefits associated with **job training** could provide new employment opportunities in the low carbon economy
- CCS activities support **employment** for skill sets which may otherwise become obsolete in a clean energy transition

Source: Energy Futures Initiative and Stanford University, 2020.

ENERGY FUTURES INITIATIVE

Stanford SCHOOL OF EARTH, ENERGY & ENVIRONMENTAL SCIENCES | Stanford Center for Carbon Storage

Stanford | ENERGY Precourt Institute for Energy

Engaging Stakeholders to Identify Challenges for CCS

Industry/Affiliation	#
Cement	3
Chemicals	3
Diversified Energy	15
Environmental Advocacy	5
Infrastructure	8
Investment	3
Labor Unions	2
Power	6
Private Equity	2
Public Sector	3
Refinery	5
Reinsurance	2
Utility	2
Total*	**59**

* Indicates number of interviews; most interviews included multiple interviewees.

- Technology developers
- Industry
- Power producers
- Project financers
- NGOs

Stakeholder interviews

- Ambiguity
- Regulatory complexity
- Financial uncertainty
- Education and public support

Assessment of challenges

Analysis identified key challenges for CCS project development in California through interviews with project developers, financiers, and industry stakeholders, as well as archival research and analysis of California's policy landscape.

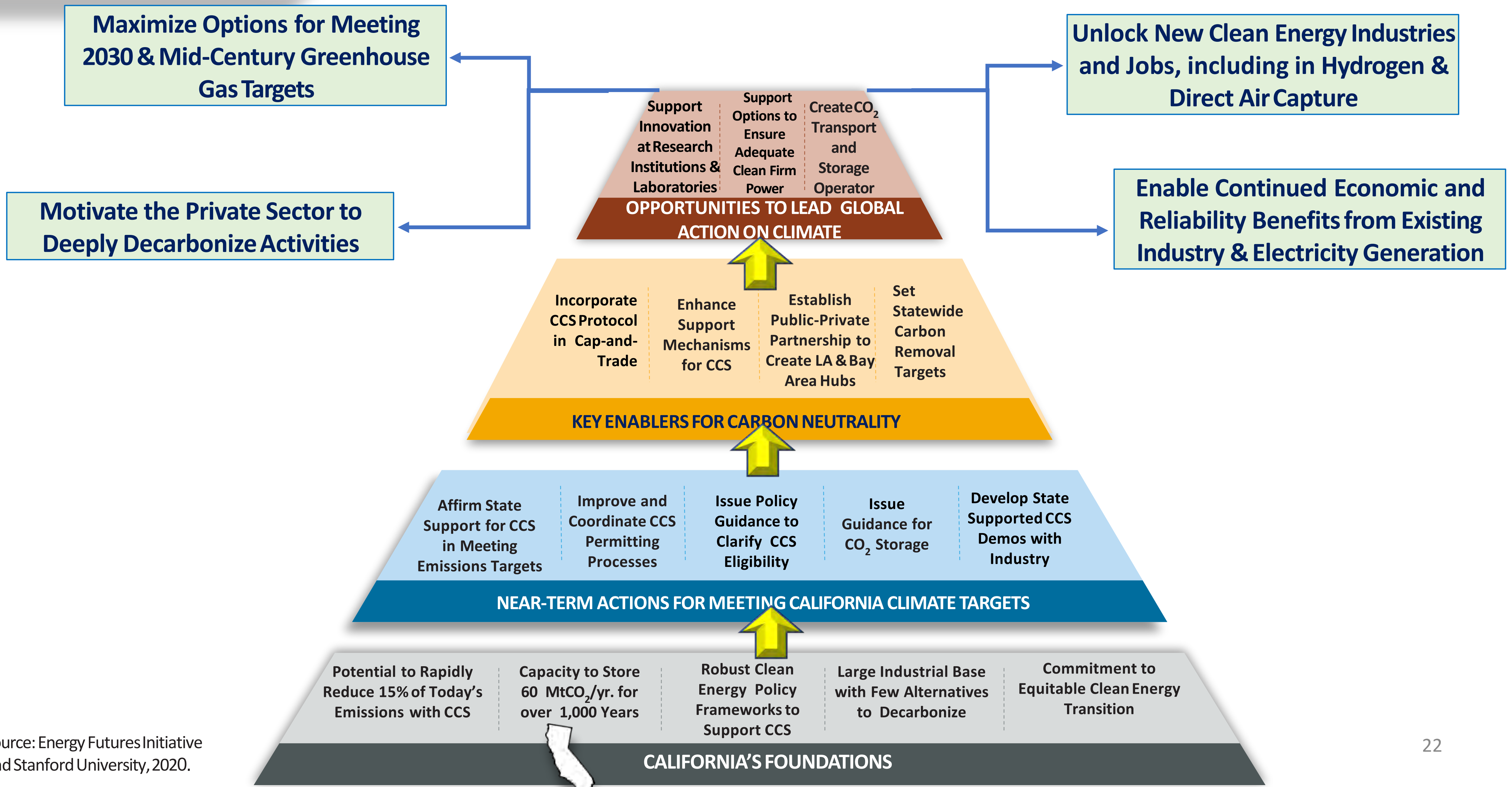
Source: Energy Futures Initiative and Stanford University, 2020.

Complexity and Uncertainty Reduce Attractiveness of Investment in CCS

Ambiguous Position of the State on the Future Role of CCS	Complex and Untested Regulatory Process for Getting Permits for CCS	Revenue and Cost Uncertainty Discourage Project Finance	Lack of Public Awareness and Support for CCS
CCS Ineligible Under Cap-and-Trade	Numerous Regulatory Jurisdictions and Unclear CEQA Lead for Industry CCS Projects	Revenue Challenge: LCFS Credit Market Uncertainty and Policy Risk	Concern that CCS Allows for Continued Fossil Fuel Use
Unclear Eligibility of CCS for SB100 Zero-Carbon Electricity Target	Uncertain Permitting Timelines	Revenue Challenge: Limitations of the Federal 45Q Tax Credit Design	Low Public Awareness and Varied Opinions of CCS
CCS is Not Included in Other State Energy Planning	State and Federal Post-Injection Site Care Requirements Vary	Cost Challenge: Aligning Players, Permitting, and Financing	Historic Inequities in Energy Infrastructure Siting
	Inadequate Legal Framework for Obtaining Pore Space Rights	Cost Challenge: Financial Responsibility Associated with UIC Class VI Wells	

Source: Energy Futures Initiative and Stanford University, 2020.

A Policy Action Plan for CCS in California to Meet the High-Level Goals



Source: Energy Futures Initiative and Stanford University, 2020.

Near-Term Actions for Meeting California's Climate Targets with CCS

ENERGY FUTURES INITIATIVE | Stanford SCHOOL OF EARTH, ENERGY & ENVIRONMENTAL SCIENCES | Stanford Center for Carbon Storage | Stanford ENERGY Precourt Institute for Energy

Issue Policy Guidance to Clarify CCS Eligibility

As new energy technologies emerge, questions often emerge of their compatibility with existing policies and regulations.

- *California could incorporate CCS into its biennial integrated resource plan and long-term procurement planning process.*
- *California could make CCS an eligible resource under the SB100 goal of 100 percent of retail electricity sales from renewable and zero-carbon resources by 2045.*

Develop State Supported CCS Demos with Industry

Demonstration projects could provide valuable insights into the technical and regulatory challenges of a CCS project.

- *California should consider supporting a large CCS demonstration project to help overcome high at-risk costs in the project's early stages; untested permitting processes throughout the value chain; and public acceptance of CCS.*
- *California could prioritize projects that have demonstratable local air quality benefits and local job opportunities in line with its climate and equity goals.*

Affirm State Support for CCS in Meeting Emissions Targets	Improve and Coordinate CCS Permitting Processes	Issue Policy Guidance to Clarify CCS Eligibility	Issue Guidance for CO_2 Storage	Develop State Supported CCS Demos with Industry

NEAR-TERM ACTIONS FOR MEETING CALIFORNIA CLIMATE TARGETS

Source: Energy Futures Initiative and Stanford University, 2020.

Key Enablers for Carbon Neutrality

Incorporate CCS Protocol into Cap-and-Trade Program

CCS is not an eligible pathway under California's Cap-and-Trade program. There is no incentive for covered entities to deploy CCS though it could contribute large emission reductions.

- *CARB could adopt the CCS Protocol from the LCFS program into the existing Cap-and-Trade Program to provide additional financial incentive for projects to pursue CCS. This is especially important for NGCCs and cement, which are not eligible for LCFS credits but are covered under Cap-and-Trade.*

Incorporate CCS Protocol in Cap-and-Trade	Enhance Support Mechanisms for CCS	Establish Public-Private Partnership to Create LA & Bay Area Hubs	Set Statewide Carbon Removal Targets

KEY ENABLERS FOR CARBON NEUTRALITY

Source: Energy Futures Initiative and Stanford University, 2020.

ENERGY FUTURES INITIATIVE

Stanford SCHOOL OF EARTH, ENERGY & ENVIRONMENTAL SCIENCES | Stanford Center for Carbon Storage

Stanford | ENERGY Precourt Institute for Energy

Opportunities to Lead Global Action on Climate Change

Support Options to Ensure Adequate Clean Firm Power

Studies show clean firm resources can have significant benefits to a deeply decarbonized electric grid. Clean firm resources can reduce overall system costs, complement renewable energy resources, and enable overall operational flexibility. These benefits will be even more critical as California faces increasing threats from climate change.

California should support policies that:

- *provide a more precise understanding of how much firm power is needed for a grid that is decarbonizing;*
- *inform grid reliability planning processes;*
- *identify key technologies for providing clean firm power; and*
- *identify policy options for the scaleup and deployment of those technologies that are essential for ensuring reliable, affordable, and clean power.*

Support Innovation at Research Institutions & Laboratories

Support Options to Ensure Adequate Clean Firm Power

Create CO_2 Transport and Storage Operator

OPPORTUNITIES TO LEAD GLOBAL ACTION ON CLIMATE

Source: Energy Futures Initiative and Stanford University, 2020.

ENERGY FUTURES INITIATIVE
Stanford SCHOOL OF EARTH, ENERGY & ENVIRONMENTAL SCIENCES | Stanford Center for Carbon Storage
Stanford | ENERGY Precourt Institute for Energy

Thank You for Joining Us!

- California has some of the most ambitious decarbonization targets in the country. Additional actions to accelerate meeting these targets—by a coalition of Californians—are needed to ensure that the state rapidly and equitably transitions to a carbon neutral economy.
- **Strong foundations for CCS in California** include: the urgent need for rapid emission reductions; policy support from LCFS CCS Protocol; the commercial readiness of CCS; commitment to equitable and clean transition, among others.
- **Opportunities to leverage CCS to rapidly decarbonize and create new clean industries and jobs**:
  - sizeable geologic storage resources
  - the need for clean firm electricity generation as intermittent renewable generation grows;
  - the need for clean transportation fuels, such as hydrogen;
  - and the state's experience advancing strong climate policies and innovative industries.
- **An Action Plan for Policymakers was developed to fulfill California's CCS potential and to:**
  - ✓ Maximize the value of CCS for meeting the state's economywide decarbonization goals
  - ✓ Motivate the private sector to decarbonize
  - ✓ Enable economic and reliability benefits from existing industries and power generation, and
  - ✓ Unlock new clean energy industries and jobs

Thank You to Our Project Team

PROJECT EXECUTIVES

SALLY M. BENSON
Stanford University

MELANIE KENDERDINE
Energy Futures Initiative

PROJECT MANAGERS

ANNE CANAVATI
Energy Futures Initiative

SARAH D. SALTZER
Stanford University

CONTRIBUTING AUTHORS

EJEONG BAIK
Stanford University

ALEX BRECKEL
Energy Futures Initiative

JEFF BROWN
Brown Brothers Energy & Environment, LLC

VICTOR CARY
Energy Futures Initiative

STEPHEN COMELLO
Stanford University

ALEX KIZER
Energy Futures Initiative

ALEX MARANVILLE
Energy Futures Initiative

ADDITIONAL CONTRIBUTORS

ERICK ARAUJO
Stanford University

JUSTIN BRACCI
Stanford University

TIM BUSHMAN
Energy Futures Initiative

MAX DRICKEY
Energy Futures Initiative

DAVID ELLIS
Energy Futures Initiative

CATHERINE HAY
Stanford University

JOE HEZIR
Energy Futures Initiative

TAE WOOK KIM
Stanford University

ANTHONY R. KOVSCEK
Stanford University

TOM MILLER
Stanford University

JEANETTE PABLO
Energy Futures Initiative

RICHARD RANDALL
Energy Futures Initiative

EMILY TUCKER
Energy Futures Initiative

NATALIE VOLK
Energy Futures Initiative

SEAN YAW
Montana State University

MARK ZOBACK
Stanford University

Thank You to Our Advisory Board

EFI and Stanford wish to thank the following individuals for contributing subject-matter expertise during the development of this study. Their participation does not imply endorsement of the analysis approach or conclusions.

BOARD CO-CHAIRS

ERNEST MONIZ
Energy Futures Initiative

FRANKLIN ORR
Stanford University

BOARD MEMBERS

MATTHEW BARMACK
Calpine

BRIAN CHASE
Chevron & OGCI

JAMES HARRISON
Utility Workers Union of America

DAVID HAWKINS
Natural Resources Defense Council

JANE LONG
Environmental Defense Fund

DEEPIKA NAGABHUSHAN
Clean Air Task Force

KATIE PANCZAK
DTE Energy

GEORGE PERIDAS
Lawrence Livermore National Lab

CARLA PETERMAN
Southern California Edison

DAN REICHER
Stanford University Law School

MAXINE SAVITZ
National Academy of Engineering

JOHNNY SIMPSON
IBEW International 9th District

ERIC TRUSIEWICZ
Breakthrough Energy Ventures & Stanford University

ROGER ULLMAN
Linden Trust for Conservation

Thank You to Our Sponsors

EFI and Stanford would like to thank the following organizations for sponsoring this report.

WILLIAM AND FLORA HEWLETT FOUNDATION

LINDEN TRUST FOR CONSERVATION

CASE FOUNDATION

STEPHENSON FOUNDATION

OIL AND GAS CLIMATE INITIATIVE (OGCI)

CALPINE CORPORATION

UNITED MINE WORKERS OF AMERICA

CALIFORNIA STATE ASSOCIATION OF ELECTRICAL WORKERS

STATE BUILDING & CONSTRUCTION TRADES COUNCIL OF CALIFORNIA

INTERNATIONAL BROTHERHOOD OF BOILERMAKERS

ENVIRONMENTAL RESEARCH
LETTERS

LETTER • OPEN ACCESS

Does replacing coal with wood lower CO_2 emissions? Dynamic lifecycle analysis of wood bioenergy

To cite this article: John D Sterman *et al* 2018 *Environ. Res. Lett.* **13** 015007

Environmental Research Letters

OPEN ACCESS

RECEIVED
29 August 2017

REVISED
1 December 2017

ACCEPTED FOR PUBLICATION
4 January 2018

PUBLISHED
18 January 2018

LETTER

Does replacing coal with wood lower CO_2 emissions? Dynamic lifecycle analysis of wood bioenergy

John D Sterman[1,4], **Lori Siegel**[2] **and Juliette N Rooney-Varga**[3]

[1] MIT Sloan School of Management, 100 Main Street, Cambridge, MA 02139, United States of America
[2] Climate Interactive, 1201 Connecticut Avenue NW, Suite 300, Washington, DC, 20036, United States of America
[3] UMass Lowell Climate Change Initiative and Deptartment of Environmental, Earth, and Atmospheric Sciences, 265 Riverside Street, Lowell, MA 01854, United States of America
[4] Author to whom any correspondence should be addressed.

E-mail: jsterman@mit.edu

Keywords: bioenergy, biofuels, wood pellets, greenhouse gas emissions, climate change, system dynamics

Supplementary material for this article is available online

Abstract

Bioenergy is booming as nations seek to cut their greenhouse gas emissions. The European Union declared biofuels to be carbon-neutral, triggering a surge in wood use. But do biofuels actually reduce emissions? A molecule of CO_2 emitted today has the same impact on radiative forcing whether it comes from coal or biomass. Biofuels can only reduce atmospheric CO_2 over time through post-harvest increases in net primary production (NPP). The climate impact of biofuels therefore depends on CO_2 emissions from combustion of biofuels versus fossil fuels, the fate of the harvested land and dynamics of NPP. Here we develop a model for dynamic bioenergy lifecycle analysis. The model tracks carbon stocks and fluxes among the atmosphere, biomass, and soils, is extensible to multiple land types and regions, and runs in $\approx$1s, enabling rapid, interactive policy design and sensitivity testing. We simulate substitution of wood for coal in power generation, estimating the parameters governing NPP and other fluxes using data for forests in the eastern US and using published estimates for supply chain emissions. Because combustion and processing efficiencies for wood are less than coal, the immediate impact of substituting wood for coal is an increase in atmospheric CO_2 relative to coal. The payback time for this carbon debt ranges from 44–104 years after clearcut, depending on forest type—assuming the land remains forest. Surprisingly, replanting hardwood forests with fast-growing pine plantations raises the CO_2 impact of wood because the equilibrium carbon density of plantations is lower than natural forests. Further, projected growth in wood harvest for bioenergy would increase atmospheric CO_2 for at least a century because new carbon debt continuously exceeds NPP. Assuming biofuels are carbon neutral may worsen irreversible impacts of climate change before benefits accrue. Instead, explicit dynamic models should be used to assess the climate impacts of biofuels.

1. Introduction

Limiting global warming to no more than 2 °C requires large, rapid cuts in fossil fuel consumption by mid-century (Figueres *et al* 2017, IPCC 2014). In response, governments around the world are promoting biomass to reduce their greenhouse gas (GHG) emissions. The European Union declared biofuels to be carbon-neutral to help meet its goal of 20% renewable energy by 2020, triggering a surge in use of wood for heat and electricity (European Commission 2003, Leturcq 2014, Stupak *et al* 2007). The United Kingdom subsidizes wood pellets for electric power generation and has become the world's largest pellet importer (Thrän *et al* 2017). The US federal government and a number of US states are considering whether to declare wood fuels carbon-neutral or to promote their use (Cornwall 2017), while at COP23 in Bonn 'China and 18 other nations representing half the world's population said…they planned to increase the use of wood...to generate energy as part of efforts to limit climate change' (Biofuture Platform 2017, Doyle and Roche 2017).

But do biofuels actually reduce GHG emissions? The appeal is intuitive: fossil fuels inject carbon sequestered in geological reservoirs for millions of years into the atmosphere, where it accumulates and causes global warming (IPCC 2013). In contrast, biofuels recycle carbon from the atmosphere, helping to keep fossil carbon in the ground (IPCC 2013).

However, a molecule of CO_2 added to the atmosphere today has the same impact on radiative forcing and warming whether it came from coal millions of years old or biomass grown last year. Biofuels can only reduce atmospheric CO_2 over time by increasing net primary production (NPP) above what it otherwise would have been (DeCicco 2013). Assessing the climate impact of wood and other biofuels therefore depends on two critical questions: first, at the point of combustion, do biofuels generate more or less CO_2 per unit of end-use energy than fossil fuels? Second, what are the dynamics of biomass (re)growth and how do NPP and carbon fluxes from biomass and soils depend on the fate of the harvested land?

Confusion over these questions has caused the scientific debate over the climate impact of bioenergy and, especially wood, to remain 'contentious' (Creutzig *et al* 2015, Ter-Mikaelian *et al* 2015). The wood industry and many governments promote wood as a renewable, carbon-neutral fuel, while many environmental groups oppose wood bioenergy because it causes deforestation, harming natural carbon sinks, ecosystems, and biodiversity (Cornwall 2017). Advocates emphasize a long time horizon to evaluate the impact of biofuels, a century or more, by which time it is assumed forests will regrow, offsetting initial emissions. Opponents point to the potential for wood energy to increase CO_2 levels in the short run, incurring a 'carbon debt' that can only be paid off slowly, and worry that the resulting increase in atmospheric CO_2 will worsen global warming and lead to irreversible impacts before the benefits of new growth can occur (Brack 2017, Buchholz *et al* 2016, Cornwall 2017).

Life cycle analysis is commonly used to answer the first question. Results vary with the assumed system boundary and biofuel harvesting, processing and transport methods (e.g. Buchholz *et al* 2016). However, although wood has approximately the same carbon intensity as coal (0.027 vs. 0.025 tC GJ^{-1} of primary energy; see supplementary material), combustion efficiency of wood and wood pellets is lower (Netherlands Enterprise Agency; IEA 2016). Estimates also suggest higher processing losses in the wood supply chain (Röder *et al* 2015). Consequently, wood-fired power plants generate more CO_2 per kWh than coal (supplementary table S5 available at stacks.iop.org/ERL/13/015007/mmedia). Burning wood instead of coal therefore creates a carbon debt—an immediate increase in atmospheric CO_2 compared to fossil energy—that can be repaid over time only as—and if— NPP rises above the flux of carbon from biomass and soils to the atmosphere on the harvested lands.

Dynamic analysis is required to answer the second question (e.g. Helin *et al* 2013). The carbon cycle and climate impacts of bioenergy involve multiple stocks of carbon (e.g. in biomass, soils and dead organic matter, and the atmosphere) and the processes that control the flow of carbon among those stocks including NPP, transfer of carbon from biomass to soil, decomposition of organic matter, consumption and respiration of carbon in biomass and soils, etc. Tools are needed to assess the dynamic climate impact of bioenergy over policy-relevant time horizons. Because of the uncertainty and debate over the impacts of biofuels, such tools should allow users to examine alternative assumptions and scenarios easily and quickly, and would avoid the need to use static summary metrics such as global warming potentials (GWP) and contentious debate over the appropriate time horizon for these approximations, e.g. whether to use GWP20 or GWP100 (Ocko *et al* 2017).

To address this need we developed an interactive decision-support model that enables policymakers and other stakeholders to explore the dynamic impact of biofuels on carbon emissions and climate. The model is fully documented, freely available, runs in about a second on ordinary laptops and is extensible to any number of land use categories and spatial scales. Users receive immediate feedback on the impacts of their scenarios and assumptions. Here we describe the model and use it to explore the dynamics of substituting wood for coal in electric power production, using wood sourced from a range of forest types in the US to estimate model parameters governing NPP and carbon fluxes.

2. Methods

2.1. Model structure

We build on the widely-used C-ROADS climate policy model (Sterman *et al* 2012, Sterman *et al* 2013), developing a more detailed representation of land use, the carbon stocks associated with different types of land and the fluxes arising from them. C-ROADS is a member of the family of simple climate models, consisting of a system of differential equations representing the carbon cycle, budgets and stocks of GHGs, radiative forcing and the heat balance of the Earth. C-ROADS closely replicates GHG concentrations, global mean surface temperature, and other climate metrics from 1850, and matches CMIP5 model projections through 2100 across a wide range of Representative Concentration Pathways (RCPs) (Knutti and Sedlacek 2013, Vuuren *et al* 2011). C-ROADS has been used by policymakers (Sterman *et al* 2012) and is freely available (www.climateinteractive.org).

The carbon cycle in the original C-ROADS model includes globally aggregated stocks of carbon in fossil fuels, the atmosphere, terrestrial biomass and soils, and a four-layer ocean. Here we disaggregate the treatment

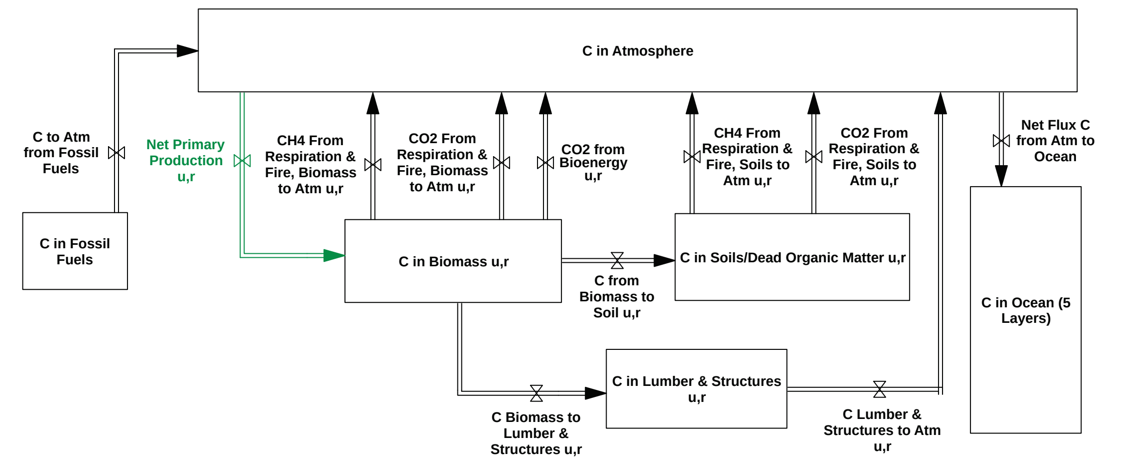


Figure 1. Modified carbon cycle in extended C-ROADS model. Carbon in biomass, soils, and structures (e.g. lumber in buildings), and fluxes among these compartments, are disaggregated by land type, *u*, and region, *r*. Carbon can flow from biomass and soils from each patch, *u*, *r*, to the atmosphere as CO_2 or CH_4. In addition, bioenergy harvest and combustion generate CO_2. CO_2 and CH_4 fluxes associated with changes in land use, e.g. from forest to pasture, cropland or developed land are included in the model but not shown here. On the policy-relevant time scale (e.g. through 2100), creation of new fossil fuels from terrestrial or oceanic carbon sources assumed to be negligible. Note: as described in the text and supplementary material, CH_4 fluxes from biomass and soils are set to zero for forest scenarios considered here to isolate the impact of bioenergy in the scenarios tested.

of terrestrial carbon stocks both geographically and by land type (e.g. forest, pasture, cropland, developed land, etc.). For each region, the model represents the area of each type of land and changes in land use resulting from natural processes and human activity, along with the carbon stocks and fluxes associated with each. The model is extensible to any number of land/land use categories and geographic areas. For example, one could configure the model to represent different types of forests, with similar disaggregation for other land types, and at geographic scales from regions to nations to, if data are available, even smaller areas.

Figure 1 shows an overview of the carbon cycle in the extended model. As in the original model, combustion of fossil fuels injects carbon into the atmosphere. Unlike the original model, carbon stocks in biomass and soil are now represented for each category of land and geographical area. The model also includes a compartment for carbon stored in lumber and structures. Consistent with reporting approaches for the IPCC, FAO, and US Forest Service (FAO 2016, Penman *et al* 2003, Smith *et al* 2006), biomass in forest land includes living trees, including stems, branches, foliage, and coarse roots in both mature and understory trees; the stock denoted 'soil carbon' includes soil organic matter, dead roots, litter (dead foliage, dead branches, etc), downed and standing dead trees, and living fine roots (Woodall *et al* 2015). Biomass is increased by net primary production. Carbon in biomass can return to the atmosphere as CO_2 or CH_4 and is transferred to the soil stock via litterfall and tree mortality. Carbon is also lost from both biomass and dead organic matter by fire. Carbon in the soil stock is transferred to the atmosphere through the activity of decomposers and other heterotrophs (Fahey *et al* 2005). The supplementary material provides full documentation.

Although the model can be configured for any number of land types and uses, here we focus on wood harvested for electricity generation. For simplicity, we configure the model to represent one region with three categories of land: unmanaged forest, recently harvested forest, and 'other,' which includes all other land use categories (cropland, pasture, developed land, etc.).

2.2. Parameter estimation

Each unit of end-use bioenergy displaces the same end-use energy generated from fossil fuels, so net CO_2 emissions from biomass at the point of combustion depend on which energy source is more efficient overall, given fuel carbon intensity, combustion efficiency, processing losses, and emissions from their supply chains. Typical combustion efficiencies for wood are approximately 25%, compared to 35% for coal (Netherlands Enterprise Agency 2011, IEA 2016). Published estimates vary with the process examined and the system boundary considered, but processing losses (in energy content) for the wood pellet supply chain are on the order of approximately 27% if biomass is used in the drying process (Röder *et al* 2015), compared to losses of approximately 11% for coal (IEA 2016). Differences in supply chain emissions from extraction/harvest, and transportation are uncertain but relatively small compared to the large differences in combustion and processing efficiencies (e.g. Odeh and Cockerill 2008, Röder *et al* 2015). Consequently, wood pellets emit approximately 0.071 tC more CO_2 per GJ of end-use energy than coal (see supplementary material).

The determinants of NPP and carbon fluxes from biomass and soil to the atmosphere are therefore critical to assessing the dynamic impact of bioenergy including the carbon debt payback period and long-run reduction in atmospheric CO_2. To estimate the parameters

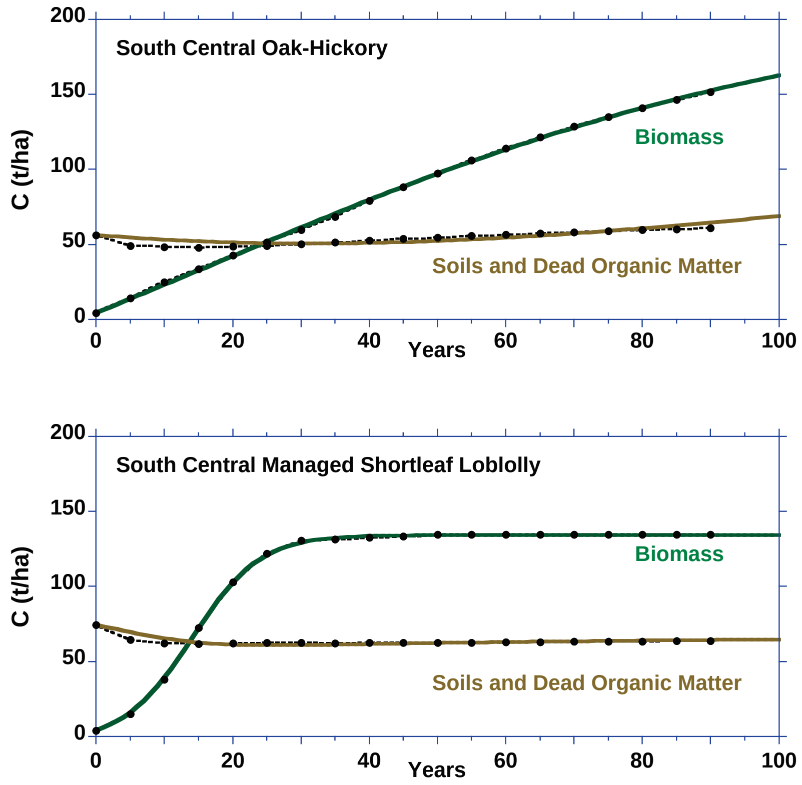


Figure 2. Growth curves showing carbon density (tC ha^{-1}) for oak–hickory (top) and managed shortleaf loblolly pine plantations (bottom) in the south-central US, comparing Smith *et al* (2006) growth curves (dashed lines with data points) to the model (solid lines), with best-fit parameters. Supplementary figure S2 and tables S2–S3 show results for all forest types estimated.

governing NPP and these fluxes we use the post-harvest growth curves in Smith *et al* (2006), which span many regions and species in US forests. To illustrate, figure 2 shows the Smith *et al* growth curves for south-central US oak–hickory forest and managed shortleaf loblolly pine plantations. The growth patterns differ markedly in both their shape and time required to reach maximum biomass. After harvest, the managed loblolly plantation regrows quickly, following a classic S-shaped curve and reaching maximum biomass after about three decades, while the hardwood forest grows roughly linearly for about 50 years and is still growing after a century. Note that in both cases, soil carbon declines for several decades after harvest because the C flux from biomass to soils is cut while heterotrophic respiration continues to release C from soils and dead organic matter to the atmosphere.

To model NPP we specify a variant of the Richards (1959) growth model, widely used in forest growth modeling. The US wood pellet industry is growing rapidly, and much of the production is exported to the EU and UK. We therefore estimate the carbon cycle parameters from growth curves for temperate US forests reported by Smith *et al* (2006). We estimate the parameters of NPP jointly with those governing fluxes of CO_2 from biomass to soil and from each compartment to the atmosphere using nonlinear least squares and Markov Chain Monte Carlo methods (supplementary material). The model fits the Smith *et al* growth curves closely: the mean absolute error relative to the mean ranges from 0.008%–0.065% for biomass and from 0.006%–0.074% for soils (figure 2, table S2).

3. Results

In the scenarios below, we adopt assumptions that favor bioenergy. Specifically, we assume bioenergy from wood pellets is used to offset coal, the most carbon intensive fossil fuel; if wood offsets power generated from natural gas its carbon debt would be much larger. Estimates of net CH_4 fluxes from forest biomass and soils are poorly constrained and considered to be insignificant in most global methane budgets (e.g. Ito and Inatomi 2012, Saunois *et al* 2016, Shoemaker *et al* 2014); we therefore assume them to be zero. We assume all land harvested for bioenergy is allowed to regrow without any fire (Buchholz *et al* 2016), erosion, disease, unplanned logging, or other ecological disturbances, including climate change impacts, that could limit regrowth or inject GHGs into the atmosphere beyond the direct impact of the bioenergy harvest. We further assume that the decline in coal use resulting from wood does not lower coal prices, increasing coal demand elsewhere, an effect estimated to be large (e.g. York 2012).

To isolate the dynamic impact of bioenergy on CO_2 emissions we run the model from an initial equilibrium

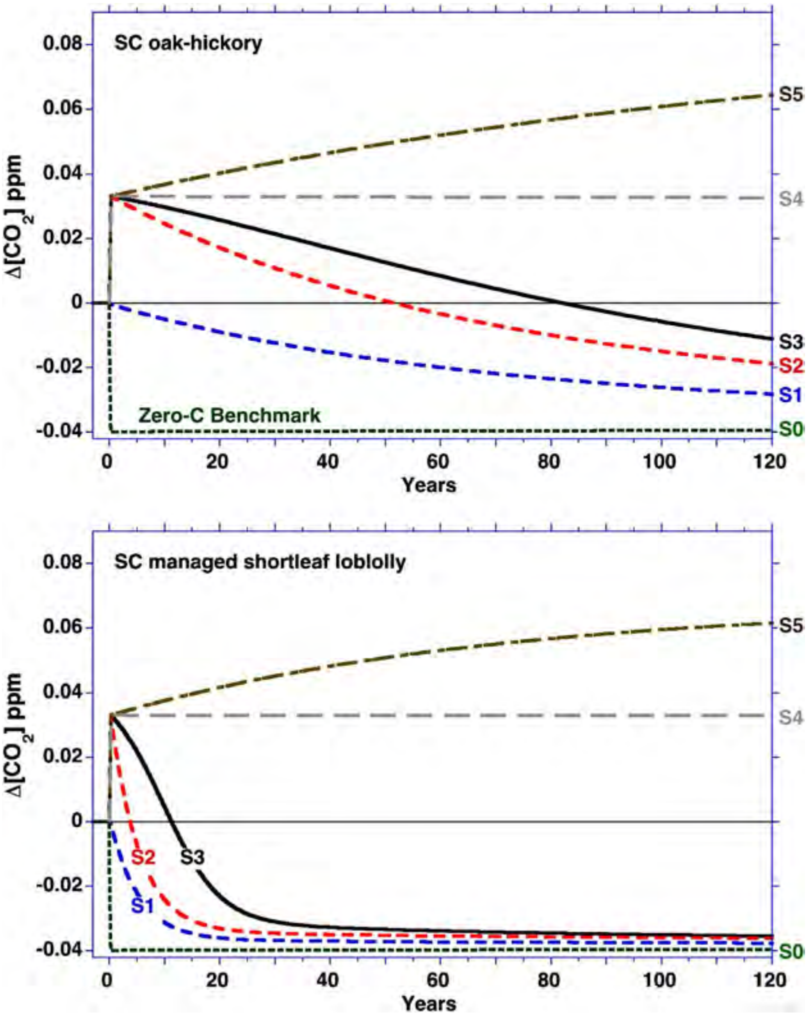


Figure 3. Change in atmospheric CO_2 concentration resulting from displacement of coal by wood. $\Delta[CO_2]$ is relative to continued coal use. All scenarios show the change in atmospheric CO_2 (ppmv) resulting from a single 1 EJ pulse of end-use energy from biomass used to displace coal in year 0. Top: south-central (SC) oak–hickory forest; bottom: SC managed shortleaf loblolly plantation. The bioenergy pulse causes an immediate increase in CO_2 concentration (the initial carbon debt) in scenarios 2–5 due to lower combustion and processing efficiencies for wood compared to coal. The year in which $\Delta[CO_2]$ falls below zero is the carbon debt payback time. Supplement figure S3 shows the results for all eight forest types examined. S0: Benchmark showing impact of 1 EJ pulse of zero carbon energy. S1: Bioenergy assumed to have the same combustion and processing efficiency as coal, and the same supply chain emissions; with 25% of biomass removed from the land harvested through thinning. S2: Actual efficiencies and supply chain emissions for wood pellets; 25% of biomass harvested through thinning. S3: S2 with 95% of biomass harvested (clear cut). S4: S3 with clear cut and no regrowth of harvested land and no C released from soil stocks. S5: S4 with C released from soil stocks at the estimated fractional rate.

in which the carbon fluxes from biomass and soils to the atmosphere are balanced by NPP, and in which net CO_2 flux to the ocean is zero throughout, identifying the impacts of bioenergy separate from other sources of disequilibrium, e.g. prior logging and marine uptake of CO_2. Including ocean CO_2 uptake would moderate increases in atmospheric CO_2 from bioenergy but worsen ocean acidification and other impacts. These effects are left for future work.

Figure 3 shows the results for a set of scenarios using parameters estimated for oak–hickory forest in the south-central US (supplementary figure S3, table S7 provide results for all eight forest types we estimated). All scenarios examine a 1 exajoule (EJ) pulse of end-use electric energy generated from wood pellets in year 0, offsetting 1 EJ of end-use electricity generated from coal (total world energy use exceeds 550 EJ yr^{-1}, US EIA 2016).

Scenario 0 provides a benchmark showing how atmospheric CO_2 would change if 1 EJ of end-use energy from coal were offset by a zero-carbon energy source, such as solar or wind (and assuming zero emissions from the supply chain). Displacing 1 EJ of end-use energy from coal with a zero C alternative keeps 0.07 GtC of fossil carbon in the ground, immediately and permanently lowering atmospheric CO_2 by approximately 0.04 ppm relative to continued coal use.

Scenario 1 simulates the counterfactual case in which bioenergy is assumed to have the same carbon emissions per EJ of end-use energy as coal, including the same combustion and processing efficiency and supply chain emissions. We assume that 25%

of the biomass is removed from each hectare of the harvested forest by thinning, not clear cutting, that the forest is allowed to regrow with no subsequent harvest, fire, disease, or other disturbances. Because emissions are counterfactually assumed to be the same as coal, there is no immediate change in atmospheric CO_2. However, as the forest grows back, carbon is gradually removed from the atmosphere to biomass and soils. After 100 years, the forest has recovered enough to lower atmospheric CO_2 by 0.026 ppm, still 34% above the zero C case.

Scenario 2 shows the realistic case with the combustion efficiency and supply chain emissions estimated for wood pellets (supplementary table S5), again assuming 25% of the biomass is harvested by thinning. Because production and combustion of wood generate more CO_2 than coal, the first impact of bioenergy use is an increase in atmospheric CO_2. Regrowth gradually transfers C from the atmosphere to biomass and soil C stocks, leading to a carbon debt payback time of 52 years; after 100 years CO_2 remains 62% above the zero C case.

Scenario 3 is the same as S2 except we now assume the land is clear cut instead of thinned, with 95% of the biomass removed. Near-complete biomass removal reflects the growing practice of harvesting whole trees and residues (branches, litter, etc) (Achat *et al* 2015). A 95% clear cut requires only 26% as much land as in S2, but the carbon debt payback time increases to 82 years; after 100 years CO_2 remains 86% above the zero C case.

Scenario 4 shows the impact of assuming that the harvested area is clear cut as in S3 but never allowed to regrow, for example, because it is developed, with the additional assumption that the flux of C from soils and dead organic matter to the atmosphere is set to zero. Without regrowth, the carbon debt is never repaid and atmospheric CO_2 remains permanently higher.

Scenario 5 is the same as S4 except the flux of C to the atmosphere from soils and dead organic matter continues at the original fractional rate. Without regrowth, there is no flux of CO_2 from the atmosphere to terrestrial biomass or soils, but continued C flux from soils to atmosphere, causing CO_2 concentrations to rise beyond the immediate impact of the bioenergy. After a century atmospheric CO_2 has risen by 0.076 ppm, 2.3 times more than the initial impact. The actual impact of converting harvested forests to other uses will likely lie between the results of Scenarios 4 and 5, but could rise further if conversion of forest to other uses increases C fluxes from soils above the values estimated from the Smith *et al* (2006) data. Such an outcome could result from disturbances to soils from, e.g. plowing, development, fire or increasing methanogenesis, all of which we assume to be zero.

In Scenario 6 (figure 4) oak–hickory forest is clear cut and replanted as a shortleaf loblolly pine managed plantation. Loblolly pine grows faster than hardwoods (figure 2), so intuitively the conversion from unmanaged hardwood forest to managed pine plantation should speed the repayment of the carbon debt. As expected, atmospheric CO_2 initially falls faster in the plantation case compared to regrowth of the oak–hickory forest. However, the concentration bottoms out after approximately 20 years and then starts to rise, exceeding the CO_2 level when the forest is allowed to regrow. The explanation lies in the different maximum carbon densities of the two forest types: loblolly plantation grows faster but reaches a lower equilibrium carbon density compared to the unmanaged forest (figure 4), with estimated equilibrium values of 130 tC ha^{-1} for loblolly plantation vs. 211 tC ha^{-1} for oak–hickory. Consequently, although plantations grow faster, they do not remove as much C from the atmosphere as was lost when the hardwood forest was harvested, even if allowed to grow to their maximum biomass and remain unharvested. In reality, plantations are thinned every few years and harvested about every decade (US Forest Service 2000), further lowering their average C density and increasing atmospheric CO_2. Furthermore, repeated harvests can degrade the productivity of the soils, lowering NPP. To compensate, managed plantations are typically fertilized several times per rotation, increasing N_2O emissions that would further worsen the climate impact of Scenario 6 (Schulze *et al* 2012).

The supplementary material reports the 95% confidence intervals (CIs) for the estimated parameters (table S4), and sensitivity analysis across the eight forest types arising from parameter uncertainty, computed by Markov Chain Monte Carlo (table S8). The 95% CIs for the carbon debt payback times vary from 74–110 years for the hardwood species under clear cut (Scenario 3) and 11.25–12 years for the managed plantations. The supplementary material also reports the long-run CO_2 reductions for Scenarios 1–5 (table S7). For Scenario 3, after 100 years CO_2 falls an average of 51% of the maximum possible reduction (the difference between the initial carbon debt and the zero-C level in Scenario 0) for the forests and 92% for the plantations.

The supplementary material also reports sensitivity analysis of combustion efficiencies and supply chain emissions. Clearly, innovation that improves the combustion and processing efficiencies of wood *relative to coal* reduces the initial carbon debt of wood and reduces the carbon debt payback time and climate impacts of wood. However, innovations that improve the efficiencies of *both* fuels yield smaller benefits. For example, combined heat and power systems offer substantially higher combustion efficiency than conventional boilers, but would still cause an initial carbon debt since the combustion and processing efficiencies of wood remain lower than coal in such systems (supplementary figures S5–6).

The wood pellet industry is expanding rapidly and many projections call for substantial growth through 2030 or beyond (IEA 2012, IRENA 2015). Scenario 7 (figure 5) shows the impact of linear growth in

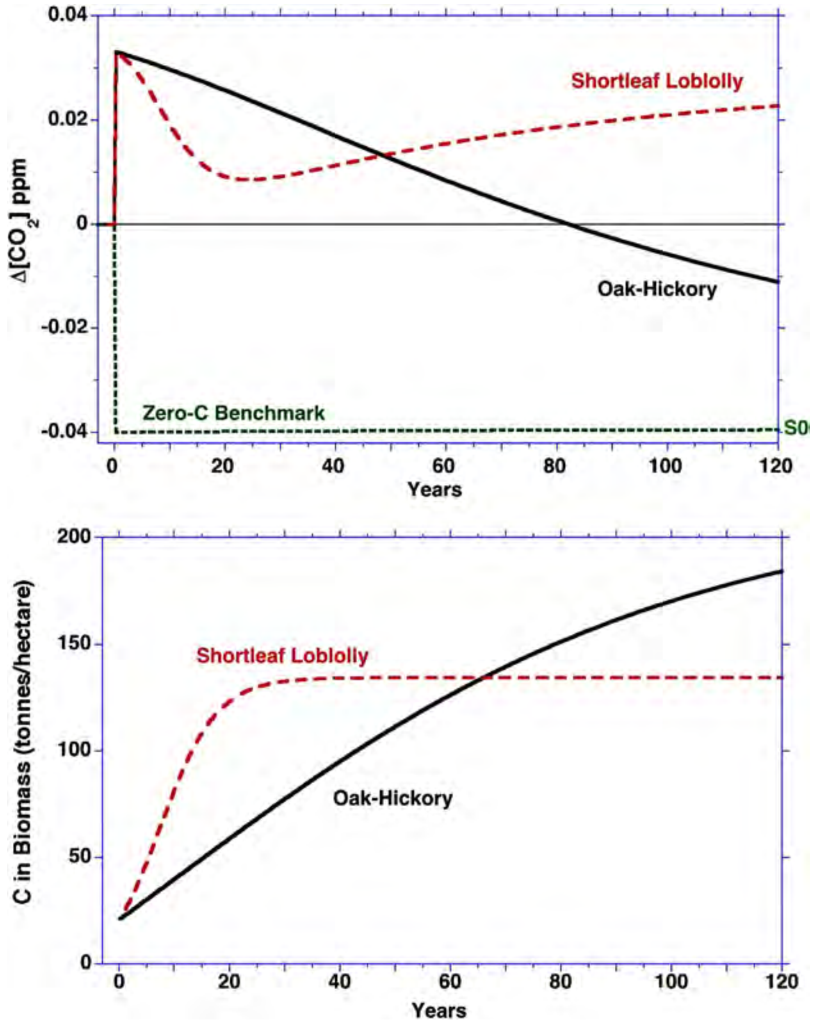


Figure 4. Scenario 6: replanting harvested oak–hickory forest after clear cut with managed plantation of shortleaf loblolly pine (south-central US), compared to allowing the oak–hickory forest to regrow (Scenario 3 in figure 2). Top: change in atmospheric CO_2 (ppmv) resulting from a single 1 EJ pulse of end-use energy from biomass used to displace coal in year. $\Delta[CO_2]$ is relative to continued coal use. Bottom: carbon in biomass (tC ha^{-1}). For the first 20 years, faster-growing loblolly pine lowers atmospheric CO_2 compared to regrowth of the oak–hickory forest, but the estimated maximum carbon density of oak–hickory forest is larger than the managed loblolly plantation (211 vs. 131 tC ha^{-1}, respectively; supplementary table S3). Consequently, the carbon debt is never repaid even if the loblolly plantation is never harvested. Due to CO_2 flux from soils, atmospheric CO_2 rises after approximately 20 years, exceeding the level from regrowth of oak–hickory after approximately 50 years.

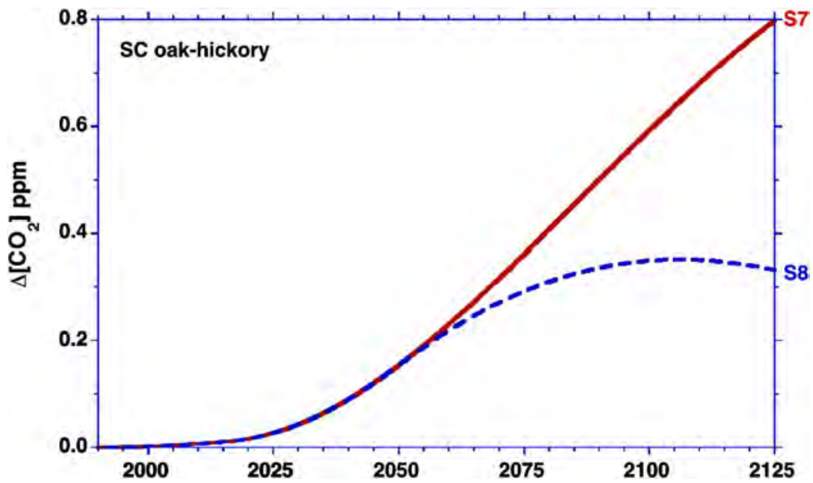


Figure 5. Change in atmospheric CO_2 concentration resulting from growth in end-use energy supplied by wood, displacing coal. $\Delta[CO_2]$ is relative to continued coal use. Scenario 7 (solid line): linear growth in end-use energy supplied by US wood pellet production, from the 2016 value of 0.028 EJ to 0.28 EJ yr^{-1} by 2050 and continuing linearly thereafter. Parameters estimated for south-central US oak–hickory forest, with harvest by clearcut. Scenario 8 (dashed line): the same as S7 except growth in end-use energy supplied by wood ceases in 2050. Supplementary figure S4 reports results for all forest types considered.

end-use bioenergy; Scenario 8 is the same except growth ceases in 2050. Growth in wood supply causes steady growth in atmospheric CO_2 because more CO_2 is added to the atmosphere every year in initial carbon debt than is paid back by regrowth, worsening global warming and climate change. The qualitative result that growth in bioenergy raises atmospheric CO_2 does not depend on the parameters: as long as bioenergy generates an initial carbon debt, increasing harvests mean more is 'borrowed' every year than is paid back. More precisely, atmospheric CO_2 rises as long as NPP remains below the initial carbon debt incurred each year plus the fluxes of carbon from biomass and soils to the atmosphere. Note further that in Scenario 8, CO_2 continues to rise for 56 years after bioenergy production growth stops and only falls below initial levels 144 years after growth stops. Results for the other forest types are similar (supplementary figure S4).

4. Discussion and conclusion

We extended the carbon cycle model in the C-ROADS climate policy model to account for different land and land use types, by region. The model explicitly treats stocks of carbon in fossil fuels, biomass, soils and dead organic matter, the atmosphere, and the fluxes among them including combustion, supply chain emissions, and regrowth of harvested lands. The model is extensible to any number of land types and uses, and geographic scales. To demonstrate the approach, we analyzed the dynamic impact of displacing coal with wood in electricity production, finding:

First, yet contrary to the policies of the EU and other nations, biomass used to displace fossil fuels injects CO_2 into the atmosphere at the point of combustion and during harvest, processing and transport. Reductions in atmospheric CO_2 come only later, and only if the harvested land is allowed to regrow.

Second, the combustion and processing efficiencies of wood in electricity generation are lower than for coal (supplementary material). Consequently, the first impact of displacing coal with wood is an increase in atmospheric CO_2 relative to continued coal use, creating an initial carbon debt.

Third, after the carbon debt is repaid, atmospheric CO_2 is lower, showing the potential long-run benefits of bioenergy. However, before breakeven, atmospheric CO_2 is higher than it would have been without the use of bioenergy, increasing radiative forcing and global average temperatures, worsening climate change, including potentially irreversible impacts that may arise before the long-run benefits are realized.

Fourth, biofuels are only beneficial in the long run if the harvested land is allowed to regrow to its pre-harvest biomass and maintained there. Natural forests have high carbon density compared to pasture, cropland, developed land and managed tree plantations. The carbon debt incurred when wood displaces coal may never be repaid if development, unplanned logging, erosion or increases in extreme temperatures, fire, and disease (all worsened by global warming) limit regrowth or accelerate the flux of carbon from soils to the atmosphere. Further, lower coal prices caused by the drop in power sector demand may stimulate coal use elsewhere, offsetting even the potential long-run benefits of bioenergy (e.g. York 2012).

Fifth, counter to intuition, harvesting existing forests and replanting with fast-growing species in managed plantations can worsen the climate impact of wood biofuel. Although managed loblolly pine grows faster than hardwood, speeding the initial recovery of forest biomass, the equilibrium carbon density of managed plantations is lower than unmanaged forest, so carbon sequestered in plantations never offsets the carbon taken from the original forest. This is true even if the managed plantation is never reharvested, and worse if the plantation is periodically reharvested. Further, typical plantations require periodic fertilization, increasing N_2O emissions and worsening their climate impact beyond what we report here (Schulze *et al* 2012).

Sixth, growth in wood harvest for bioenergy causes a steady increase in atmospheric CO_2 because the initial carbon debt incurred each year exceeds what is repaid. With the US forest parameters used here, growth in the wood pellet industry to displace coal aggravates global warming at least through the end of this century, even if the industry stops growing by 2050.

Seventh, using wood in electricity generation worsens climate change for decades or more even though many of our assumptions favor wood, including: wood displaces coal (the most carbon intensive fossil fuel); all harvested land is allowed to regrow as forest with no subsequent conversion to pasture, cropland, development or other uses; no subsequent harvest, fire or disease; no increase in coal demand resulting from lower prices induced by the decline in coal use for electric power; no increase in N_2O from fertilization of managed plantations; and no increase in CO_2 emissions or methanogenesis from disturbed land. Relaxing any of these assumptions worsens the climate impact of wood bioenergy.

In sum, although bioenergy from wood can lower long-run CO_2 concentrations compared to fossil fuels, its first impact is an increase in CO_2, worsening global warming over the critical period through 2100 even if the wood offsets coal, the most carbon-intensive fossil fuel. Declaring that biofuels are carbon neutral as the EU and others have done, erroneously assumes forest regrowth quickly and fully offsets the emissions from biofuel production and combustion. The neutrality assumption is not valid because it ignores the transient, but decades to centuries long, increase in CO_2 caused by biofuels.

Methodologically, we demonstrate the feasibility of integrating static life cycle considerations around the efficiencies of and emissions from biofuels with explicit modeling of biomass dynamics in a model that runs fast enough to enable policymakers and other stakeholders to design and test their own scenarios. Future work will integrate the model into full climate models such as C-ROADS, creating a fast, interactive simulator that can model the impacts of different biofuel technologies and scenarios on CO_2 concentrations, radiative forcing, warming, ocean acidification, sea level rise and other impacts.

Acknowledgments

This work was supported by the National Science Foundation under grants DUE-124558 and ICER-1701062. We thank Tom Fiddaman, William Moomaw and Hazhir Rahmandad for helpful suggestions.

ORCID iDs

John D Sterman https://orcid.org/0000-0001-7476-6760
Juliette N Rooney-Varga https://orcid.org/0000-0001-7102-6919

References

Achat D, Deleuze C, Landmann G, Pousse N, Ranger J and Augusto L 2015 Quantifying consequences of removing harvesting residues on forest soils and tree growth–a meta-analysis *Forest Ecol. Manage.* **348** 124–41

Biofuture Platform 2017 Biofuture@COP23: major countries agree to scale up the low carbon bioeconomy and develop sustainable biofuels targets (http://biofutureplatform.org/major-countries-agree-scale-low-carbon-bioeconomy-develop-sustainable-biofuels-targets/)

Brack D 2017 *The Impacts of of the Demand for Woody Biomass for Power and Heat on Climate and Forests* (London: Chatham House, the Royal Institute of International Affairs)

Buchholz T, Hurteau M D, Gunn J and Saah D 2016 A global meta-analysis of forest bioenergy greenhouse gas emission accounting studies *Glob. Change Biol. Bioenergy* **8** 281–9

Cornwall W 2017 Is wood a green source of energy? Scientists are divided *Science* **355** 18–21

Creutzig F *et al* 2015 Bioenergy and climate change mitigation: an assessment *Glob. Change Biol. Bioenergy* **7** 916–44

DeCicco J M 2013 Biofuel's carbon balance: doubts, certainties and implications *Clim. Change* **121** 801–14

Doyle A and Roche A 2017 Nineteen nations say they will use more bioenergy to slow climate change *Reuters* (www.reuters.com/article/us-climatechange-accord-biofuels/nineteen-nations-say-theyll-use-more-bioenergy-to-slow-climate-change-idUSKBN1DG2DO)

European Commission 2003 *Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003* (Brussels: European Parliament) pp 32–46 (http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32003L0087)

Fahey T J *et al* 2005 The biogeochemistry of carbon at Hubbard Brook *Biogeochemistry* **75** 109–76

FAO 2016 *Global Forest Resources Assessment 2015: How are the World's Forests Changing?* (Rome: Food and Agriculture Organization of the United Nations) (www.fao.org/3/a-i4793e.pdf)

Figueres C, Schellnhuber H J, Whiteman G, Rockstrom J, Hobley A and Rahmstorf S 2017 Three years to safeguard our climate *Nature* **546** 593–5

Helin T, Sokka L, Soimakallio S, Pingoud K and Pajula T 2013 Approaches for inclusion of forest carbon cycle in life cycle assessment—a review *Glob. Change Biol. Bioenergy* **5** 475–86

IEA 2012 *Technology Roadmap: Bioenergy for Heat and Power* (Paris: International Energy Agency) (www.iea.org/publications/freepublications/publication/2012_Bioenergy_Roadmap_2nd_Edition_WEB.pdf)

IEA 2016 *World Energy Outlook* (Paris: International Energy Agency) (www.iea.org/newsroom/news/2016/november/world-energy-outlook-2016.html)

IPCC 2013 *Working Group I Contribution to the IPCC Fifth Assessment Report Climate Change 2013: The Physical Science Basis* (Cambridge: Cambridge University Press) (www.ipcc.ch/report/ar5/wg1)

IPCC 2014 *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed C B Field *et al* (Cambridge: Cambridge University Press) pp 1–32 (www.ipcc.ch/report/ar5/wg2)

IRENA 2015 *Renewable Power Generation Costs in 2014* (Abu Dhabi: International Renewable Energy Agency) (www.irena.org/DocumentDownloads/Publications/IRENA_RE_Power_Costs_2014_report.pdf)

Ito A and Inatomi M 2012 Use of a process-based model for assessing the methane budgets of global terrestrial ecosystems and evaluation of uncertainty *Biogeosciences* **9** 759–73

Knutti R and Sedlacek J 2013 Robustness and uncertainties in the new CMIP5 climate model projections *Nat. Clim. Change* **3** 369–73

Leturcq P 2014 Wood preservation (carbon sequestration) or wood burning (fossil-fuel substitution), which is better for mitigating climate change? *Ann. Forest Sci.* **71** 117–24

Netherlands Enterprise Agency 2011 CO_2-tool electricity gas and heat from biomass—version 1.0.1 (Assen, The Netherlands) (www.rvo.nl/file/1252)

Ocko I B, Hamburg S P, Jacob D J, Keith D W, Keohane N O, Oppenheimer M, Roy-Mayhew J D, Schrag D P and Pacala S W 2017 Unmask temporal trade-offs in climate policy debates *Science* **356** 492–3

Odeh N A and Cockerill T T 2008 Life cycle GHG assessment of fossil fuel power plants with carbon capture and storage *Energ. Policy* **36** 367–80

Penman J, Gytarsky M and Hiraishi T 2003 *Good Practice Guidance for Land Use, Land Use Change, and Forestry* (Hayama, Kanagawa: Institute for Global Environmental Strategies for the Intergovernmental Panel on Climate Change) (www.ipcc-nggip.iges.or.jp/public/gpglulucf.html)

Richards F J 1959 A flexible growth function for empirical use *J. Exp. Bot.* **10** 290–300

Röder M, Whittaker C and Thornley P 2015 How certain are greenhouse gas reductions from bioenergy? Life cycle assessment and uncertainty analysis of wood pellet-to-electricity supply chains from forest residues *Biomass Bioenergy* **79** 50–63

Saunois M *et al* 2016 The global methane budget 2000–2012 *Earth Syst. Sci. Data* **8** 697–751

Schulze E-D, Körner C, Law B, Haberl H and Luyssaert S 2012 Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral *Glob. Change Biol. Bioenergy* **4** 611–6

Shoemaker J K, Keenan T F, Hollinger D Y and Richardson A D 2014 Forest ecosystem changes from annual methane source to sink depending on late summer water balance *Geophys. Res. Lett.* **41** 673–9

Smith J E, Heath L S, Skog K E and Birdsey R A 2006 Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States (www.fs.usda.gov/treesearch/pubs/22954)

Sterman J, Fiddaman T, Franck T, Jones A, McCauley S, Rice P, Sawin E and Siegel L 2012 Climate interactive: the C-ROADS climate policy model *Syst. Dyn. Rev.* **28** 295–305

Sterman J D, Fiddaman T, Franck T, Jones A, McCauley S, Rice P, Sawin E and Siegel L 2013 Management flight simulators to support climate negotiations *Environ. Modell. Softw.* **44** 122–35

Stupak I *et al* 2007 Sustainable utilisation of forest biomass for energy—possibilities and problems: policy, legislation, certification, and recommendations and guidelines in the Nordic, Baltic, and other European countries *Biomass Bioenergy* **31** 666–84

Ter-Mikaelian M T, Colombo S J and Chen J 2015 The burning question: does forest bioenergy reduce carbon emissions? A review of common misconceptions about forest carbon accounting *J. Forest.* **113** 57–68

Thrän D, Peetz D and Schaubach K 2017 *Global Wood Pellet Industry and Trade Study 2017* (Paris: IEA Bioenergy) p 243 (http://task40.ieabioenergy.com/wp-content/uploads/2013/09/IEA-Wood-Pellet-Study_final-2017-06.pdf)

US Forest Service 2000 *Landowners Handbook for Managing Southern Pines* (Atlanta, GA: US Forest Service-Southern Region) (http://ncforestry.info/fs/managing_southern_pines/)

US EIA 2016 *International Energy Outlook 2016* (Washington, DC: US Energy Information Administration) p 276 (www.eia.gov/outlooks/ieo/pdf/0484(2016).pdf)

Vuuren D *et al* 2011 The representative concentration pathways: an overview *Clim. Change* **109** 5–31

Woodall C W *et al* 2015 *The US Forest Carbon Accounting Framework: Stocks and Stock Change 1990–2016* (Newtown Square, PA: US Forest Service) (www.fs.usda.gov/treesearch/pubs/49858)

York R 2012 Do alternative energy sources displace fossil fuels? *Nat. Clim. Change* **2** 441–3

White House Environmental Justice Advisory Council

Justice40

Climate and Economic Justice Screening Tool

&

Executive Order 12898 Revisions

Interim Final Recommendations

May 13, 2021

ACKNOWLEDGEMENTS

The White House Environmental Justice Advisory Council (WHEJAC) acknowledges the efforts of the NEJAC Executive Order 12898 Revisions Work Group, Justice40 Initiative Work Group and Climate and Economic Justice Screening Tool Work Group in preparing the initial draft of this report. The WHEJAC acknowledges the stakeholders and community members who participated in the work groups' deliberation by providing public comments. In addition, the work groups' efforts were supported by the U.S. Environmental Protection Agency staff, notably, Karen L. Martin as the Designated Federal Officer, George Q.E. Ward and Paula Flores-Gregg.

DISCLAIMER

This report of recommendations has been written as part of the activities of the WHEJAC, a public advisory committee providing independent advice and recommendations on the issue of environmental justice to the Administrator, The Council of Environmental Quality (CEQ) and other officials of the White House. In addition, the materials, opinions, findings, recommendations, and conclusions expressed herein, and in any study or other source referenced herein, should not be construed as adopted or endorsed by any organization with which any Work Group member is affiliated. This report has not been reviewed for approval by the EPA or CEQ, and hence, its contents and recommendations do not necessarily represent the views and the policies of the EPA or CEQ, nor of other agencies in the Executive Branch of the Federal government.

WHITE HOUSE ENVIRONMENTAL JUSTICE ADVISORY COUNCIL

- **Richard Moore,** Los Jardines Institute (WHEJAC Co-Chair)
- **Peggy Shepard,** WEACT for Environmental Justice (WHEJAC Co-Chair)
- **Catherine Coleman Flowers,** The Center for Rural Enterprise and Environmental Justice (WHEJAC Vice-Chair)
- **Carletta Tilousi,** Havusapai Tribal Council (WHEJAC Vice-Chair)
- **LaTricea Adams,** Black Millennials for Flint
- **Susana Almanza,** People Organized in Defense of Earth and Her Resources
- **Jade Begay,** NDN Collective
- **Maria Belen Power,** GreenRoots
- **Dr. Robert Bullard,** Texas Southern University
- **Tom Cormons,** Appalachian Voices
- **Andrea Delgado,** United Farmworkers Foundation
- **Jerome Foster II,** One Million of Us
- **Kim Havey,** City of Minneapolis Division of Sustainability
- **Angelo Logan,** Moving Forward Network
- **Maria López-Núñez,** Ironbound Community Corporation
- **Harold Mitchell,** ReGenesis
- **Dr. Rachel Morello-Frosch,** UC Berkeley
- **Juan Parras,** Texas Environmental Justice Advocacy Services
- **Michele Roberts,** Environmental Justice Health Alliance
- **Ruth Santiago,** Comité Dialogo Ambiental and El Puente, Latino Climate Action Network
- **Dr. Nicky Sheats,** Kean University
- **Viola Waghiyi,** Alaska Community Action on Toxics
- **Dr. Kyle Whyte,** University of Michigan
- **Dr. Beverly Wright,** Deep South Center for EJ
- **Hli Xyooj,** Advancement of Hmong Americans
- **Miya Yoshitani,** Asian Pacific Environmental Network

***Karen L. Martin**, Designated Federal Officer, U.S. EPA Office of Environmental Justice*

JUSTICE40 WORK GROUP MEMBERS

- **LaTricea Adams,** Black Millennials for Flint
- **Dr. Robert Bullard,** Texas Southern University
- **Lucas M. Brown**, Office of Management and Budget
- **Scott Burgess,** Office of Management and Budget
- **Tom Cormons,** Appalachian Voices
- **Andrea Delgado,** United Farmworkers Foundation
- **Paula Flores-Gregg,** U.S. EPA Region 6
- **Jerome Foster II,** One Million of Us
- **Kim Havey,** City of Minneapolis Division of Sustainability
- **Nathaniel Hillard**, Office of Management and Budget
- **Kameron Kerger**, Office of Management and Budget
- **Harold Mitchell,** ReGenesis
- **Maria López-Núñez,** Ironbound Community Corporation
- **Harold Mitchell,** ReGenesis
- **Maria Belen Power,** GreenRoots
- **Ruth Santiago,** Comité Dialogo Ambiental and El Puente, Latino Climate Action Network
- **Peggy Shepard,** WEACT for Environmental Justice (WHEJAC Co-Chair)
- **George Q.E. Ward**, U.S. EPA Office of Environmental Justice
- **Dr. Beverly Wright,** Deep South Center for EJ
- **Miya Yoshitani,** Asian Pacific Environmental Network

CLIMATE AND ECONOMIC JUSTICE SCREENING TOOL WORK GROUP MEMBERS

- **Catherine Coleman Flowers,** The Center for Rural Enterprise and Environmental Justice (WHEJAC Vice-Chair)
- **Jade Begay,** NDN Collective
- **Andrea Delgado,** United Farmworkers Foundation
- **Katherine D.** Milkan, Office of Management and Budget
- **Harold Mitchell,** ReGenesis
- **Dr. Rachel Morello-Frosch,** UC Berkeley
- **Juan Parras,** Texas Environmental Justice Advocacy Services
- **Michele Roberts,** Environmental Justice Health Alliance
- **Dr. Nicky Sheats,** Kean University
- **Viola Waghiyi,** Alaska Community Action on Toxics
- **Kameron Kerger**, Office of Management and Budget
- **Matthew Lee,** U.S. EPA Office of Environmental Justice
- **Lucas M. Brown**, Office of Management and Budget

- **Tai Lung**, U.S. EPA Office of Environmental Justice
- **Nicholas B. Holtz,** Office of Management and Budget
- **Paula Flores-Gregg,** U.S. EPA Region 6
- **Katherine D. Milkan**, Office of Management and Budget

EXCUTIVE ORDER 12898 REVISIONS WORK GROUP MEMBERS

- **Susana Almanza,** People Organized in Defense of Earth and Her Resources
- **Marianne Engelman-Lado,** U.S. EPA Office of General Counsel
- **Charles Lee,** U.S. EPA Office of Environmental Justice
- **Angelo Logan,** Moving Forward Network
- **Richard Moore,** Los Jardines Institute (WHEJAC Co-Chair)
- **Juan Parras,** Texas Environmental Justice Advocacy Services
- **Carletta Tilousi,** Havusapai Tribal Council (WHEJAC Vice-Chair)
- **Dr. Kyle Whyte,** University of Michigan
- **Hli Xyooj,** Advancement of Hmong Americans

WHITE HOUSE ENVIRONMENTAL JUSTICE ADVISORY COUNCIL

May 13, 2021

The Honorable Ms. Brenda Mallory, Chair
The Council on Environmental Quality
Executive Office of the President
Washington, DC 20500

Dear Chair Mallory:

The White House Environmental Justice Advisory Council (WHEJAC) enthusiastically submits its interim final report to you and President Biden. This report is in response to a charge issued in March 2021, from The Council on Environmental Quality to provide recommendations on Justice40, Climate and Economic Justice Screening Tool, and Executive Order 12898 Revisions. Over the next few months, the WHEJAC will also consider and submit recommendations on the Scorecard, the administration and implementation of Justice40, and final recommendations on the Climate and Economic Justice Screening Tool.

The WHEJAC urges President Biden, Vice President Harris and the CEQ to consider the following requests:

- The careful administration of Justice40 is paramount to the effectiveness of the Biden Administration's signature Environmental Justice initiative. WHEJAC members strongly believe that there must be a transformative and accountable process developed for the fair and just distribution of 40% or more of the benefits to be invested in frontline communities. Otherwise, the investment will not reach frontline communities, given the bias and ambivalence of many state and local governments, and the systemic racial bias, inertia, and resistance to change that we must never underestimate. In order to avoid primarily helping those communities that already have the advantage, transformative investments must be made in capacity building, technical assistance and consultation, and creating a user-friendly federal process for the administration of funding and other support.

- Justice40 must start today. All local investments from energy benefits (such as through The American Jobs Plan) must utilize a Justice40 framework as outlined in the WHEJAC recommendations.

We will submit the final report early next week as we work over the next several days to incorporate additional comments received during the meeting today. We are encouraged by this new beginning and the Biden Administration's commitments to frontline/EJ and Indigenous communities.

Sincerely,

Richard Moore, WHEJAC Co-chair

Peggy M. Shepard, WHEJAC Co-chair

cc: Members of the WHEJAC
Michael S. Regan, EPA Administrator
Cecilia Martinez, PhD, Senior Director for Environmental Justice, CEQ
Corey Solow, Deputy Director for Environmental Justice, CEQ
White House Environmental Justice Interagency Council
Karen L. Martin, Designated Federal Officer

Contents

ABOUT THE WHEJAC

Through President Biden's Executive Order 14008, titled Tackling the Climate Crisis at Home and Abroad , the White House Environmental Justice Advisory Council (WHEJAC) was established to advise the Chair of The Council of Environmental Quality (CEQ) and the White House Environmental Justice Interagency Council (WHEJIC) to increase the Federal Government's efforts to address environmental injustice. The WHEJAC's efforts will include a broad range of strategic, scientific, technological, regulatory, community engagement, and economic issues related to environmental justice.

This Council advises on how to increase the Federal Government's efforts to address current and historic environmental injustice through strengthening environmental justice monitoring and enforcement. The duties of the WHEJAC are to provide advice and recommendations to the WHEJIC and the Chair of CEQ on a whole-of-government approach to environmental justice, including, but not limited, to environmental justice in the following areas:

- Climate Change Mitigation, Resilience, and Disaster Management
- Toxics, Pesticides, And Pollution Reduction in Overburdened Communities
- Equitable Conservation and Public Lands Use
- Tribal and Indigenous Issues
- Clean Energy Transition
- Sustainable Infrastructure, Including Clean Water, Transportation, And the Built Environment
- NEPA, Enforcement and Civil Rights
- Increasing the Federal Government's Efforts to Address Current and Historic Environmental Injustice.

WHITE HOUSE ENVIRONMENTAL JUSTICE ADVISORY COUNCIL CHARGE QUESTIONS

JUSTICE40 WORK GROUP CHARGE QUESTIONS

Executive Order 14008 Sec. 223. Justice40 Initiative

a) *Within 120 days of the date of this order, the Chair of the Council on Environmental Quality, the Director of the Office of Management and Budget, and the National Climate Advisor, in consultation with the Advisory Council, shall jointly publish recommendations on how certain Federal investments might be made toward a goal that 40 percent of the overall benefits flow to disadvantaged communities. The recommendations shall focus on investments in the areas of clean energy and energy efficiency; clean transit; affordable and sustainable housing; training and workforce development; the remediation and reduction of legacy pollution; and the development of critical clean water infrastructure. The recommendations shall reflect existing authorities the agencies may possess for achieving the 40-percent goal as well as recommendations on any legislation needed to achieve the 40-percent goal.*

b) *In developing the recommendations, the Chair of the Council on Environmental Quality, the Director of the Office of Management and Budget, and the National Climate Advisor shall consult with affected disadvantaged communities.*

Justice40 Is to Increase Investment in Priority Communities

The highest goal of the Justice40 initiative is to ensure that more investments are directed into historically overburdened and underserved communities.

Key components that require further development for effective implementation of Justice40 and require WHEJAC input are:

1) Identifying the programs and policies federal (investments) in that can be included in Justice40. Note: the areas of investment are listed in the Executive Order – and include clean energy and energy efficiency; clean transit; affordable and sustainable housing; training and workforce development; remediation and reduction of legacy pollution; and development of critical clean water infrastructure.
    a. Existing programs that EJ communities have found critical and important to serving their needs.
        i. What components of these programs are most effective?
        ii. What components present challenges to EJ communities?
    b. Ideas for potential new programs that would meet a gap In EJ needs.

2) What are the key elements that are important in developing definitions of "investment benefits"?
    a. Are there examples of definitions from federal or state legislation that would be helpful to review?
3) What are the key elements that should be included in defining "disadvantaged communities?" Note: We understand there are concerns about this term – are there other terms that you consider more appropriate, i.e., underserved, overburdened, etc.
    a. Are there examples of definitions from federal or state legislation that would be helpful to review?

SCORECARD WORKGROUP CHARGE QUESTION

Executive Order 14008 Sec. 220 (d)

Executive Order 14008 requires in Sec. 220 (d) that the EJ Interagency Council (IAC) develop clear performance metrics to ensure accountability, and publish an annual public performance scorecard on its implementation, and that the IAC do so by consulting with the White House Environmental Justice Advisory Council. The scorecard would provide a method for evaluation and accountability to assess progress on the agency's progress in addressing current and historic environmental injustice. Note: This is not an immediate deliverable, however we would like to initiate WHEJAC input.

1) What types of indicators or data would be useful in an agency scorecard? At this time, your input can be in the form of general ideas or specific data. As noted, this will be a continuing process, and the WHEJAC will have ongoing opportunity for providing further input.

The WHEJAC established this workgroup during the May 13, 2021, public meeting and will begin to develop recommendations over the next several months.

CLIMATE AND ECONOMIC JUSTICE SCREENING TOOL WORK GROUP CHARGE QUESTION

Executive Order 14008 Sec. 222 (a)

Executive Order 14008, Sec. 222 (a) The Chair of the Council on Environmental Quality shall, within 6 months of the date of this order, create a geospatial Climate and Economic Justice Screening Tool and shall annually publish interactive maps highlighting disadvantaged communities.

Executive Order 14008 requires the creation of a Climate and Economic Justice Screening Tool, to be established by July 2021. At this time, a phased approach for implementation is being considered to ensure a continuous process of improvement for a robust, effective, valid, and responsive tool. Therefore, the goal is to establish a base Climate and Economic Justice Screening Tool in July in compliance of EO 14008, and to establish a plan for building up the Screening Tool with benchmark dates for completion of the phases of development

1) What should be the goal and purpose of the Climate and Economic Justice Screening Tool?
    a. What is the target user(s) for the tool?
    b. For what purpose would EJ communities and other target users need/use the tool?
    c. Are there other existing tools {other than CalEnviroScreen) used by state and local governments, or other entities that are effective and should be reviewed for consideration in development of the Climate and Economic Justice Screening Tool? Note: Discussions with California and New York stakeholders have been ongoing, and ideas on other tools beyond CalEnviroScreen would be valuable information.
2) What indicators/data should, if possible, be included in the Climate and Economic Justice Screening Tool in the July 2021 release? Note: your input can be in the form of general ideas or specific data.
    a. Are there indicators in the current EPA EJSCREEN that are useful and, if possible, should be included in the Climate and Economic Justice Screening Tool?
    b. Are there indicators in the current EPA EJSCREEN that are not useful and should not be considered in the Climate and Economic Justice Screening Tool?

EXECUTIVE ORDER 12898 REVISIONS WORK GROUP CHARGE QUESTIONS

Executive Order 14008 Sec. 220 (h)

Executive Order 14008 Sec. 220 (h) The Interagency Council shall, within 120 days of the date of this order, submit to the President, through the National Climate Advisor, a set of recommendations for further updating Executive Order 12898.

1) What sections of Executive Order 12898 should be revised?
2) What components should be added to Executive Order 12898?
3) What components should be removed from Executive Order 12898?

JUSTICE40 INITATIVE RECOMMENDATIONS

Justice40 Initiative Question 1: Recommendations for Identifying Programs and Polices to Include in Justice40

Justice40 investments should be administered and overseen by a central unit/office that approves agency investments and monitors and tracks the investments. It will ensure that monies are spent as intended and can audit agencies or recipients. Justice40 Initiative program is a whole of government program applicable to all federal agencies and not limited to the federal agencies listed in the Executive Order 140008.

CLEAN ENERGY & ENERGY EFFICIENCY

Current Program / Agency: U.S. Department of Energy - Office of Energy Efficiency and Renewable Energy

Recommendation: Establish a grant program that incentivizes community solar projects in cities and rural communities with discounted subscriptions for low income households whose monthly cost burden for conventional electricity is 12.5% percent or greater, first prioritizing households with the greatest energy burden.

Current Program / Agency: U.S. Department of Energy & U.S. Department of Commerce

Recommendation: Installing rooftop solar, community solar, energy efficiency upgrades to homes and buildings would lower the cost of electricity to most individuals in frontline and low-income communities. In addition, community resilience projects, including sustainable and regenerative agriculture, other nature based solutions (e.g. green roofs for mitigation of extreme heat, mangroves/wetlands, porous roads for flood mitigation), clean water infrastructure (e.g. sewage management and drinking water access), and broadband installation projects would provide significant benefits to frontline and low-income communities. It is important to note that much of the demand side technology for energy management requires stable internet access. However, individuals in these communities cannot afford to put any funds down to obtain a loan and cannot afford to repay loans at commercial interest rates. Grants alone will not support the level of scale that is needed.

Recommendation: To scale up rooftop and community solar, energy efficiency upgrades, and resilience projects in frontline and low-income communities, a green bank should be created to provide low-interest loans covering 100% of costs so that no upfront capital is needed. The loan would be at a low enough interest rate so that the combined energy bill and loan repayment will be less than a participant's current energy bill. Where the cost of repayment plus electricity costs would exceed the current cost of electricity, the bank would provide grants that lower the cost so that electricity costs go down. Currently, there is proposed green bank legislation in both the House and the Senate, (often with a different name for the bank). It is critical for frontline and low-income communities that the legislation specify that a specific percentage of the bank's funds (40%) must go to frontline and low-income communities. Low cost green bank financing would also be available for a wide range of traditional infrastructure projects in frontline and low-income communities to supplement direct infrastructure funding in these communities. Green bank financing can reach the necessary scale because loans are repaid and can be securitized, resulting in a revolving source of funds, and loans can be leveraged with private capital and green bonds. Funds will cover costs to develop onsite solar, storage and other renewable energy and energy efficiency projects. Funds also to pay for new roofs, electrical system upgrades, and other infrastructure improvements needed to make sites ready for renewable energy production. Funding decisions and allocation should be led and informed by Biden's Interagency Climate Equity Task Force and local community leadership. Funds must be dedicated solely to investments that benefit frontline communities and restricted from use for any other purposes.

Current Program / Agency: U.S. Department of Energy & U. S. Department of Housing and Urban Development

Challenge: HUD services our most disadvantaged communities; ensuring access to affordable clean energy through HUD is key to reaching disadvantaged communities.

Recommendation: Identify key barriers to solar access at U.S. Department of Housing and Urban Development, including reviewing utility allowances. DOE and HUD should collaborate to identify barriers to solar in HUD housing and ensure sufficient financing programs for low income households.

Recommendation: Establish a joint DOE and HUD study on home repair and structural barriers to solar installations by 2022 and deploy at least 3 gigawatt of local solar on HUD assisted housing by 2025, with at least 1.2 gigawatt in disadvantaged communities.

Recommendation: Increase funding to DOE for distributed renewable energy programs and ensure that at least 40% of incentives and program funds for clean energy support disadvantaged communities. DOE programs have been an important part of expanding clean energy access across the country, but modifications are needed to ensure the benefits reach disadvantaged communities.

Current Program / Agency: U.S. Department of Agriculture

Recommendation: Ensure that U.S. Department of Agriculture (USDA) Rural Utilities Service (RUS) electric programs prioritize support for clean, distributed energy, and ensure 40% of funds are directed to disadvantaged communities. The RUS program currently provides loans, loan guarantees, and grants for rural electric utilities, electric distribution, transmission, and generation facilities, as well as efficiency, conservation, and renewable energy programs; ensuring these programs prioritize clean energy deployment for disadvantaged communities is crucial to bringing equity to USDA programs.

Recommendation: Expand the USDA Rural Energy for America Program (REAP) to tax-exempt entities including nonprofits and government entities and increase program funding to $100 million per year to support tribal energy and energy efficiency projects. Require 40% of funds to be directed to disadvantaged communities. The REAP program has been very successful in bringing clean energy to some rural communities, but program eligibility expansion and increased funding is needed to ensure the program is reaching the most disadvantaged communities, among them, farmworkers.

Current Program / Agency: U.S. Department of Homeland Security - Federal Emergency Management Agency & U.S. Department of Housing and Urban Development

Recommendation: Prioritize federal funding for rooftop/on-site/localized solar and battery energy storage systems (BESS) as proposed in the We Want Sun Civil Society Proposal (https://www.queremossolpr.com/). The Federal Emergency Management Agency (FEMA) has allocated $9.7 billion for electric system work in Puerto Rico. In addition, HUD will provide Community Development Block Grant Disaster Recovery (CDBG-DR) funds for the 10% cost share. Most of the FEMA funding is authorized pursuant to section 528 of the Stafford Act. Additional funding could be available under sections 404 and 406 of the Stafford Act. The 2018 Bipartisan Budget Act (Public Law 115-123), allows for the use of funds for alternative technologies, such as rooftop on-site localized solar and storage (BESS). FEMA Building Resilient Infrastructure and Communities (BRIC) can also be used for rooftop/on-site/localized solar and battery energy storage systems.

Recommendation: Prohibit FEMA funding for going to permanent fossil fuel generation and infrastructure; require plans and recovery dollars for energy systems to go toward energy efficiency and literacy programs, including solar water heaters, efficient appliances, clean energy, and battery storage.

Recommendation: Require public input and hearings for investments in disaster recovery efforts to ensure impacted communities have a voice in how funds are spent.

Current Program / Agency: U.S. Department of Energy

Recommendation: Energy conservation, efficiency, customer engagement, and demand response programs. Quick-Start Energy Efficiency programs:

- Widescale solar water heaters implementation,
- Energy audits,
- Appliance replacement programs,
- Tuning up air conditioners or replacing old air conditioners,
- Expanding low-income weatherization programs,
- Energy literacy and prosumer education programs.

Current Program / Agency: Tennessee Valley Authority

Recommendation: As the nation's largest public power provider, Tennessee Valley Authority should lead by example by implementing a transition to clean energy well ahead of the President's industry-wide target of 2035, as well as by ensuring the large population of disadvantaged communities in their territory receive the benefits of this transition. Specific actions the administration should take include calling on TVA to set an ambitious goal of transitioning to clean energy by 2030 in its next integrated resource plan, creating a specific carve out for TVA in federal Clean Energy Standards, and prioritizing the rapid and safe cleanup of coal ash contaminated sites across its territory.

Current Program / Agency: Legislation Needed

Recommendation: Expand Department of Energy low-income programs by Enacting the Affordable Solar Energy for Our Communities Act (116th Congress H.R. 8165) to create new DOE low-income solar programs to ensure DOE programs are reaching the most disadvantaged communities.

Recommendation: Federal Renewable Energy Investment Tax Credit Revisions. Extend a 30% renewable energy tax credit for 10 years, and to ensure that the benefits of clean energy reach disadvantaged communities, and service organizations: (1) allow for 100% credit refundability for projects on the distribution grid, and (2) clarify that tax exempt entities are eligible for a cash grant/direct pay refundable version of the ITC. The ITC has been crucial for renewable energy growth across the country, but these modifications are needed to ensure disadvantaged communities are able to benefit from the incentive.

CLEAN TRANSIT & TRANSPORTATION INVESTMENT

Current Program / Agency: U.S. Department of Transportation, U.S. Department of Energy, U.S. Department of Housing and Urban Development

Investment Topic: Investing in transit hubs to catalyze economic and small business development in commercial corridors.

Recommendation: We should invest in transportation hubs because the communities that are most impacted by the lack of access to transportation are the low-income, people of color, and elderly communities. In New York, WE ACT, along with the assistance from the 40 local community groups and Farzana Gandhi Design Studio, created the "East 125th Community Visioning Action Plan" that focused on making transit accessible and sustainable. This plan would improve mobility amongst commuters by reducing congestion and improving flow of traffic, create efficient public transit lines to connect and make it easier for riders and commuters, and implement sustainable infrastructure for noise, waste, and lighting management in prevention of extreme weather. Transit hubs catalyze housing and small business development, cultural and historic preservation, and attract investment in sustainability especially if they are in a flood zone.

Current Agency: U.S. Department of Transportation and U.S. Environmental Protection Agency

Investment Topic: Electrify Fleets of School Buses and Sanitation Trucks and Other Public Vehicles

Recommendation: School buses and sanitation trucks are some of the dirtiest vehicles that travel throughout EJ communities spewing diesel exhaust and fine particulates which contribute to poor air quality.

Current Agency: U.S. Department of Transportation and U.S. Department of Energy

Recommendation: Support development of alternate shared transit entrepreneurship. Many communities have little to no public transit, and many low-income communities have a low percentage of car ownership. Many low-income residents and young people have no way in small towns and suburbs and under-resourced cities like Detroit or Los Angeles to get to jobs without public transit. Many new ways of van sharing and other entrepreneurial ventures are starting that can address this challenge. These startups need to be resourced with incentives and seed money.

SAFE, AFFORDABLE & SUSTAINABLE HOUSING & COMMUNITIES

Current Program / Agency: U.S. Department of Housing and Urban Development – Community Planning and Development Program - Federal housing assistance include HUD Project-based Section-8, Conventional Public Housing, Section 202 and Section 811, and Housing Vouchers

Challenge: There are no funds for the relocation of residents whose homes were built on contaminated land or toxic sites with HUD funds, such as the Urban Development Action Grant (1977-1988). Within this program, there is the Environment and Energy Office, but it does not provide ongoing assessments of the environmental health conditions at sites where HUD-financed homes are built.

Recommendation: HUD should establish a voluntary community relocation program that provides replacement housing cost to residents whose homes were built with HUD funds on toxic sites, such as former waste dumps.

Recommendation: The relocation of residents whose homes were built on contaminated land or toxic sites with HUD funds, such as the Urban Development Action Grant (1977-1988).

Recommendation: HUD should establish a voluntary community relocation program that provides replacement housing cost to residents whose homes were built with HUD funds on toxic sites, such as former waste dumps.

Recommendation: Develop HUD policy to align with its mandate to provide assisted housing to elderly, disabled and low-income households that is affordable, safe, sanitary, and outside of flood plains.

Recommendation: HUD should establish guidance and a policy for recipients of assistant housing to use their rent certificates and housing vouchers to locate housing outside flood plains. The current HUD policy ties the assisted housing voucher to housing units.

Current Program/ Agency: U.S. Environmental Protection Agency and U.S. Department of Housing and Urban Development

Investment Topic: Clean Water State Revolving Fund

Recommendation: Expand project eligibility criteria of the Clean Water State Revolving Fund (CWSRF) to include homes, residences, schools, and childcare facilities. Eligibility criteria should include prioritizing highly impacted communities with a legacy of drinking water contamination in homes & apartment buildings. Eligibility requirements should allow access to families and renters. CWSRF Project Eligibilities

Current Program/ Agency: U.S. Department of Health & Human Services

Investment Topic: Expand Low Income Home Energy Assistance Program (LIHEAP)to Support Cooling as Well as Heating

Challenge: As climate change brings more heat waves each year as well as cold to southern areas that do not anticipate the need for heating, more communities are left in the cold or sweltering in the heat. Both extremes are deadly for vulnerable households.

Challenge: The challenges we may encounter include a lack of national impact data and household recipients. There hasn't been a rigorous evaluation on the performance outcomes or impact of LIHEAP, but a national study in 2014 used a simulation, which estimated that if LIHEAP were cut, the population of energy-secure households would decrease by 17%, leading to late and unpaid energy bills among vulnerable population. When utilities are cut off, some households turn to their last resort of alternative, unsafe heating options, such as turning ovens on for an extended period of time to heat a home. The average cost of heating a home costs around $911 per year nationally, making it one of the highest house-hold expenses.

Recommendation: Adequate home heating and cooling are a human necessity. Without proper temperature control the effects can be devastating and lead to extreme health and safety issues, and even death. We should invest in the Low-Income Home Energy Assistance Program (LIHEAP) because it helps eligible families with energy costs by providing federally funded assistance for energy bills, weatherization, and other energy crises and home repairs. With help from LIHEAP grants, there are currently over 6 million families around the U.S. who are able to pay heating and cooling bills, emergency services such as utility shutoffs, and low-cost home improvements, which make homes more energy efficient and lower utility bills. Additional funding for LIHEAP is crucial to help support low-income families with energy bills and protect the most vulnerable.

Current Program/ Agency: U.S. Department of Health & Human Services U.S Department of Homeland Security - Robert T. Stafford Disaster Relief and Emergency Assistance Act, Federal Emergency Management Agency – Building Resilient Infrastructure and Communities, U.S. Department of Commerce – Small Business Administration Disaster Assistance Loans and Grants & Department of Housing and Urban Development – Community Development Block Grant

Recommendation: Develop guidance and policy for governors requiring them to certify relief assistance and funds received during major declared disasters and emergencies are spent in an equitable and nondiscriminatory way, including individual assistance, hazard mitigation, and public assistance.

Current Program/ Agency: U.S. Department of Health & Human Services – Health Resources and Services Administration, U.S. Environmental Protection Agency, U.S. Department of Housing and Urban Development – Office of Sustainable Communities, U.S. Department of Transportation

Investment Topic: The U.S. Department of Health & Human Services, The U.S. Environmental Protection Agency, The U.S. Department of Housing and Urban Development, and The U.S. Department of Transportation should establish a grant program for cities and towns to address major infrastructure deficits and environmental protection that do not exist in many EJ and other communities. These grant programs could be designed in a fashion that imitates other large and consequential programs that the government has supported which resulted in substantive change for the country; e.g. the Housing Urban Development first time homeowner's project.

Challenge: Establishing a "whole of government" approach to rebuild whole communities will require several government agencies coming together and working in tandem to address the major sustainability problems of entire communities.

Recommendation: Establish a sustainable communication office for communities that have been so egregiously neglected by government and impacted by racist public policy, environmental pollution and climate change. This office will be established to utilize a “whole of government” approach to address the enormous challenges that exist for improving the quality of life of these communities. “The Black Belt” of rural Alabama is an example of an area that needs a “whole of government approach to address the challenges that exist in this area. “The Black Belt” of rural Alabama has several environmental justice communities in need of federal investments to improve air and water quality and basic health services, especially the City of Uniontown. The city needs fundamental infrastructure such as a hospital, local ambulance service, a fire department, equipment for local police, and storm shelters to protect residents from tornados which are prevalent in the area. The community also needs a community youth center to create a safe, clean space for community engagement and education. Importantly, any federal investments to the area must involve transparency and public participation. For example, residents of Uniontown have not been given basic information about the U.S. Department of Agriculture’s grant to improve wastewater infrastructure, and as a result there is a lack of trust and accountability.

TRAINING & WORKFORCE DEVELOPMENT

Current Program/Agency: National Institute of Environmental Health Sciences - Worker Training Program

Recommendation: Increase funding for the NIEHS Environmental Career Worker Training Program. Expand this program to provide grants to support nonprofits, labor, academic institutions, etc. in establishing worker training programs, in particular for un- and underemployed individuals, that prepare people for careers in renewable solar and wind energy infrastructure, installment and maintenance; as well as green infrastructure development and maintenance for community resilience, flood mitigation, and storm surge defense.

What Works: Grant program for non-profits, labor, health and safety organizations, and academic institutions to workers for occupations in environmental cleanup and restoration, disaster and emergency response, critical facilities maintenance and operation, construction, etc. Includes training tailored for un- and underemployed individuals and non-English speakers.

Current Program/Agency: U.S. Department of Labor - Occupational Safety and Health Administration & U.S. Department of Agriculture

Challenge: At the national level, there is a lack of parity regarding provision of and access to basic sanitation facilities and supplies. OSHA's Field Sanitation Standards require agricultural employers with 11 or more workers to provide "hand laborers" with: toilets, potable drinking water, and hand-washing facilities. Across the country there are approximately 2.4 million farmworkers who are predominantly of Latinx and/or indigenous ancestry. More than 1 million work farmworkers work in farms with 10 or less workers per the 2017 Census of Agriculture. A 2018 study on field sanitation in U.S. agriculture also found that workers with less education, who do not speak English well, and who hail from Mexico are more likely to lack access to field sanitation than other workers (Pena & Teather-Posadas, 2018).

Recommendation: Access to basic sanitation supplies and handwashing facilities for all agricultural workers.

Recommendation: Leverage federal funds to ensure that employers, including those that receive federal funds and/or benefit from federal government procurement, provide all agricultural workers, not just "hand laborers" with access to toilets, potable drinking water and hand washing facilities, regardless of the number of workers in the establishment.

Current Program/Agency: U.S. Environmental Protection Agency, U.S. Department of Agriculture & The White House

Challenge: The EPA estimates that updating water infrastructure in rural America (water systems serving populations of less than 10,000) would require an investment of approximately $190 billion in the coming decades.

Recommendation: Justice40 investments AND any federal investments in infrastructure should prioritize the establishment of and/or modernization of water infrastructure in rural America and in environmental justice communities to ensure low-income and BIPOC households, including those in unincorporated communities, have access to reliable, clean and safe drinking water that protects public health.

Current Program / Agency: Appalachian Regional Commission and Economic Development Administration

Recommendation: Increase funding for the Partnerships for Opportunity and Workforce and Economic Revitalization (POWER) and Assistance to Coal Communities (ACC) programs. POWER and ACC have provided critical support for planning activities in communities affected by the coal transition, but they remain underfunded compared to the scale of communities' needs. This problem will worsen as mine and plant closures accelerate in the coming years.

Current Program / Agency: U.S. Department of Labor

Recommendation: Expand funding for existing training programs as well as union apprenticeship and pre-apprenticeship programs. These programs include the Adult and Dislocated Worker programs at the Department of Labor. This is a way to support workers getting paid while also up-skilling in real work environments. Expand the National Dislocated Worker Grants to ensure a focus on dislocated workers in coal communities with an additional $5.4 billion. This is also a way to ensure the new jobs created are good paying jobs with benefits. A genuine focus on diversity, equity, and inclusion is crucial in order for apprenticeship programs to be open and available to all workers and should be prioritized in the recommendations of the task force.

Current Program / Agency: U. S. Housing and Urban Development, U.S. Department of Agriculture, Appalachian Regional Commission and Economic Development Administration, U.S. Economic Development Administration, National Telecommunications and Information Administration Broadband Programs

Recommendation: Reduce or eliminate matching requirements for broadband construction projects in environmental justice coal-impacted communities. It is critical to subsidize broadband construction in coal-impacted communities and existing grant programs. Programs at ARC, EDA, USDA, and NTIA are important tools for increasing access. In coal-impacted areas, the match requirements are prohibitive and limit the number of communities who can apply for funding.

Recommendation: Expand covered functions of the HUD Utility Allowance to include internet service. Currently, HUD's Utility Allowance doesn't cover internet service. However, without this service, those in public housing lack access to opportunities to find new work, workers cannot attend training programs, and children lack access to complete homework after school.

Current Program / Agency: Legislation Needed

Recommendation: Incentivize hiring of remote workers in environmental justice coal-impacted areas by extending the Work Opportunity Tax Credit to include employees in coal-impacted communities. With the expansion of remote work, there is an opportunity to close the rural-urban divide and leverage larger economic markets to create jobs in coal-impacted communities.

Recommendation: Regional Energy Transition Commission. Use ARC as a model for helping communities in other regions impacted most by the decline of fossil fuels to transition economically.

Recommendation: Support workers in Coal-Impacted Communities. Workers affected by coal closures need targeted workforce development and training programs, in addition to investment in broader economic development strategies that spur quality job creation. Provide immediate support to contractor businesses to afford online training in home energy performance (such as through Reps. Welch & McKinley's Hope for Homes Act or Rep. Rush's Blue Collar to Green Collar Jobs Act/H.R. 1315). Workforce development more broadly should be provided through funding to promote high-quality, family-sustaining, environment- or infrastructure-related jobs in communities that need them the most (such as through Rep. Bass' Build Local, Hire Local Act, H.R.4101/S.2404 or Rep. Rush's Blue Collar to Green Collar Jobs Act/H.R. 1315.

Recommendation: Comprehensive Wage Replacement for Dislocated Workers for Five Years. Comprehensive wage replacement means a worker's full salary to include continued health care coverage and employer-sponsored retirement contributions (which can come through 401(k) or defined-benefit plans). This benefit is essential to providing temporary support to workers and their families as they prepare for new career opportunities.

Recommendation: Expand funding for and give priority to training programs that pay the trainees. The federal government should directly fund creative pilot projects which focus on direct employment and job training in emerging sectors and environmentally sustainable industries. For example, the Jobs for Economic Recovery Act (introduced in 2020 by Sen. Wyden) would directly fund community-based social enterprises that prioritize the well-being and economic mobility of the workers staffing the enterprise.

Recommendation: Increase broadband access for rural communities. H.R. 2 (Sec. 31301, 31141) would provide $100 billion to deliver affordable, high-speed broadband Internet access to every part of the country, prioritizing underserved communities, and the American Jobs Plan would make these investments to ensure that all Americans have affordable broadband access.

Recommendation: Develop a sliding scale broadband subscription program to make the internet accessible to those who need it most for attending school, finding new work, and taking advantage of the opportunity of remote work. The federal government should work with telecommunications providers to develop negotiated sliding scale subscriptions rates and an accompanying tax credit to offset agreed upon operating costs necessary for the additional subscriber.

Recommendation: Invest in programs that support Historically Black Colleges and Universities (HBCUs), Hispanic Serving Institutions (HSIs), Tribal Colleges and Universities (TCUs) and Asian American and Pacific Islander Serving Institutions (AAPISIs). These institutions provide quality, affordable training for the Black, Latinx, Asian, Pacific Islanders and Tribal populations and serve as key partners in local economic development initiatives. Expanding federal programs that support tribal colleges and universities is critical to supporting communities' efforts to develop local workforces and diversify their economies. Important programs are administered by the Bureau of Indian Education, Department of Education, USDA, Department of Labor, National Science Foundation, and Health and Human Services.

Current Program/ Agency: U.S. Department of Labor

Recommendation: Develop a frontlines climate corps to support youth leadership development and training of underemployed workers.

Recommendation: Develop a Frontline Climate Corps of youth 16-24. First track is Job Training. Partner with Historically Black Colleges and Universities (HBCUs), Hispanic Serving Institutions (HSIs), Tribal Colleges and Universities (TCUs) and Asian American and Pacific Islander Serving Institutions (AAPISIs) to recruit candidates and set up new job training programs that prepare students to succeed in these industries. Hire people of color in leadership positions in relevant federal agencies for these programs, and work with community leaders for local outreach and recruitment to improve cultural competency and ensure equitable program design. Pre-identify roles that do not require a college education and invest in outreach and recruitment from high schools in communities of color and low-income. Where appropriate, provide federal funding for a network of trade schools and scholarships across the country for high schoolers to train for these industries without needing to pursue a college education.

Recommendation: The second track is Youth Climate Leadership Development. Creating a climate leadership pipeline of youth from frontline communities working in their communities on identified citizen science projects with grassroots EJ groups. Investment in frontline communities can address underserved youth and under-resourced grassroots groups on the frontlines of fighting for environmental and climate justice through the federal development of a corps targeting youth of color and low income living in environmental justice communities.

Recommendation: The corps can develop young leadership on issues of climate and environmental degradation while linking those youth to grassroots groups fighting for climate and environmental justice. The youth can develop a career path, compensation, education awards, and job skills while living in their own communities and being part of the solution.

Current Program/ Agency: U.S. Department of Labor and U.S. Department of Energy

Recommendation: Incentivize Development of Green Worker Cooperatives. Underemployed workers of color who have been trained in construction skills and solar installation have a difficult time getting employment through labor unions (construction trades) which are often biased against people of color and tend to be tightly controlled by white ethnic groups for multi generations. One effective response to this challenge is for workers to own and develop their own worker businesses or associations where they incorporate and bid on jobs and become certified as MWBEs.

Current Program / Agency:

- CALIFORNIA §3395. Heat Illness Prevention in Outdoor Places of Employment https://www.dir.ca.gov/title8/3395.html
- WASHINGTON § 296-62-095–296-62-09560. Outdoor heat exposure. http://ap+p.leg.wa.gov/WAC/default.aspx?cite=296-62&full=true#296-62-095
- U.S. MILITARY Heat stress control and heat casualty management. (2003) https://apps.dtic.mil/dtic/tr/fulltext/u2/a433236.pdf
- NIOSH Criteria for a Recommended Standard Occupational Exposure to Heat and Hot Environments. (2016) https://www.cdc.gov/niosh/docs/2016-106/pdfs/2016-106.pdf

Investment Topic: Climate Change and Heat Stress

Challenge: There is no federal standard to protect outdoor workers, and other workers that don't work in climate-controlled spaces from heat stress. The California and Washington standards apply to outdoor workers but not indoor workers. In California, the Standard is in effect year-round. In Washington State, the Standard is in effect from May 1st through September 30th. Both the Military heat stress management and the NIOSH recommendations apply to all worksites, year-round.

Recommendation: Establish heat illness safeguards for all outdoor workers that don't have the luxury to work in climate-controlled spaces.

Recommendation: Leverage federal funds to ensure that employers, including those that benefit from federal government procurement, have a heat illness prevention plan in place that at a minimum includes training, access to potable and cool water, shade, paid rest breaks, and protocols for emergency response.

Current Program / Agency: U.S. Environmental Protection Agency Office of Chemical Safety and Pollution Prevention, Office of Enforcement and Compliance Assurance, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health

Challenge: EPA is not considering how climate change and the risks of heat-related illness associated with Personal Protective Equipment (PPE) affect farmworkers. When workers apply pesticides, they must do so wearing any personal protective equipment required by EPA. The Agency has acknowledged that the use of such equipment when working in hot temperatures increases the risk of heat-related illness. EPA does not evaluate this risk when conducting occupational risk assessments for pesticides that assume varying levels of personal protective equipment.

Challenge: Farmworker organizations arduously fought for and secured historic changes to the Agriculture Protection Standard (WPS), the only federal safeguards designed to protect the nation's 2.4 million farmworkers and their families from pesticide exposure and drift.

Challenge: It is current EPA policy to mitigate a chemical's risks early in the registration review process rather than wait for the completion of a chemical's registration review. Moreover, when modifying, leaving in effect, or revoking a tolerance or exemption for a pesticide chemical residue, EPA has the authority to consider "available information concerning the cumulative effects of such residues and other substances that have a common mechanism of toxicity" (21 U.S.C. § 346a).

Challenge: EPA is recommending continued use of a temporary guidance issued in June 2020 by the Trump EPA regarding respiratory protection for agricultural pesticide handlers, a move that puts these workers at risk of pesticide exposure. In delaying respirator fit testing for agricultural pesticide handlers, EPA suggests doing so is necessary based on an assumption of shortage of N95s, even though U.S. manufacturers say they have vast surpluses for sale and the FDA recently recommended that "health care personnel and facilities transition away from crisis capacity conservation strategies," referring to a return to single use of N95s. In doing so, EPA is allowing employers to continue avoiding an important requirement regarding fit testing, either initially when they buy a new respirator model or annually. Extended use or reuse of filtering facepiece respirators for pesticide handling puts pesticide handlers at increased risk of pesticide exposure because a) pesticide residue contamination may not be readily evident; b) some pesticides degrade very slowly and others, like neurotoxic organophosphates degrade initially to more toxic oxons. Additionally, certain alternatives to filtering facepiece respirators are not designed to provide an adequate seal on the face and pose an increased risk of pesticide exposure.

Recommendation Assess the risk of heat-related illness associated with any and all personal protective equipment that the Agency assumes that workers will wear when conducting occupational risk assessments for pesticides.

Recommendation: Repeal the Trump Administration revisions to the Application Exclusion Zone (AEZ) provision within the Agricultural Worker Protection Standard.

Recommendation: Restore the 2015 version of the AEZ adopted by the Obama Administration.

Recommendation: Direct EPA to consult with farmworkers and farmworker-serving organizations and ensure that farmworker input is integrated into agency decisions on mitigation measures relevant to pesticides.

Recommendation: Direct EPA to leverage existing policy to immediately protect pesticide applicators, farmworkers, agricultural communities and consumers from pesticide exposure and drift BEFORE the pesticide registration review process is completed and even while revocation and/or cancellation proceedings are in progress for certain pesticides.

Recommendation: Account for all cumulative exposures to organophosphate pesticides in the registration review process. Currently, EPA is conducting risk assessments for each organophosphate pesticide individually without taking into account cumulative exposures.

Recommendation: Implement the 2009 guidance adopted by the Obama Administration called "2009 Revised Risk Assessment Methods for Workers, Children of Workers in Agriculture Fields, and Pesticides with No Food Uses." Improve cost-benefit analyses by considering the availability of safer alternatives early in the process and considering social costs of use of pesticides. DEVEOP methods for gathering true exposure data showing the extent of farmworker exposure, rather than relying on industry-generated data.

Recommendation: Invest in research on pesticide illness and injury surveillance documenting work-related pesticide poisoning incidents as well as broader pesticide exposure and its impact on pesticide applicators, farmworkers, farmworker children, farmworker women of childbearing age. Additionally, invest in the Sentinel Event Notification System for Occupational Risk (SENSOR) Pesticides Program to build, maintain and bolster occupational illness and injury surveillance capacity within state health departments.

Recommendation: Finalize the 2015 proposed rule revoking all food tolerances of chlorpyrifos.

Recommendation: Ensure the food tolerance revocation of chlorpyrifos is based on the 2014 and 2016 human health risk assessments, the full administrative record and review of the comments submitted on the 2020 update to the human health risk assessment.

Recommendation: The California Department of Pesticide Regulation's (DPR) Pesticide Use Report (PUR) is the largest database on pesticide use in the world and could serve as a model for national pesticide use reporting. In addition to requiring pesticide use reporting for agricultural uses (Sec. 6626) and making that information publicly available, PUR also requires "Pesticide Use Report for School Sites and Child Day Care Facilities" (Sec. 6224). According to the California Code of Regulations Sections 6624 and 6626, pesticide use records must include the following information: "(1) date of application; (2) name of the operator of the property treated; (3) location of property treated; (4) crop commodity, or site treated; (5) total acreage or units treated at the site; (6) pesticide, including the U.S. Environmental Protection Agency (U.S. EPA)," among other relevant information.

Recommendation: Require full and nationwide reporting of agricultural uses of pesticides regulated by the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) for agricultural uses.

Recommendation: Require full and nationwide reporting of pesticide usage on school sites and child day care facilities.

Recommendation: Ensure that at a minimum, disclosure of pesticide use data is publicly accessible and includes the information required by California's Pesticide Use Report (PUR).

Challenge: Hazard information in languages workers can understand.

Recommendation: Require the translation of pesticide labels into Spanish and any language common to a significant portion of the pesticide applicators or agricultural workers that are not fluent in English.

Recommendation: EPA must prioritize the health of those who are on the frontlines of exposure to a range of agricultural pesticides and should not offer guidance that undermines handler protection and/or the directions provided on pesticide labels. Use of contaminated or otherwise compromised respirators is of particularly high concern for pesticide handlers, including those of reproductive age. We must protect the health and safety of all agricultural workers, including pesticide handlers. This means that if adequate personal protective equipment is not available, handlers should not be authorized to apply the pesticide product.

Challenge: The revised TSCA requires EPA to specially consider groups who are at greater risk of harm from chemical exposures when it evaluates, and then manages, chemical risks. The Trump Administration failed to protect fenceline communities from unreasonable risk.

Recommendation: Office of Chemical Safety and Pollution Prevention (OCSPP) must Account for the greater risks that fenceline communities face, including cumulative exposures to many chemicals which makes them more susceptible to harm from individual chemicals, as it develops risk management rules for the first 10 TSCA chemicals.

Recommendation: OCSPP must revise the TSCA scope documents for the 20 high-priority chemicals undergoing review so fenceline communities are identified as subpopulations that face greater risk than the general population. If it does this, EPA would have to calculate these communities' risks separately from the risks the general population faces, and then ultimately it would have to manage the specific risk they experience from TSCA chemicals so it is no longer unreasonable.

Recommendation: OCSPP must act aggressively to gather information about fenceline communities' real-world exposures to all of the chemicals subject to review and risk management under TSCA, including reasonably foreseeable releases from extreme weather events.

Current Program / Agency: U.S. Environmental Protection Agency, U. S. Department of Labor and U.S. Congress

Recommendation: A bedrock principle of occupational hygiene is the "hierarchy of controls," which the Occupational Safety and Health Administration (OSHA) and others rely on to identify options for controlling worker exposures to occupational hazards. The hierarchy prioritizes the elimination of the hazardous agent or substitution of a less hazardous agent. These are preferable to the implementation of engineering controls, which in turn are preferable to requiring personal protective equipment. For workers who are protected by OSHA, personal protective equipment is always the mitigation measure of last resort. When it comes to protecting workers from pesticides, EPA is in charge and the agency starts by considering personal protective equipment, then considers engineering controls, and never considers substitution with less toxic options or practices. To protect a predominantly BIPOC workforce from exposure to a range of toxic pesticides, EPA should follow the hierarchy of controls when selecting options to reduce occupational risk from pesticides for farmworkers and pesticide applicators.

Recommendation: Collaboration between the EPA Office of Chemical Safety and Pollution Prevention (OCSPP), the Department of Labor and the Occupational Safety and Health Administration (OSHA) to provide technical assistance in integrating the hierarchy of controls when selecting options to reduce occupational risk from pesticides for farmworkers and agricultural pesticide applicators.

Current Program/Agency: U.S. Department of the Interior & U.S. Geological Survey, Pesticide National Synthesis Project

Investment Topic: Investing in data collection to allow individuals and communities to be aware of their exposure to a range of agricultural pesticides

Recommendation: Invest in the USGS Pesticide National Synthesis Project which estimates annual agricultural use for a range of pesticides.

Recommendation: Update the survey to ensure it contains the most recent data (the latest data available is from 2017).

Recommendation: Integrate data from the Pesticide National Synthesis Project into EJSCREEN.

Current Program / Agency: U.S. Environmental Protection Agency, U.S. Department of Education and The White House

Recommendation: Environmental education (EE) is the process used to achieve the goal of environmental justice. A curriculum that is focused on teaching students about environmental justice (EJ) would provide the history of the movement and what environmental issues frontline and EJ communities face that are different from other communities, in addition to the knowledge and skills a student learns through environmental education.

Recommendation: Any EE curriculum focused on achieving environmental justice must meet the same standards for all EE curriculum, as outlined in the Materials Guidelines for Excellence (linked below). Environmental education can and should promote the development of the attitudes, knowledge, skills, and motivations that people need for meaningful involvement in and resolution of environmental justice issues. The focus should always be on helping students develop the critical thinking, problem-solving, decision-making skills that students need to both understand and take actions that support the ideas that environmental protection is for all, regardless of who you are and where you live.

Recommendation: A clear distinction between helping students understand environmental justice and advocating a specific set of actions needs to be made. Environmental education does not focus on specific recommendations on how to act but teaches students that they have the knowledge and skills and empowers them to take actions in support of environmental protection and environmental justice goals.

Recommendation: It is important to recognize that there are actions within the environmental justice sphere that do not involve education (e.g., advocacy, political activism, taking legal actions, lobbying) and that there are aspects of the environmental education process (e.g., teaching basic environmental science) that are not necessarily directly related to environmental justice. However, environmental knowledge, skills, and attitudes gained through environmental education should empower meaningful involvement in environmental justice decision-making.

Recommendation: "In terms of policy recommendations, the federal government can be really helpful at providing capacity building grants either for professional development, pre-service teacher preparation, and curriculum development. Ultimately, I think this can best be leveraged in conjunction with the established programs at the Department of Education, given they are large enough to achieve maximum scale—Title II (teacher pd), Title IV (curriculum and pd) for ESSA primarily and Title II (teacher prep) of HEA. I would recommend staying away from any prescriptive curriculum requirements on things like standards. In thinking about this, you might consider developing a program to support building capacity and elevating some of the promising work occurring—a federal effort could help further incentive this work in other districts or states but would be most helpful to be grounded in local assets, context, and need."

Examples where this has been successfully implemented:

- Local level: Learning in Places in Seattle, with Megan Bang (mbang@spencer.org) and Carrie Zhou (tzouct@uw.edu) as researchers heading up this project.
- ClimeTime is a robust professional development network funded by Washington State with a Climate Justice Focus through the lens of science education. Lead: Deb Morrison eddeb@uw.edu

Recommendation: Identify climate justice education as an essential component of K-12 curriculum in the district. Schools for Climate Action's website offers free resolution templates for teachers, students and allies to draft a school board resolution calling for a climate justice curriculum.

Examples where this has been successfully:

- Portland Public Schools: Climate Justice Curriculum was the first EJ curriculum requirement in the nation. Their department's mission is to "Support the teaching and learning of climate change and climate justice in all classrooms in Portland Public Schools. Collaborate to develop transdisciplinary curriculum and professional learning that empowers educators and youth to become transformative racial equity leaders and global stewards and ambassadors. Collaborate with district and community partners to empower youth to lead the district and the world in becoming more sustainable." This initiative was created via school board resolution: "the Board of Education directs the Superintendent in collaboration with PPS students, teachers, and community members to develop an implementation plan so that there is curriculum and educational opportunities that address climate change and climate justice in all Portland Public Schools. implemented an environmental justice curriculum across all levels"

Recommendation: Ensure that climate justice education is transdisciplinary with touchpoints in literature, social studies, history, mathematics, and science.

- "Too often we see climate change in educational settings relegated to science classrooms and students may not be able to make the connection that our local/state/federal government is responsible for the big climate change decisions, such as policies that affect greenhouse gas emissions. Students can examine systemic racism in social studies classes and make clear connections to environmental policies that have disproportionately affected communities of color for decades- including redlining, fossil fuel extraction concentrated in communities of color and link to the rates of health impacts of these communities."(Source EPA)

Recommendation: From the National Environmental Justice Advisory Council (NEJAC) Youth Perspectives on Climate Change Report to increase accessibility to climate change curricula and educational resources:

- Create a youth climate change educational hub with curricular materials, presentations, and interactive workshop plans on EPA website
- Strengthen accessibility of these resources to those not in college or in the college pipeline
- Validate alternative ways of understanding climate change
- Integrate climate change curricula into the broader context of other social justice movements.

Examples of these recommendations in action:

- The Harambee House, INC./ Citizens for Environmental Justice (HH/CFEJ) is a tax-exempt organization located in Savannah, Georgia. HH/CFEJ created the Black Youth Leadership Development Institute (BYLDI), whose mission is to empower African American youth to be change agents able to facilitate transformation of themselves, their communities, and the nation by building capacity, skills, culturally-competent models, and developing confident youth leaders. The organization consists of a group of young black teachers, community educators, parents, and professionals committed to redirecting the talent and energy of black youth into positive growth and development. In practice, the program puts youth in charge of work assignments, asks for and uses their input, and lets them lead in a structured space with guidance and feedback. One useful curriculum around climate change, the Climate Change and Civic Engagement Course, is required for all BYLDI students, and gives them a stronger foundation in scientific knowledge.
- Alliance for Climate Education's ACE Assembly, as well as the digital climate education resource and scaled-up version of the assembly, Our Climate Our Future. The ACE assembly, like the fellowship, is geared toward and serves many Title I schools. This hour-long series of video clips conveys the science of climate change and related health impacts in an accessible and action-oriented manner. (Source: NEJAC)

Recommendation: Develop a Youth Environmental Justice Education Grant for K-12 Schools in majority BIPOC school districts. This can target creating a funding mechanism and collaboration between the Office of Children's Health Protection in the Program Implementation Coordination Division Schools Coordinators (to manage the program evaluation and monitoring for the program) along with the Office of Environmental Justice, and Office of Ground Water Drinking Water. Funding should be available for remediation of drinking water sources at schools, testing, etc., parameters should include special consideration for schools and child care facilities serving environmental justice communities by accounting for factors such as (but not limited to): race/ethnicity of the student population, public funding allocation to schools, test-score and performance of students.

Recommendation: Develop a Youth White House Environmental Justice Advisory Council

Recommendation: Develop a Career Technology Education (CTE) grant program to support middle schools and high schools (6-12) to design and implement environmental justice high school to career pathways curriculum prioritizing schools serving majority (75%> BIPOC student populations)

Recommendation: Develop a grant program exclusively for Historically Black Colleges and Universities (HBCUs), Hispanic Serving Institutions (HSIs), Tribal Colleges and Universities (TCUs) and Asian American and Pacific Islander Serving Institutions (AAPISIs) to develop green workforce & training (environmental justice) development programming prioritizing career development opportunities in frontline communities

Recommendation: Invest in Historically Black Colleges and Universities (HBCUs), Hispanic Serving Institutions (HSIs), Tribal Colleges and Universities (TCUs) and Asian American and Pacific Islander Serving Institutions (AAPISIs) agricultural programming to address food equity issues (e.g. fresh fruits and vegetables) in frontline communities with a history of elevated lead exposure and food deserts/swamps.

Recommendation: Invest in Historically Black Colleges and Universities (HBCUs), Hispanic Serving Institutions (HSIs), Tribal Colleges and Universities (TCUs) and Asian American and Pacific Islander Serving Institutions (AAPISIs) (via grant funding) to develop innovative career pathways focused on the care and increased growth of trees through urban planning and development through an environmental justice lens Source: Black Millennials 4 Flint

REMEDIATION & REDUCTION OF LEGACY POLLUTION

Current Program/ Agency: U.S. Environmental Protection Agency

Challenge: Black and other communities of color are disproportionately exposed to permitted emissions of hazardous air pollutants that cause an exceedance of the EPA's guidelines for cancer risk and non-cancer risk.

Recommendation: Establish a program requiring the reduction of permitted emissions of hazardous air pollution to prevent the exceedance of EPA's cancer and non-cancer risk guidelines.

Recommendation: Conduct civil rights compliance reviews under Title VI of the Civil Rights Act of states with delegated environmental authorities. These reviews should prioritize states where there are decades of civil rights complaints by Black and other communities of color against permitted pollution in their communities, such as Louisiana's Cancer Alley and the Houston Ship Channel.

Recommendation: Establish a policy for disaster recovery dollars to fund healthy land restoration in environmental justice communities.

Recommendation: Invest in urban agriculture to provide sustainable, healthy and affordable food choices.

Recommendation: Invest in flood mitigation and climate resilience infrastructure (green and gray) in Black and other communities of color who are systemically overlooked when disaster strikes and systemically excluded from investments in stormwater management, drainage and flood protection. This investment needs to correct the cost-benefit analysis applied by FEMA that has an inherent racial bias against Black and other communities of color due to historic redlining and present-day low appraised values placed on homes and properties owned by Black and other people of color.

Recommendation: Invest in educating the public about environmental justice and the impacts of environmental racism.

Recommendation: Fund environmental monitoring located inside communities exposed to pollution, along with funds for compliance enforcement.

Recommendation: Fund the implementation of programs and policies in the bill by Sen. Booker and Rep. Haaland -- The Environmental Justice Legacy Pollution Clean-up Act.

Current Program/ Agency: U.S. Department of Transportation - Federal Highway Administration Air Quality Program

Challenge: Black and other communities of color are disproportionately exposed to interstates and highways that expose residents to high levels of PM2.5 and other air pollutants in vehicle exhaust.

Recommendation: Develop an air monitoring network that includes the detection of PM 2.5 in areas where a DOT-funded transportation project, a fossil-fired power plant, or PM 2.5 major emitting facility is located within three miles of a residential area. Provide public access to the air quality data. Coordinate with the Centers for Disease Control a public health response that removes the threat of air pollution exposure for residents.

Recommendation: Conduct civil rights compliance reviews under Title VI of the Civil Rights Act to ensure that DOT funds allocated to states are not invested in transportation projects that exacerbate or otherwise perpetuate racial discrimination.

Current Program/Agency: U.S. Environmental Protection Agency - Office of Enforcement and Compliance Assurance.

Investment Topic: Reduction of legacy pollution

Recommendation: Develop guidance for the EPA to use targeted enforcement and resources priorities directed at legacy environmental justice "hot-spots" with the goal of reducing combined risks to human health or the environment from multiple agents or stressors.

Current Program / Agency: Legislation Needed

Recommendation: Pass the RECLAIM Act (H.R. 1733) to use mine reclamation as an economic driver. The RECLAIM Act would direct $1 billion over five years to reclaim and repurpose abandoned mine lands (AML) sites for community and economic development. This bipartisan legislation will cleanup sites while spurring immediate job creation and creating the conditions for longer term, locally driven economic development efforts to build better, brighter futures in coal communities across the country.

Current Program/Agency: U.S. Environmental Protection Agency

Investment Topic: Clean Air: Mandate new air quality monitoring in frontline and fence line communities

Recommendation: Fund and ensure that each state adequately monitors environmental pollution, including emissions, criteria pollutants, and toxics, in frontline and fence-line communities. This should include generating hyperlocal measurements in frontline communities where they are lacking to provide accurate and publicly available data.

Current Program/Agency: U.S. Environmental Protection Agency & U.S. Department of Housing and Urban Development

Investment Topic: Engage Communities in Regional Office Action Teams

Recommendation: Support development of regional office action teams. Institutionalize representation of fenceline and frontline communities in enforcement decision-making through development and convening of community-based Regional Environmental Justice Action Teams; Direct the Interagency Environmental Justice Enforcement Task Force to work with Action Teams to develop regional community protection and action plans; Provide dedicated funding for communities to access representation and conflict resolution resources. Hold regular public comment sessions so people do not have to travel to Washington and to ensure that regional officers are engaged with the public on enforcement concerns.

Current Program/Agency: U.S. Department of Housing and Urban Development

Investment Topic: Support HUD to expand the Lead Education and Lead Abatement Program

Recommendation: Reinstate HUD lead education outreach and lead abatement programs. Children of low-income families, African Americans, people living in large metropolitan areas, and people living in houses built before 1978 are most at risk of lead poisoning which is a neurotoxin and affects the brain development of children who are exposed under the age of six. HUD used to have a robust Lead Education program which ended over a decade ago despite the prevalence of lead in frontline communities where children of color are predominantly affected by poor maintenance in their homes. It has been found that removing lead paint hazards from homes of children from low-income families would provide $3.5 billion in future benefits and protect more than 311,000 children. Investing in lead education and abatement will lead to the health and economic benefits of greater brain development and lifetime productivity.

Current Program/Agency: U.S. Department of Housing and Urban Development & U.S. Department of Energy

Investment Topic: Energy Efficiencies in Frontline Communities

Recommendation: Address legacy pollution by supporting development of green zones. Bring green benefits to frontline communities that need it the most. Aggregate investments in solar, energy efficiency, weatherization, open streets, green infrastructure, tree planting, bioswales, flood resilience, extreme heat impacts, targeted enforcement, mitigation of mobile sources, electrification.

Current Program/Agency: U.S. Department of Interior, Office of Surface Mining Reclamation and Enforcement

Recommendation: Ensure that OSMRE assesses the new wave of post-1977 abandoned mine lands and assesses the scale of the problem in each state. In bankruptcy, coal companies are abandoning their permits and associated reclamation responsibilities, but even coal companies that have not filed for bankruptcy are functionally abandoning permits such that there has been little to no coal production or reclamation activity occurring on the permit for months or years. Reforms to the bonding system and to reclamation plans are needed to ensure adequate bond amounts to cover reclamation and water treatment obligations, regulators must act to ensure that reclamation is occurring contemporaneously with mining rather than delayed, and OSMRE must be equipped with the tools and staff it needs to actively engage in coal bankruptcies and ensure that reclamation standards are upheld even on abandoned permits and in order to improve agency data collection and databases to better track violations and outstanding coal company liabilities.

Current Program/Agency: U.S. Department of Agriculture

Recommendation: Fund the Rural Utility Service Hardship Loan Program at $100 billion, which is equal to the value of all electric cooperative debt and establish conditions for forgiveness for rural electric cooperatives. Such loan forgiveness should include conditions to facilitate the retirement of all coal plants currently in operation in exchange for new investment in clean energy, distributed energy resources, energy efficiency, high-speed broadband, storage, workforce development, and electric transportation with new loans at U.S. Treasury rates. These conditions would also prompt electric co-ops to forgive unpaid residential utility bills, continue service for the hardest-hit families, and deliver more affordable power to rural households. Rural electric cooperatives serve 42 million Americans, including many Black, Indigenous and People of Color, and low-income communities. Members of these cooperatives face far higher energy burdens than other utility customers, and many are facing shutoffs and growing debts because of the COVID-19 crisis.

Current Program/Agency: U.S. Environmental Protection Agency

Recommendation: Coal Combustion Residuals Rules are not being enforced. Impoundments are being capped in place, closures are being slow walked, and proper groundwater monitoring is not being followed, causing environmental disasters in disadvantaged communities. Funding should be allocated to monitor and remediate coal ash waste pollution and health monitoring for disadvantaged communities, and workers handling the coal ash must be protected.

Recommendation: Strengthen the Coal Combustion Residuals Rule to require enforceable coal ash cleanup measures such as removal of the pollutants in groundwater. Justice 40 funding could be used to monitor and remediate coal ash waste pollution in water bodies and land and provide medical monitoring for EJ communities and the funding to ensure closure of coal-fired power plants.

Current Program / Agency: Legislation Needed

Recommendation: Pass the Abandoned Mine Land Reauthorization Act (H.R. 1734) to reauthorize the Abandoned Mine Land (AML) fee under the Surface Mining Control and Reclamation Act (SMCRA) for 15 years. In 1977, Congress established the Abandoned Mine Land (AML) fund under the Surface Mining Control and Reclamation Act (SMCRA). This act established a per-ton coal fee to finance the reclamation of lands permitted to be mined prior to 1977. Cleaning up AML sites will not only make our communities safer and our water cleaner but will generate thousands of jobs. Without action from Congress, the fee that funds the AML program will expire in September 2021.

Recommendation: Ensure continued funding for black lung benefits. Many individuals can no longer participate in any kind of future workforce because they are disabled by black lung disease. The Black Lung Disability Trust Fund (BLDTF) provides monthly stipends and medical benefits to disabled coal miners (and surviving dependents). Revenues for the BLDTF come from a small tax on coal sales, but without congressional action, the tax will be cut in half at the end of 2021. It is critical that Congress extend the excise tax for 10 years (see Rep. Scott's Black Lung Benefits Disability Trust Fund Solvency Act/H.R. 3876.) and also develop a long-term funding solution as coal sales decline. In addition, Congress should change the fee from an excise tax to a severance tax in order to close the current loophole that allows exported coal (including much metallurgical coal) to go untaxed.

Recommendation: Increase black lung benefits to provide immediate economic stimulus to coal communities. Coal states receive millions of dollars annually from the BLDTF. Not only are these benefits critical for miners and their families, but they are also a direct input into local coal community economies. Currently, a disabled miner receives $693 a month. In an effort to provide immediate economic stimulus to coal communities, Congress should increase the monthly benefits that a miner receives. Additionally, the process by which miners and their survivors file claims for black lung benefits must be improved. Currently, the claims process demands that claimants meet unreasonable bureaucratic proof requirements and allows exhaustive opportunities for employers to challenge claims and appeal decisions. This process is discouraging and burdensome for people who are sick and worried about the financial stability of their families. In consultation with experts in the Department of Labor and attorneys that litigate federal black lung claims, Congress should enact legislation that makes the benefits process fairer to miners and their families.

Current Program / Agency: U. S. Department of Labor - Mine Safety and Health Administration

Recommendation: The Mine Safety and Health Administration should strengthen regulations and enforcement procedures to protect coal miners from excessive levels of respirable silica dust, a primary culprit behind the ongoing epidemic of black lung in Appalachia. Currently, the permissible exposure limit for respirable silica dust in coal mines is 100 micrograms per cubic meter. This limit should be reduced to 50 micrograms per cubic meter to be brought into parity with regulations applicable to all non-mining industries and per the recommendation of the National Institute for Occupational Safety and Health. Additionally, the silica standard is not separately enforceable but, instead, based on a complicated calculation of silica as a percentage of total respirable dust. This indirect enforcement method should be replaced by a separately enforceable standard whereby any exceedance of 50 micrograms of silica per cubic meter causes MSHA to issue a citation and compel corrective action on the part of the operator.

Current Program/Agency: U.S. Department of Defense - U.S. Navy

Recommendation: Decontamination of Vieques and Culebra. Invest Justice 40 funds to allocate $10 million to purchase closed detonation chambers in the efforts to rid Vieques of unexploded ordnance. Community groups are calling for "genuine community participation in the process of decontamination, so that the cleanup will be thorough and effective" and the budget to carry out a complete cleanup.

Current Program/Agency: U.S. Environmental Protection Agency

Recommendation: Require decontamination of legacy sites, and sustainable development projects at the old refinery and the petrochemical complex in Tallaboa, Penuelas and Guayanilla, Puerto Rico that promote integral community development. Polluting industries such as industrial landfill operators must be prosecuted and punished. Investments to address the serious deterioration of the health of residents, and the environment, especially fishing areas are imperative. Energy independence should be promoted and encouraged through rooftop photovoltaic systems with battery energy storage systems. The community urgently needs new schools and training programs to create community-based businesses and employment opportunities to avoid dependence on the government.

Recommendation: The Biden Administration should consult with the South-Central St. Croix community to determine how Justice 40 investments can best be made to address environmental injustice, including but not limited to groundwater, air quality, and coastal zone cleanup. The St. Croix Environmental Association requests that EPA exercise "strict enforcement of the law and to investigate violations" of the Limetree Bay Refinery since the refinery restarted operations in Dec. 2020 after being closed for nearly a decade. They also request transparency and reporting on incidents, including online, real time access to emissions data and notices of unscheduled releases to the community via text message. Sustained funding and trained personnel are needed for air and water quality monitoring using federally approved methods, including a community-based monitoring center in partnership with the Department of Natural Resources and the local university. Crucians need household surveys conducted to gather data on the odors, health impacts, and property damage caused by the refinery restart. EPA must take a "hard look at the Reactivation Policy that EPA abandoned under the Trump Administration to grandfather Limetree Bay as an operating facility." Crucians indicate that the Limetree Bay Refinery should be recognized as a new facility and undergo new source review, adopt the best available control technology and that EPA's ECHO database and EJSCREEN tools be updated with demographic and environmental information for St. Croix and the USVI in general. St. Croix needs capacity for community-led discussions of a just transition to wean the economy off the fossil fuel industry, including stakeholder meetings, education programs, workshops, and job retraining.

Investment Topic: Superfund Site Program

Recommendation: Prioritize cities and states with significantly high counts of superfund sites and designate local EPA staff in satellite offices/locations to support with liaising and local oversight and accountability with cleanups

Current Program/Agency: U.S. Department of Defense U.S. Army Corp of Engineers

Recommendation: Require the U.S. Army Corp of Engineers to proceed with plans to dredge the Caño Martin Peña (CMP/channel). Specifically, the Biden Administration should select the Caño Martin Peña Ecosystem Restoration Project (ERP) as a construction New Start for the FY22 US Army Corps of Engineers Work Plan or include the resources in the Justice 40 investments, any upcoming Supplemental related to President Biden's Infrastructure Plan or through direct spending.

Current Program/Agency: U.S. Department of Agriculture

Investment Topic: Food and Nutrition Service

Recommendation: Expand the Food and Nutrition Services program to include increased funding for lead soluble fruits and vegetables prioritizing school districts with evidence of elevated lead levels in school drinking water, soil, air, buildings (lead-based paint), and proximity to superfund sites, landfills, incinerators and/or brownfields. Free and Reduced Lunch Status of 75%> and schools designated as Title I schools are also eligible. (Source: Black Millennials 4 Flint)

Recommendation: Funding for a Green jobs center in Black, Latinx, Tribal and other people of color environmental justice communities. Government grants and subsidization for local food cooperatives and community gardens.

Recommendation: Expanding grants & training program for Black organic & regenerative farmers. Source: Generation Green

Current Program/Agency: U.S. Department of Health and Human Services

Investment Topic: The Centers for Medicare & Medicaid Services (CMS)

Recommendation: Expand Medicare/Medicaid for lifetime access for individuals from frontline communities directly impacted by environmental racism and injustice (e.g. the Flint Water Crisis)

Recommendation: Extend Medicaid coverage for a year for ALL mothers and child birthing people with inclusion of body burden & risk factors associated with climate issues: extreme heat, air pollution, lead-poisoned water, and other environmentally induced health conditions

Current Program/Agency: U.S. Department of Health and Human Services - National Institutes of Health

Investment Topic: Eunice Kennedy Shriver National Institute of Child Health & Human Development

Recommendation: Increase appropriations in the Great American Outdoors Act to prioritize frontline and BIPOC communities as well as local schools receiving Title I funding and majority BIPOC serving schools with improvements and developments of community/local parks and investment in urban tree nurseries to mitigate environmental hazards such as increased CO_2 emissions and other toxic air pollutants. Source: Black Millennials 4 Flint and American Forests

Recommendation: The Federal Health Equity For All Act will institute infrastructure and mechanisms to fund communities in creating conditions for well-being and aims to reinvent our health infrastructure to promote inclusive, community-driven, and localized interventions, with well-being and equity as core metrics. There are three approaches in the act: (1) a network of health equity innovation hubs led by community-based organizations and (2) supporting social entrepreneurs through flexible and non-programmatic funding streams to change the system from the ground up (3) funding for local government entities to implement community approved racial equity plans. Source: Act on Health Equity

Recommendation: Implement and utilize environmental health assessment data combined with maternal health and birth outcomes in the agency's cost-benefit analyses.

Recommendation: Allocate research funding to HBCUs, HSIs, TCUs and ASPISIs to research impacts of environmental racism associated with miscarriages & other characteristics of at-risk pregnancies.

Recommendation: Allocate research funding to HBCUs, HSIs, TCUs and ASPISIs to research impacts of climate on lead exposure in BIPOC communities.

Recommendation: Develop (expand funding) grant programs for child-care based centers (including family centers/home-based daycares), traditional daycares, head start and pre-k for lead remediation and environmental safety education (Example Programming: Children's Environmental Health Network's Eco-Healthy Child Care Program).

DEVELOPMENT OF CRITICAL CLEAN WATER INFRASTRUCTURE

Current Program/Agency: U.S. Department of Housing and Urban Development & U.S. Department of Energy

Investment Topic: Lead Water Pipe Infrastructure Replacement

Recommendation: Create a federal low-income water and sewer bill assistance program. This program will assist low-income customers with paying their water and sewer bills. This will be structured as grants to state and Tribal entities to provide direct assistance to low-income water and sewer customers, similar in concept to the established Low-Income Home Energy Assistance Program (LIHEAP). This would bring parity to water, as the federal government already recognizes heat and home energy as essential to well-being.

Recommendation: Support the retrofit of lead water pipe infrastructure.

Recommendation: Ensure that environmental justice communities are tested for lead water pipe infrastructure and replace those pipes where necessary to protect the most vulnerable (children and pregnant women) from lead exposure.

Investment Topic: Development of Critical Clean Water Infrastructure

Recommendation: Ensure Every Home Has a Wastewater System and Indoor Plumbing.

Recommendation: Many homes throughout the south, Appalachia and rural areas are forced to use septic tanks even though they pay municipal taxes for water and sewer. Many do not have indoor plumbing as well. A wastewater treatment system receives, stores, treats, and disposes wastewater not only from a septic tank, but accompanying pipes, drains, percolation areas, and fitting, which ensure that the water is treated and discharged correctly. Wastewater systems are a way to reduce waste from our environment, save money, and ensure removing chemically treated water in a safe, environmentally friendly way. Furthermore, toxins are removed during the treatment process which produces clean and safe water. About 3% of the earth's water is drinkable and through this renewable resource it helps provide crystal clear, and safe reusable water. The main challenges we may encounter with wastewater systems are the cost and energy consumption. It is estimated that the United States must invest $271 billion towards wastewater systems and their upgrades.

Recommendation: Develop mapping tools and GIS of where these homes are so they can be identified and retrofitted.

Current Program/Agency: Legislation Needed

Recommendation: Permanently institutionalize water and wastewater affordability programs. In addition to investment in water and wastewater infrastructure, it is also essential to ensure that households can afford to access these services. Prior to the COVID-19 pandemic, there were no customer assistance programs to help low-income or families in economic crises pay water bills. Section 533 of the Consolidated Appropriations Act, 2021, authorized a new program to provide $638 million in federal water and wastewater bill assistance to low-income customers. An additional $500 million was included in the American Rescue Plan. We encourage Congress and the administration to create a permanent assistance program by adding the following: $22.5 billion (for a total of $45 billion) for replacing all lead service lines and a $100 billion infusion into the Clean Water and Drinking Water State Revolving Funds with at least a 20 percent set-aside as grants for disadvantaged communities and at least a 20 percent set aside for green infrastructure. Direct an additional $10.5 billion for the Small & Disadvantaged Communities program, Alaska Native Villages and Rural Communities Water Grant program, US-Mexico Border Water Infrastructure program, Sewer Overflow Grant program, and the Water and Waste Disposal Loan and Grant program. Also, permanently extend the Buy America provision for the Drinking Water State Revolving Fund (see Sec. 22110 and Sec. 33104 of H.R. 2). In addition to investment in water and wastewater infrastructure, it is also essential to ensure that households can afford to access these services. Congress should continue to invest in the newly created low-income household water assistance program (LIHWAP) at HHS.

Current Program/Agency: U.S. Environmental Protection Agency

Investment Topic: Lead and Copper Rule

Recommendation: Continues to treat full lead service line (LSL) replacement as a last resort. LSL replacement should be an integral part of a long-term solution, including periodic benchmarks for all water systems to achieve regardless of water testing results.

Recommendation: Continues to allow water systems to conduct partial replacements where the property owner is unwilling or unable to pay the cost for the portion not owned by the water system. Partial replacement significantly increases short-term lead in water levels and fails to provide the long-term lead exposure reductions provided by full replacement.

Recommendation: Backslides on the rate of mandatory LSL replacement. When a water system's lead levels are so high that full LSL replacement is mandated, EPA proposes an annual replacement rate of 3% instead of the current 7%, effectively giving a system with high levels of lead in water 33 years rather than the current 15 years to replace all of its LSLs. While more systems are likely to have to conduct mandatory full LSL replacement because of the stricter sampling requirements, most will not. **Source:** Environmental Defense Fund

Recommendation: Incentivize States with mandatory lead testing policies/laws in public schools and childcare facilities through non-competitive grant funding.

Recommendation: Incentivize cities and municipalities that prioritize BIPOC contractors for lead service line replacement.

Recommendation: Develop a robust and (public) transparent national database and GIS map(s) to centralize and locate lead testing data for schools, cities/municipalities, and states.

Recommendation: Develop a grant program for cities and municipalities and states to create robust and (public) transparent databases and GIS maps to centralize and locate lead testing data for schools, residential, agricultural, and commercial areas.

Recommendation: Establish medical monitoring, preventive medicine, healthy nutrition and care-giving programs for vulnerable populations, especially seniors in EJ communities and training programs for care-givers from EJ communities.

CLIMATE MITIGATION & RESILIENCY

Current Program/Agency: U.S. Department of Defense, U.S. Army Corp of Engineers & U.S. Geological Survey

Recommendation: Pending flood control projects such as the Nigua River in Salinas, Puerto Rico and the Rio Piedras-Puerto Nuevo River in San Juan, Puerto Rico and coastal protection projects should incorporate ecosystem bio-remediation measures and robust community consultation prior to investment of funds and not allow for projects that impede sustainable flood control work or adversely impact public water supply.

Recommendation: Invest Justice 40 funds to designate the South Coast Aquifer in Puerto Rico as a sole source public water resource and decontaminate the aquifer.

Current Program/Agency: U.S. Department of Labor, U.S. Department of Agriculture - Rural Development Housing and Community Facilities Programs Office

Recommendation: Modernize temporary labor camp standards and farm labor camp standards to mitigate the risks that climate change, extreme weather events and pandemics pose on migrant and seasonal farmworkers and their families.

Recommendation: Invest in USDA Section 521, 515, and Section 514 and 516 Farm Labor Housing to invest in building resiliency to extreme weather events, energy efficiency, climate control, and facilities such as water and waste disposal systems.

Recommendation: Ensure investments in Farm Labor Housing prioritize housing for U.S.-based workers and their families, without regard to legal status, and do not promote the displacement of the domestic agricultural workforce.

Current Agency: U.S. Environmental Protection Agency, U.S. Department of Energy, Department of Housing and Urban Development

Recommendation: Support funding for frontline and EJ communities to organize, convene and develop climate action plans that address climate resilience, communication and prioritize potential climate impacts. Each community has differing levels of potential impacts and issues associated with blackouts, flooding, extreme heat, evacuation, right of return to homes by climate refugees and ensuring that climate gentrification potential is addressed through education of relevant government officials.

INTERSECTIONAL RECOMMENDATIONS: COMMUNITY AND UNIVERSITY PARTNERSHIPS

Current Program/Agency: White House Initiative on HBCUs, HSIs, TCUs and ASPISIs

Investment Topic: Reduction of Legacy Pollution & Workforce Development

Recommendation: Develop guidance and directives for Historically Black Colleges and Universities (HBCUs), Hispanic Serving Institutions (HSIs), Tribal Colleges and Universities (TCUs) and Asian American and Pacific Islander Serving Institutions (AAPISIs) to support communities addressing legacy pollution problems and challenges.

Recommendation: New funding for Environmental and Climate Justice Centers and Centers of Excellence at HBCUs, HSIs, TCUs and ASPISIs to support education, training, mentoring, research, policy and civic engagement work in underserved, economically disadvantaged, and environmentally vulnerable communities threatened by the climate crisis. https://www.doi.gov/pmb/eeo/doi-minority-serving-institutions-program.

Current Program/Agency: U.S. Health and Human Services Administration, Health Resources and Services Administration (HRSA)

Investment Topic: Climate Change & Health

Challenge: There is a need to address the vulnerability and health care needs of uninsured, isolated, or medically vulnerable individuals and communities to the threats posed by climate change.

Recommendation: Invest in Community & Migrant Health Centers which serve migrant and seasonal farmworkers across the U.S.

Recommendation: Invest in Community Health Centers that partner with Community Based Organizations (CBOs), labor unions and worker organizations with experience serving migrant and seasonal farmworkers, BIPOC and low-income communities in rural and agricultural communities.

Recommendation: Prioritize grants to academic institutions that establish partnerships and fund-sharing agreements with CBOs and other organizations with experience serving migrant and seasonal farmworkers, BIPOC and low-income communities in rural and agricultural communities.

Current Program/Agency: The White House, Cabinet Secretaries, and the Broader Executive Branch

Investment Topic: Climate Change, Workforce Development & Protection of BIPOC and undocumented workers and communities

Challenge: Lack of immigration status fundamentally limits the ability of immigrants to enforce their rights and have access to programs and services that would promote their food, housing, economic security, and improved environmental quality. In a changing climate, undocumented immigrants are vulnerable to disasters and are represented in industries and work settings where they cannot get refuge from the elements.

Recommendation: The Administration should leverage its discretion and resources to ensure that undocumented individuals and families are not left out or ineligible to benefit from EJ40 investments.

Recommendation: Where limitations in servicing undocumented individuals require statutory changes, the Administration, at the highest levels, should work aggressively with Congress to secure a path to legalization for undocumented immigrants as well as other improvements to prevent the exclusion of the undocumented from Justice40 investments, given that they are predominantly BIPOC.

Current Program/Agency: U.S. Department of Health and Human Services, National Institute of Environmental Health Sciences; U.S. Environmental Protection Agency

Recommendation: Improve health equity by mandating that NIH support community-academic partnerships in all relevant research centers and in grant programs

Recommendation: NIEHS should reinstate its Environmental Justice through Communications grant program that supported the development of Community Principal Investigators (PIs) and partnerships between academic research centers and community organizations that carried our Community-Based Participatory Research, community education on environmental health, and translation of research to policy and action. These partnerships have been evaluated to increase the quality and dissemination of research, provide communities with relevant data, support citizen science, and create trust.

Recommendation: In addition, the EPA used to have Community-University Partnership (CUP) grants which provided funds for EJ and CBOs to partner with academic institutions to develop data and studies of interest to both partners.

Current Program/Agency: All Federal Agencies

Recommendation: Carry out the nation-to-nation consultative duties of the U.S. to federally-recognized Tribes in the identification, planning, and implementation of infrastructure investments and projects, consistent with the January 21, 2021, *Memorandum on Tribal Consultation and Strengthening Nation-to-Nation Relationships and Best Practices on Consultation.*

Recommendation: Review the letter from over 580 federally recognized Trible governments on infrastructure legislation from April 13, 2021. Though about legislation, it covers important information and positions from Tribal leaders relevant to Justice 40: The Indian Country

Infrastructure Letter covers comprehensive infrastructure programs in the federal government needing reform, including programs in infrastructure tied to healthcare, water, telecommunications and broadband, energy, housing, transportation, law enforcement, public safety, and justice, lands and natural resources, climate, education, Indian child welfare, agriculture and rural development, tax parity and equity, economic and workforce development, and Tribal governance and funding stability. The letter offers recommendations:

- funds must be provided directly to Tribal recipients and not as pass-through funding to states or another entity;
- indirect costs must be an eligible use of funds and Tribal recipients must be given the maximum flexibility possible in their use of federal funds;
- funds must not be limited to shovel-ready projects;
- all funds for Tribal recipients should be available until expended;
- funds must not be subject to competitive grants and match requirements;
- explicitly require the Indian canons of construction be applied to provisions of this bill.

Recommendation: Review other significant inter-Tribal and government reports related to Tribal infrastructure that identified key programs, priorities, and needs. They include The Report on the Unmet Infrastructure Needs of Tribal Communities and Alaska Native Villages in Process of Relocating to Higher Ground as a Result of Climate Change; The U.S. Government Accountability Office Report Climate Change: A Climate Migration Pilot Program Could Enhance the Nation's Resilience and Reduce Federal Fiscal Exposure and the Affiliated Tribes of Northwest Indians Policy Briefing: Tribal Perspectives on Proposed Policies in the Congressional Action Plan on the Climate Crisis, which has several sections on infrastructure.

Recommendation: Federally-recognized Tribes have inherent sovereignty, and exercise sovereignty in the U.S. context with states and the federal government. The federal government has an obligation to have a government-to-government or nation-to-nation relationship with Tribes. The federal government also has a trust responsibility to Tribes, obligations tied to treaties (treaty rights) and statutes, and obligations to ensure equity and environmental justice. Tribal consultation, including how it is referenced in the January 21, 2021 Memorandum on Tribal Consultation and Strengthening Nation-to-Nation Relationships, is a cornerstone of a genuine nation-to-nation relationship. Consultation has an important connection to free, prior, and informed consent. Infrastructure investments and projects, including their identification, planning, and implementation, must occur through Tribal consultative processes when such investments and projects relate to federally-recognized Tribes. Infrastructure investments and projects may relate to federally-recognized Tribes when they involve activities and technologies that Tribal governments have the potential lead, administer, operate, and own the assets too. They also relate to Tribes when the investments or projects may occur outside of Tribal government jurisdictions, but where the expected impacts – including benefits and risks – will have economic, social, environmental, cultural, and political (jurisdictional) ramifications and implications for Tribes. Permitting processes are key areas where Tribes must be involved as decision-makers, planners, and leaders. Regarding projects affecting public lands and other relevant lands, Tribal co-management must be an available option.

Recommendation: Tribes must have comparable and fair opportunities to benefit from infrastructure investments and projects that are delegated to states. There must be parity in federal investments to Tribes and states. There should be consideration of a Tribal set aside, as is used in other federal programs.

Recommendation: Under the Biden/Harris administration, consultative activities have already taken place through the Department of Interior and other agencies. These consultative activities have or are likely to yield critical information about how the federal government is planning to invest in infrastructure relating to Tribes.

Recommendation: There is a growing literature on best practices for Tribal consultation that aims to improve the quality of nation-to-nation relationships, literature produced by both university researchers and major non-governmental organizations, such as the National Congress of American Indians, and inter-Tribal organizations, such as Midwest Tribal Energy Resources Association. A major best practice that reflects a nation-to-nation relationship is that Tribes should be part of the earliest discussions about infrastructure development and design, which means as early as any other governing entity, such as states, are involved in such discussions.

Recommendation: There are currently underfunded programs for federally-recognized Tribes tied to energy infrastructure, and Tribal consultation is crucial as connected to recommendations for how to build on and improve these programs, and whether there are lessons learned that can be carried over to other agencies and to new or forthcoming investments and projects. Major examples are the Department of Energy's Office of Indian Energy Policy and Programs, Department of Interior Indian Affairs Department of Energy and Mineral Development, USDA's Rural Energy Programs (which Tribes qualify for), USDA's High Energy Cost Grants Program, the Tribal Energy Guarantee Program (Energy Policy Act), among others that may be in existence. Grid modernization is a major area of need given that 14.2% of households in Tribes lack basic electric services. Regarding other areas of infrastructure, here is a further listing of programs: Division of Sanitation Facilities Construction (Indian Health Service); Clean Water State Revolving Fund; Water and Waste Disposal Grant Program (EPA); Tribal Climate Resilience Program (Bureau of Indian Affairs); Safety of Dams Program (Bureau of Indian Affairs) (including, dam maintenance programs that Tribes can use); Irrigation Program (BIA); Indian Water Settlements Funding (Bureau of Reclamation); Indian Housing Block Grant Program; Roads Maintenance (BIA); Tribal Transit Program (Federal Transit Administration); healthcare infrastructure aspects of Indian Health Services and other agency programs tied to Tribal health; infrastructure needs tied to Bureau of Indian Education, Indian Community Development Block Grant Program, USDA Community Facilities Programs, Tribal law enforcement, emergency management, and broadband and wireless; Native Community Development Financial Institutions; Tribal Colleges and Universities.

Recommendation: In 2009, a group of U.S. senators wrote a letter claiming a $50 billion unmet need for infrastructure on reservations. The Tribal consultative process should gain updated information on the size of the need in today's terms.

Recommendation: Permitting processes and infrastructure planning must be strategically organized so that the implementation of infrastructure investments and projects can proceed successfully in Tribal nations. Given the unmet infrastructure needs, certain infrastructure projects should be implemented in a certain order or together. Tribal consultation should pave the way for a coordinated, strategic implementation of infrastructure investments given the challenges to infrastructure developed posed by the unmet infrastructure needs in Tribal nations. See for example, Principles to Advance Energy Justice for Native Americans.

Recommendation: Tribal Historic Preservation Offices must have sufficient funding and support for increases in on and off-reservation infrastructure projects that must be reviewed.

Recommendation: Cultural impacts of infrastructure are critical to consider, whether for projects operated by Tribes or for projects that will affect Tribes. Tribal ecological knowledge has an important role in the design of projects and the assessment of risks.

Recommendation: Tribes should have access to resources for feasibility studies, and such funding for feasibility studies must be flexible for Tribes.

Recommendation: Funding for infrastructure projects, such as grants, should be multi-year, providing support for Tribes to build long term capacity, stability, consistency, and a strong foundation.

Current Program/Agency: All Federal Agencies

Recommendation: Federal agencies must consider the self-determination of non-federally-recognized Indigenous peoples and grassroots organizations, community organizations, and entrepreneurship in infrastructure development

Recommendation: Indigenous peoples who are not recognized as sovereigns by the U.S. federal government have the right to self-determination as collective societies with their own cultures, heritage, and economic and political organizational systems, which can include the ownership and administration of infrastructure. State- and un-recognized Tribes, working without affirmation of their self-government, have strategically used incorporation as 501c3 nonprofits as a way to build capacities to provide services for their members. They have used private conservation tools as well to protect their lands. Native Hawaiians have organized through institutions such as the Office of Hawaiian Affairs (OHA), a self-governing corporate body established in the 1978 state constitution of Hawaii. Federal infrastructure investments must ensure that programs and policies work with and advance the self-determination of non-federally-recognized Indigenous peoples.

Recommendation: Infrastructure investments must include opportunities for Indigenous peoples' community organizations, grassroots organizations, and entrepreneurs to receive relevant infrastructure funds for the development of their own capacities for infrastructure projects, such as community solar, and many others. Investments and benefits in infrastructure funding and programs should not fund federally-recognized Tribal governments in ways exclude Tribal members and other Indigenous persons rights to apply for and develop relevant infrastructure programs and policies at the community and grassroots levels and as entrepreneurs.

Justice40 Initiative Question 2: Recommendations for Defining "Investment Benefits"

Recommendations for the Definition of Investment Benefits

Recommendation: Direct Investments in Geography: Investments in defined frontline geographies (by census tract or other designations based on EJ criteria such as Minneapolis Green Zones).

Recommendation: Direct Investments in People: Investments that benefits to Black, Indigenous, Latinx, Asian, Pacific Islander, GLBTQ, People of Color, and Immigrants to improve health and economic opportunities.

Recommendation: Indirect and direct Investment in Community: Investment which support local communities, community-based organizations, community ownership, cooperatives, small-business, community job training and local ownership tracks, etc.

Recommendation: External Direct Investment benefits: Investments that are outside EJ communities but provide essential services to EJ such as water, energy, and sanitation.

Recommendation: All Investments: Must do no harm to EJ Communities.

Guiding Principles: Program Criteria to Maximize Federal Investment Benefits and Avoid Harm in EJ Communities

Recommendation: 100% of investments must do no harm to Environmental Justice communities. We want 100% Justice; it would be unreasonable to have any climate investment working against historically harmed communities. To that end we acknowledge the Justice40 to be the floor not the ceiling, 40% should not be seen as a cap but as a starting point.

Recommendation: Just recovery to support community-driven recovery and mid- to long-term rebuilding and implementation projects with improvements that further equitable mechanisms for adaptation, recovery, and rebuilding.

Recommendation: For investments to be considered truly beneficial, process and implementation are key. All investments should incorporate a community driven, community-controlled approach so that communities most directly impacted benefit as intended. Investments that do not have community accountability should not be considered part of the Justice40. Community accountability in development and implementation is an important "justice" making element that must be included.

Examples of The Types of Projects That May Benefit A Community

1. Clean energy projects, including renewable energy and energy efficiency projects

2. Regenerative agriculture and green infrastructure projects

3. Clean energy jobs training

4. Lead water pipe replacement

5. Clean drinking water and environmentally sound sanitation

6. Programs that both reduce greenhouse gases and promote economic, social and environmental benefits

7. Public Transportation: operational and capital improvements

8. Community microgrids

9. Community and Green Housing

10. Housing/community preservation and or planned retreat for communities that choose to move due to unsafe conditions

11. Example of the 2501 USDA Block grant for outreach and technical assistance and training to “socially disadvantaged farmers” can be a model for block grant available with mandatory (not discretionary) budgets for groups that do outreach to EJ groups
    a. Outreach and Assistance for Socially Disadvantaged and Veteran Farmers and Ranchers (Section 2501)

12. Community climate resilience plans
13. Transit hubs that promote sustainability and small business development in EJ communities

14. Future Energy Jobs Act from Illinois (worked on by LVEJO) helped to secure worker benefits and investments that prioritized EJ communities and further those most impacted or marginalized within EJ communities
    a. LVEJO participated as a lead architect of critical policies serving low-income communities in the legislation, including the new Illinois Solar for All — a nation-leading low-income solar program with targeted goals for environmental justice communities. The program is paired with a jobs training pipeline that will target recruitment in these same communities, with additional incentives to hire 2,000 individuals with criminal records and alumni of the foster care system.
    b. http://www.lvejo.org/lvejo-statement-on-passage-of-future-energy-jobs-bill/

Examples of The Types of Projects That Will Not Benefit A Community

1. Fossil fuel procurement, development, infrastructure repair that would in any way extend lifespan or production capacity, transmission system investments to facilitate fossil-fired generation or any related subsidy.

2. Carbon capture and storage (CCS) or carbon capture, utilization, and storage (CCUS)

3. Direct air capture

4. The procurement of nuclear power

5. Research and development

6. The establishment or advancement of carbon markets, including cap and trade

7. Geoengineering and techno fixes

8. Highway expansion

9. Road improvements or automobile infra-structure, other than electric vehicle charging stations

10. Industrial scale bioenergy

11. Incentives for investor-owned utilities

12. Projects that promote gentrification without any housing policy crafted by a community to prevent displacement

13. Incineration, waste-to-energy or biomass incineration, and landfilling (Anishinabek Nation and Iroquois Caucus Transport and Abandonment of Radioactive Waste)

14. Pipeline creation, expansion, or maintenance

15. Memo to the Biden administration: What not to do on climate

16. The Conversation: Climate Scientists: Concept of Net Zero Is A Dangerous Trap

17. NAACP Environmental and Climate Justice Program: Fossil Fueled Foolery

Legislative Language for Further Consideration

Recommendation: Legislative language from Green New Deal for Cities Bill Congresswoman and Congresswoman Alexandria Ocasio-Cortez

- One Pager
- Full Text

Recommendation: Examples from California Greenhouse Gas Reduction Fund

- Reduce greenhouse gas emissions
- Maximize economic, environmental, and public health co-benefits
- Benefits should outweigh costs and burdens
- Secondary criteria from CA (page 18-21)

Recommendation: Community Engagement Towards Participatory Community Decision Making

- There should be specific funds dedicated to community engagement processes to help determine that benefits make community specific sense and are part of the local vision.

- Should provide a direct line of responsibility and accountability to these community-based organizations. Funding of up to 10% should be considered to support inclusive engagement and community decision making. Community representatives and organizations are paid for their work to represent and engage the broader community.

Recommendation: Notification About Possible Investments/Benefits

- Communities should be made aware of the possible grants and funding opportunities that are available to them. Notification must be in local languages and as widely accessible as possible.
- No project should be undertaken without community consent.
- Should include metrics, incentives and audits for agencies to adopt based on how much of their budget they have dedicated both directly and indirectly to frontline groups in a way that is transparent and reported publicly.
- Communities should be granted the "right to sue" for disparate impacts, without needing to prove intent but rather outcome or impact

Recommendation: Formulas like Community Development Block Grants need to be revised or updated. Currently some communities are severely underserved due to archaic formulas that have not been updated. Formulas to determine need should be developed in consultation with EJ communities.

Overall Goals and/or Requirements for Investment Benefits

1. Develop long term local wealth and ownership
2. Local ownership and democratic decision making for infrastructure
3. Addressing institutional racism
4. Maximize economic, environmental, and public health benefits to community
5. Labor standards must meet the living wage income, rights to organize, local hire provisions
6. Workforce development and training for underserved workers
7. Air quality improvement requirements for clean energy infrastructure
8. Tie funding to local community organizations for accountability
9. Should not be discretionary funding for state or municipal budgets
10. Reparations to address past harm and disproportionate burdens
11. Clean, affordable, and accessible public transit
12. Addressing food deserts with investments in locally owned, organic agriculture

13. Training people on long term climate adaptation and resilience jobs
14. Create long term investments and demand for climate resilience infrastructure
15. Siting of infrastructure doesn't have a negative impact on local communities
16. Requirements to assess externalities of proposed infrastructure or programs
17. Net metering requirements of utilities
18. Energy democracy and equal access to the grid: decentralization of grid ownership
19. Should include metrics, incentives, and audits for agencies to adopt based on how much of their budget they have dedicated to these groups that is transparent and reported publicly
20. Maintain public housing that is safe, healthy and community integrated
21. Address clean drinking water and repair systems to maintain clean drinking water into the future
22. Improve water quality
23. Reduce/remove exposure to environmental hazards; remediate existing pollution and hazards
24. Provide long-term health benefits/health care to people who have experienced past harm and disproportionate burden
25. Establish a fund to accelerate the decommission of coal, oil and fossil gas plants and infrastructure by 2040
26. Pass policies to accelerate utility adoption of clean renewable energy and ending use of fossil fuels by 2030
27. Ban the use of single use plastics within 5 years and all non-essential plastics by 2030
28. To maximize investment benefits delivered to EJ communities, federal agencies must provide clear EJ criteria and guidance for grant applicants and centralized oversight. Federal agencies should establish outreach offices to promote awareness of federal program funding opportunities among EJ organizations and communities. The administration should also apply an equity and justice lens governmentwide to update federal program goals and grant-making, and it should build a clear monitoring, reporting, and evaluation process for federal programs and benefits delivered to EJ communities. Federal agencies must also make EJ and stakeholder engagement a requirement to receive program grants and other financial support. Both existing and new programs, regardless of the administering agency, should have criteria to address pollution, climate change, and displacement of people and communities to help ensure that benefits are delivered to EJ communities. All Agencies including those; as IAC and others (e.g. Army Corp, FEMA), should score projects based on their ability to meet these and other EJ criteria. The CEQ should also create a Justice40 task force to recommend these project criteria to support the delivery of benefits to EJ communities.[1]

[1] Equitable & Just National Climate Forum, Center for American Progress, Tishman and Design Center

29. Establish outreach offices to promote awareness of federal program funding opportunities among EJ organizations and communities. Federal agencies should employ staff to provide application support and to answer questions about funding requirements. For instance, each agency could hire adequate community liaison staff to help support and monitor applications, or it could pair capacity-building grants for smaller, locally led organizations with resources such as program staff able to assist EJ organizations to apply for the benefits. Agency outreach programs or offices should have an outreach plan that provides adequate notice and requires feedback from EJ communities and BIPOC-led organizations through public meetings, town halls, webinars, or engagement with regional offices, in various languages. These meetings should be held regularly to inform priorities and planning. Agencies must also allocate resources to translate applications to make them accessible to non-English speakers.[2]
30. The whole of government approach requires that all agencies develop mechanisms to incorporate environmental justice into their programs. Agencies should notify EJ communities and organizations of applications for permits submitted to the agencies for projects or actions in, close to or with potential impacts to EJ communities. Agencies can fulfill the notice requirements by compiling a list of EJ communities and organizations to be notified of pending projects and actions.
31. Portland Clean Energy Fund guiding principles[3]:
    a. Justice driven. Advance systems change that addresses historic and current discrimination. Center all disadvantaged and marginalized groups – particularly Black and Indigenous people.
    b. Accountable. Implement transparent funding, oversight, and engagement processes that promote continuous learning, programmatic checks and balances, and improvement. Demonstrate achievement of equitable social, economic, and environmental benefit. Remain accountable to target beneficiaries, grantees, and all Portlanders.
    c. Community powered. Trust community knowledge, experience, innovation, and leadership. Honor and build on existing work and partnerships, while supporting capacity building for emerging community groups and diverse coalitions. Engage with and invest in community-driven approaches that foster community power to create meaningful change.
    d. Focused on climate action with multiple benefits. Invest in people, livelihoods, places, and processes that build climate resilience and community wealth, foster healthy communities, and support regenerative systems. Avoid and mitigate displacement, especially resulting from gentrification pressures.

[2] ibid

[3] Guiding principles from the Portland Clean Energy Fund

32. **Be Actively Anti-Racist** - We pursue policies and strategic investments to reverse racial inequities and strive to repair the environmental injustice of more than 500 years of institutional policies and practices.

33. **Expand Environmental Justice and Climate Energy Literacy and Education** - Building a future that requires a just transition, and collaboration with the residents and businesses. Energy and Climate Literacy are integral parts of the just transition and building equitable outcomes from the transition to a clean green future.

Justice40 Initiative Question 3: Recommendations for Defining "Disadvantaged Communities"

Recommendation: Underserved communities include:

1. Majority minority communities
2. High rate of health disparities
3. Non-attainment of clean air and water standards
4. Formerly redlined
5. Food insecurity and child nutrition levels
6. Children receiving school lunch program
7. Income and % of households on supplementary income benefits
8. Numbers of superfund, waste, landfills and toxic facilities
9. Low education attainment and low high school graduation rates
10. High maternal and infant mortality rates
11. High asthma rates and deaths
12. Poorly maintained stock of housing
13. Lack of grocery stores, proliferation of (cent stores and fast-food outlets)

CLIMATE AND ECONOMIC JUSTICE SCREENING TOOL RECOMMENDATIONS

Climate and Economic Justice Screening Statement of Principles

1. Climate and Economic Justice Screening Tool must be integrated and / or supplemented with local community knowledge and data;

2. Climate and Economic Justice Screening Tool must be continually updated and improved as new and updated data become available. The tool should also accommodate integration of new relevant metrics as new data layers become available

3. Climate and Economic Justice Screening Tool needs to acknowledge data gaps and uncertainties-- no data or poor data availability should not lead to the assumption that there is not a problem;

4. Climate and Economic Justice Screening Tool should be leveraged to track progress on EJ goals, including Justice 40 Investments and their impacts;

5. CEQ and USDS should engage private tech companies to learn about leverage their existing data sources and tools that can be leveraged for the CEJ Tool to facilitate its rapid development and deployment;

6. CEQ and USDS should facilitate a timely process of data sharing and collaboration across all relevant federal agencies to enable integration of existing data and ensure efficient development and deployment of the Climate and Economic Justice Screening Tool.

Climate and Economic Justice Screening Tool Question 1: Recommendations for Identifying the Goal and Purpose of the Climate and Economic Justice Screening Tool

1. Holding industries, institutions, agencies, governments and people accountable
    a. Industry
    b. Military
    c. Federal, state and local facilities
    d. State and local governments
2. Identifying areas of need for specific communities and directing resources/programming accordingly (for example: directing resources & benefits under Justice40)
3. Preventing further damage in disadvantaged or overburdened communities
4. Prioritizing resources
5. Informing policy changes
6. Evaluating the effects of regulatory and policy interventions (tracking progress toward EJ goals)
7. Helping communities advocate for themselves Data on the permitting process that will allow communities to meaningfully participate
8. Data on permits, what is being allowed, what kind of emissions
9. Data on emissions
10. Including federal facilities
11. What do we need?
12. Holding people accountable
13. We know we have 10 times more rates of cancer than the State of Alaska, the state is blaming cigarette smoke *(for more information: Alaska Community Action on Toxics)*
14. pollution and Emission Indicators
15. Better capture impacts to indigenous people
16. Water quality and sanitation data
17. Water access data
18. Structural & geological hazards (such as mine highways, collapsing structures, etc.)
19. Excessive/loud noise and induced earthquakes from explosives, mine collapses, or fracking
20. Health and Equity Indicators
    a. Large scale administrative data has not historically captured all impacted communities or misses critical environmental justice challenges in rural and indigenous communities.
        i. Therefore, administrative data and national screening tools need to be supplemented with local-level data and community knowledge to inform screening results and decision-making. We need health screening, our community's own knowledge of our health *(for more information: Alaska Community Action on Toxics)*

    ii. It is important to track access to amenities as part of screening (e.g. proximity and availability of fresh food, greenspace, health care facilities, etc.)

21. Process Indicators
    a. Assurance and community engagement on consent giving
    b. Tribal nations part of record of decision
    c. Community capacity to access financial, infrastructure and other resource programs that are supposed to advance environmental justice.

22. Economic Indicators
    a. Job, creation, employment trends, and infrastructure metrics are important elements of screening
        i. Alaska has so much renewable energy
        - wind, solar, this would be a way to bring jobs and training
        ii. Jobs that go to Alaska native people
        iii. Loss of jobs over time (to capture areas where jobless is occurring at a faster pace); or rate of job loss
        iv. Rate of industrial decline (e.g., in the mines and/or power plants shutting down) causing economic dislocation (often without abatement of pollution of or environmental factors)
        v. Workforce participation levels
        vi. Number of minority-owned businesses
        vii. Employment by demographic indicators (e.g., race, ethnicity, gender, age)

23. Performance metrics
    a. EPA enforcement as a performance evaluation
    b. Tracking of Justice 40 investments, including institutional recipients (e.g. local governments, versus community-based organizations)

24. Funding
    a. Adequate funding for remediation as well as new projects that support economic, climate and environmental justice

25. Accountability for Process
    a. Tracking of barriers in communities participating in the process and accessing resource through Justice 40
    b. Initiatives Telecommunications, broadband issues COVID as a barrier to communities meeting
        i. Ensuring community capacity to apply, secure, administer and oversee projects funded by Justice 40.

Climate and Economic Justice Screening Tool Question 2:

Recommendations for Identifying Indicators to be Included in the Climate and Economic Justice Screening Tool

1. **Exposure Burdens**
    a. Air quality *(data sources: CACES (https://www.caces.us/) and/or U.S. EPA modeled data on air toxics and criteria air pollutants, NATA)*
        i. $PM_{2.5}$, PM_{10}, ozone, NO_2, SO_2, Pb, hazardous air pollutants, diesel PM
    b. Pesticide Use *(data source: USGS)*
    c. Drinking water contamination (community water systems and groundwater, US EPA, Environmental Working Group)
    d. Noise levels (night and daytime) – *(Mennitt DJ, Fristrup KM. 2016. Influence factors and spatiotemporal patterns of environmental sound levels in the contiguous United States. Noise Control Eng J 64(3):342-353).*
    e. USEPA and State level drinking water surveillance for PFASs *(EPA's Unregulated Groundwater Monitoring Program)*
    f. Human environmental chemical body burden *(CDC NHANES biomonitoring data by state or county)*

<u>Other important indicators for which data are needed:</u>

g. Persistent Organic Pollutant contamination wildlife and the environment
h. Lead and lead paint
i. Acid mine drainage
j. Methane
k. Silica / silica dust
l. Asbestos
m. Indoor air pollution

2. **Proximity to Potential Hazards**
    a. Superfund sites *(US EPA Facility Registry Service (FRS)- https://www.epa.gov/frs)*
    b. *Brownfields (US EPA Brownfields Program)*
    c. Oil and gas production/development (wells and pipelines) *(ENVERUS – formerly Drilling Info)*
    d. Oil and gas refining/production downstream (like refineries) *(US EPA FRS, US Energy Information Administration (EIA))*
    e. Industrials facility *(US EPA TRI/RSEI)*
    f. Operating and retired power plants/peaker plants *(US EPA FRS or EIA)*
    g. CAFOs *(US EPA FRS)*
    h. Traffic Density *(US EPA- Department of Transportation or Bureau of Transportation Statistics)*
    i. Landfills, municipal solid waste sites *(US EPA FRS)*
    j. Incinerators *(US EPA FRS)*

k. TSDFs, treatment storage and disposal facilities, and hazardous waste sites *(US EPA FRS)*
l. Existing and former defense sites, military bases *(DOD)*
m. Coal Ash dump sites

<u>Other important indicators for which data are needed:</u>

n. Abandoned and currently operating mining sites
o. Presence of Dollar Stores
p. Lead water service lines
q. Displacement and relocation
r. Trains carrying (and storing) toxics and hazardous materials
s. Train derailments – those carrying hazardous materials
t. Number and amount of hazardous infrastructure and facilities declared critical by Homeland Security and therefore will provide no information to the community
u. Landslides

3. **Sensitive Populations**
   a. Rates of PTB/LBW births *(National Center for Health Statistics (NCHS) - CDC)*
   b. Maternal death rates *(NCHS - CDC)*
   c. Rates of cardiovascular disease *(NCHS - CDC)*
   d. Rates of asthma and chronic obstructive pulmonary disease *(COPD) (NCHS - CDC)*
   e. Rates of cancers *(CDC <u>https://www.cdc.gov/cancer/npcr/index.htm</u>)*
   f. Rates of diabetes *(NCHS -CDC)*
   g. Rates of obesity *(NCHS -CDC)*
   h. Rates of lung disease *(NCHS -CDC)* Rates of obesity and heart disease - *(NCHS - CDC)*
   i. Rates of opioid addiction - *(NCHS -CDC)*
   j. Respiratory risks due to cumulative impacts (hazard index) *(EPA EnviroAtlas)*
   k. COVID infection and mortality rates *(NCHS - CDC)* Coverage for health insurance *(US Census American Community Survey ACS)*
   l. Incarcerated residents (broadly defined, detention centers, prisons, jails, group homes) *(US Census ACS)*
   m. Disabled population *(US Census ACS)*
   n. Farmworkers (*USDA Census of Ag, among others)*
   o. Food insecurity/Food Deserts *(USDA)*
   p. Indigenous and Tribal Land
      i. *For land connected to federally-recognized Tribes*
         Is the land trust land?
         Is the land in a Tribal service area or statistical area?
         Is the land in a reservation area?

Is the land in an area with recognized treaty or other off-reservation rights?
Is the land in an area that is ancestrally significant, but where Tribal members do not have recognized rights to it?

ii. *For land connected to state recognized Tribes*
Is the land within the territory of a tribe?
Is the land ancestral land for the Tribe, but where Tribal members do not have recognized rights to it?
Is the land in a state designated boundary or statistical area for a tribe?

iii. *For land connected to Native Hawaiians*
Is the land within areas of significance for Native Hawaiians?
For land connected to unrecognized Tribes
Is the land within an area of significance for an Indigenous people who is not recognized as a Tribal Nation or Native Hawaiian by the U.S. or any state?

<u>Other important indicators for which national data are needed:</u>

q. Occupationally exposed groups (e.g. ag workers, construction & other workers that don't work in climate-controlled spaces)
r. Arctic Indigenous Peoples burdened by persistent organic pollutants (POPs) body burden
s. Marine mammals/wildlife burdened by POPs and upon which communities depend.
t. Access to mental health systems and care
u. Access to hospitals, health clinics and affordable health care
v. Access to health care: health care professionals shortage

4. **Demographic/SES factors**
   a. Crowding *(US Census ACS)*
   b. Racial/Ethnic Demographics *(US Census ACS)*
   c. Educational attainment *(US Census ACS)*
   d. Poverty *(US Census ACS*)
   e. Unemployment Rate *(US Census ACS)*
   f. Index of Concentration at the Extremes (ICE) - this indicator of concentration of wealth or deprivation can be calculated at the block group or census tract level) *(US Census ACS)*
   g. Home Ownership Rates *(US Census ACS)*
   h. Linguistic isolation *(US Census ACS)*
   i. (Voter turnout *(LS - proprietary but probably based on government data)*
   j. Housing burdened low income households *(US Census ACS)*

k. Housing affordability: percent of household income spent on housing *(US Census ACS)*
l. Housing access: evictions/foreclosures or foreclosure risk *(US Census ACS, HUD)*
m. Redlined neighborhoods (University of Richmond - https://dsl.richmond.edu/panorama/redlining/#loc=11/37.81/-122.395&city=oakland-ca)
n. Racial Segregation—multi-group dissimilarity index (county or MSA level) or isolation index at tract level *(US Census ACS)*
o. Gentrification Pressure (US Census, ACS—temporal changes in neighborhood racial/ethnic churning, changes in median income over time)
p. Racially restrictive covenants
q. Gerrymandering *(Fairmandering - https://www.fairmandering.org/index.html and http://www.cornellpolicyreview.com/rigging-elections-spatial-statistics-analysis-political-unintentional-gerrymandering/)*
r. Lack of childcare community development services
s. Age distribution (US Census ACS)
t. Gender distribution (US Census ACS)

Other important indicators for which local and/or data are needed:

u. Online, real time access to emissions data and notices of unscheduled releases to the community via text message.
v. Community-based monitoring center in partnership with the Department of Natural Resources and the local university.
w. Household surveys conducted to gather data on the odors, health impacts, and property damage caused by the refinery restart.
x. Update EPA's ECHO database and EJSCREEN tools with demographic and environmental information for St. Croix and the USVI in general.
y. The tool to include narrative explanations about the data in plain English and accessibility in languages that are prevalent in EJ communities

5. **Energy**
    a. Energy shut-offs (DOE)
    b. Percent of low- and middle-income households with access to energy efficiency programs (DOE)
    c. Weatherization investment for low- and middle-income households by census tracts (DOE)
    d. Percent of household income that goes to paying for energy (DOE) or affordability: energy burden per household per census tract (data source: LEAD)

Other important indicators for which national data are needed:

e. Community access to solar and other renewable energy sources for household energy needs (wind, geothermal, etc.)

f. Community access to benefits from local renewable energy projects (to create local green jobs)
g. Housing/community capacity to support renewable energy sources
h. LIHEAP enrollment vs LIHEAP eligibility by census tract
i. Local energy resiliency: mapping of microgrid locations and services
j. Local energy resiliency: data on battery storage capacity and locations
k. Home heating method (gas, electric, wood, propane)
l. Home cooking fuel (gas, electric, etc.)

6. **Economic Development/Investment (Treasury, HUD, data sources to be identified)**
    a. Federal investment and benefit indicators
    b. Number of small businesses
    c. Number of minority-owned businesses
    d. Number of community-based organizations
    e. Business lending rates
    f. Mortgage lending rates
    g. Average debt rate (credit card, student loans)
    h. Investment: funding opportunities for EJ communities; grant and loan programs

7. **Climate Vulnerability**
    a. Percent of elderly living alone *(US Census ACS)*
    b. Percent of car ownership *(US Census ACS)*
    c. Tree canopy *(National Land Cover Dataset)*
    d. Impervious surface (*National Land Cover Dataset*)
    e. Green space (*Normalized difference vegetation index*)
    f. Coastal sea level rise and flooding risk *(NOAA, Climate Central Surging Seas Interface and US EPA Climate Indicators site https://www.epa.gov/climate-indicators)* Projected temperature change into the future (e.g. 2050 or 2021 NOAA, and US EPA Climate Indicators site https://www.epa.gov/climate-indicators (e.g. In California, Cal-Adapt data has good information on project temperature changes that was used in the EJ Screening Method EJSM. Heat Islands check out NOAA, US EPA Climate Indicators site https://www.epa.gov/climate-indicators Portland State University, https://pdxscholar.library.pdx.edu/usp_fac/182/;
    g. Frequency of wildfires or wilderness urban interface (WUI) fires *(US EPA Climate Indicators site https://www.epa.gov/climate-indicators)*
    h. Ocean acidification *(NOAA)*

Other important indicators for which national data are needed:

i. Presence of storm shelters, cooling centers, etc. to deal with extreme weather events
j. Regionally specific climate vulnerabilities

k. Flood impacts: number of claims and policies under the National Flood Insurance Program and disaster mitigation data at the scale of buildings and individual policies
l. Air pollution events connected to disasters of both a natural nature and otherwise
m. Displacement and relocation in low-lying areas
n. Homelessness
o. Deforestation (because worsens flooding)
p. Wildfire data (data on risk of increased fires)
q. Data regarding access to clean water, age of water infrastructure

8. **Infrastructure**
   a. Internet and Broadband access /Digital Divide *(Policy Map, Simply Analytics)*
   b. Affordable housing *(HUD and National Housing Trust)*
   c. Housing on tribal land *(Office of Native American Programs)*
   d. Housing quality and type (e.g. mobile homes, etc.) *(HUD and National Housing Trust)*
   e. Migrant labor housing *(USDA)*
   f. Rural Rental Housing *(USDA Rural Development)*
   g. Section 515 housing for low, very low and moderate-income households.
   h. Section 514/516 Farm Labor Housing for migrant and seasonal farm workers
   i. Section 521 housing
   j. Erosion risk for communities (costal and non-coastal) and other vulnerable sites *(USGS)*
   k. Access to banking services *(Treasury)*
   l. Transportation access: availability of transportation, transportation to desired destination, frequency of service interruptions
   m. Transportation access: walkability, traffic density, vehicle ownership
   n. Transportation affordability: transportation cost burden, i.e. transportation cost as a percent of income including cost of vehicle ownership/maintenance and transit costs
   o. Number or percentage of manufactured or mobile homes (HUD)
   p. Age of housing infrastructure (US Census, ACS, HUD)

Other important indicators for which national data are needed:

n. Access to tap water
o. Water shut-offs
p. Water access: number of people relying on bottled water
q. Adequacy Sanitation infrastructure (sewage)
r. Quality of water infrastructure: number of failing septic systems
s. Quality of infrastructure: prevalence of lead water service lines
t. Flood control/drainage infrastructure

Additional data sources:

1. **Air pollution**
    a. Longitudinal Electric Generating Units Database (1995-2016); Air Markets Program Data; Air Data; eGRID; National emissions inventory : https://osf.io/b8zae/;https://ampd.epa.gov/ampd/;https://www.epa.gov/outdoor-air-quality-data; https://www.epa.gov/egrid; https://www.epa.gov/air-emissions-inventories
    b. National Air Toxics Assessment: National Air Toxics Assessment: https://www.epa.gov/national-air-toxics-assessment/2014-nata-assessment-results

2. **Climate Change Vulnerability**
    i. US EPA Climate Indicators site: https://www.epa.gov/climate-indicators

3. **Housing**
    a. Location affordability index; Public housing developments: https://hudgishud.opendata.arcgis.com/datasets/location-affordability-index-v-3; https://hudgis-hud.opendata.arcgis.com/datasets/public-housing-developments
    b. Percent Housing Units Built Before 1950; Deteriorated Paint Index: https://enviroatlas.epa.gov/enviroatlas/interactivemap/; https://hudgis-hud.opendata.arcgis.com/datasets/deteriorated-paint-index-by-tract

4. **Wages, employment, investment**
    a. Quarterly Census of Employment and Wages: https://enviroatlas.epa.gov/enviroatlas/interactivemap/; https://www.bls.gov/cew/downloadable-data-files.htm
    b. EPA EJ Grants are available as a point layer from EPA API: https://catalog.data.gov/dataset/us-epa-ej-grants

5. **Proximity to hazards**
    a. Blood Lead Levels in Children Aged 1–5 Years — United States, 1999–2010: https://www.cdc.gov/mmwr/preview/mmwrhtml/mm6213a3.htm

6. **Childcare, health care (access, disease prevalence)**
    a. Childcare Centers: https://hifld-geoplatform.opendata.arcgis.com/datasets/child-care-centers
    b. CDC PLACES Data (previously 500 Cities); Uninsured; FQHCs, Hospitals, Dialysis sites, etc.:
    c. https://www.cdc.gov/places/index.html
    d. Environmental Public Health Tracking Network (EPHTN): https://ephtracking.cdc.gov/DataExplorer/

  e. EPA EnviroAtlas, Respiratory risk hazard index: https://enviroatlas.epa.gov/enviroatlas/interactivemap/
  f. CDC Social Vulnerability Index (SVI): https://healthdata.gov/dataset/cdc-social-vulnerability-index-svi

7. **"Natural" environmental hazards (wildfires, flooding, precipitation, heat)**
  a. USDA Forest Service Burn Probability Layer: https://www.fs.usda.gov/rds/archive/Catalog/RDS-2015-0047-3
  b. USGS Historic Wildfire Boundaries: https://wfdss.usgs.gov/wfdss/wfdss_data_downloads.shtml
  c. USGS Historic Wildfire Boundaries, Monitoring Trends in Burn Severity (MTBS): https://www.mtbs.gov/viewer/index.html
  d. UCS Killer Heat: https://ucsusa.maps.arcgis.com/apps/MapSeries/index.html?appid=e4e9082a1ec343c794d27f3e12dd006d
  e. NOAA Storm Surge Probability Layer, SLOSH MOMs Model: https://www.nhc.noaa.gov/nationalsurge/#tech
  f. Areas at risk of chronic inundation, UCS When Rising Seas Hit Home: https://ucsusa.maps.arcgis.com/apps/MapSeries/index.html?appid=64b2cbd03a3d4b87aaddaf65f6b33332
  g. NOAA Coastal Flood Exposure Mapper: https://coast.noaa.gov/arcgis/rest/services/FloodExposureMapper
  h. FEMA National Flood Hazard Layer, FEMA NFHL: https://catalog.data.gov/dataset/national-flood-hazard-layer-nfhl; https://hazards.fema.gov/gis/nfhl/rest/services
  i. Precipitation totals and climatological anomalies (i.e., deviation from 30-year means), Advanced Hydrologic Prediction Service (AHPS): https://water.weather.gov/ahps/
  j. Flood impacts on properties such as National Flood Insurance Program (NFIP) number of claims and polices and other disaster mitigation data at the scale of buildings or individual policies: https://www.fema.gov/about/openfema/data-sets

8. **Transportation**
  a. BTS National Transit Map, LEHD data on workplace locations; vehicle ownership: https://ops.fhwa.dot.gov/freight/freight_analysis/perform_meas/index.htm#data, https://www.transit.dot.gov/ntd/data-product/safety-security-time-series-data;
  b. National Multimodal Freight Network, ATRI Truck volume data: https://www.transportation.gov/freight/INMFNTables, https://truckingresearch.org/
  c. Transportation costs: https://www.hudexchange.info/programs/location-affordability-index/

9. **Demographic/SES**
    a. Redlining: https://dsl.richmond.edu/panorama/redlining/#loc=5/39.1/-94.58
    b. Measures of segregation, 2020 USA Diversity Index (% chance that two people in a given geography will have different races): https://ucsusa.maps.arcgis.com/home/item.html?id=010f7ddc958d442d8c1583281cf416a5
    c. Gerrymandering: http://www.cornellpolicyreview.com/rigging-elections-spatial-statistics-analysis-political-unintentional-gerrymandering/

10. **COVID Related**
    a. Population mobility during COVID-19, Google Mobility Reports: https://www.google.com/covid19/mobility/
    b. COVID-19 cases, COVID-19 Dashboard by the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University (JHU): https://www.arcgis.com/apps/opsdashboard/index.html#/bda7594740fd40299423467b48e9ecf6

11. **Infrastructure**
    a. Green Space, Normalized Difference Vegetation Index (NDVI): https://modis.gsfc.nasa.gov/data/dataprod/mod13.php
    b. Imperviousness/impervious surfaces, Urban Imperviousness: https://www.mrlc.gov/data?f%5B0%5D=category%3Aurban%20imperviousness

12. **Other Existing Tools**
    a. Mapping for Environmental Justice – University of California Berkley https://mappingforej.berkeley.edu/

RECOMMENDATIONS: EXECUTIVE ORDER 12898 REVISIONS

Revision to: Federal Register Presidential Documents, Vol. 59, No. 32, Wednesday, February 16, 1994 - Title 3— The President Executive Order 12898 of February 11, 1994

These are the recommendations as to Part I – Policy:

PART I - FEDERAL ACTIONS TO ADDRESS ENVIRONMENTAL JUSTICE IN POPULATIONS OF COLOR, TRIBAL AND INDIGENOUS POPULATIONS, AND LOW-INCOME POPULATIONS

By the authority vested in me as President by the Constitution and the laws of the United States of America, it is hereby ordered as follows:

Section 101. *Policy.* Historically disadvantaged communities across the United States have experienced disproportionate harm from environmental contaminants and face disproportionate risks from climate change. The inequitable and discriminatory treatment of communities of color, low-income communities, indigenous persons or members of Tribal nations, and people with disabilities - including the legacy of de jure segregation and other forms of discrimination - has resulted in disparities in health status and life expectancies. Historically, the Federal Government has taken actions that have perpetuated, institutionalized, or defended injustices that resulted in inequality in exposure to hazardous substances and unequal access to clean water, clean air, healthy food, safe housing, transportation, and other environmental benefits. The human toll of inequality is shown in disproportionately high rates of asthma among Black Americans, disproportionately high rates of lead poisoning in children of color, life expectancy among American Indians and Alaska Natives more than five years below the national average, and other disparities that are unacceptable. In 2020, disparities in morbidity and mortality related to COVID and information on the relationship between exposure to air pollution and the effects of COVID, as well as evident forms of systemic racism, reinforced the need for a renewed commitment to root out the vestiges of these actions and to secure an equitable and sustainable future for all. Toward this end, the United States must ensure that environmental justice is fully considered in decisions made by the Federal Government that impact the environment in the places where people live, learn, worship, work, and play. This means not only repairing past and current harm and preventing future injustices, but also rooting out and dismantling systemic racism and other forms of institutionalized bias in our laws, policies, and practices.

In order to advance environmental justice, the Federal Government must recognize and acknowledge the role that past policies and practices, both intentional and unintentional, have had in land use across the country and in shaping current environmental and health conditions. The Federal Government must be committed to taking decisive action, through its policies and practices and together with state, local and private partners to dismantle the institutions and practices that inequitably place disproportionately human health, environmental, climate-related and other cumulative burdens on already disadvantaged communities, and to partner in building healthy, culturally vibrant, sustainable and resilient communities for all. And in our democracy, the Federal Government must also be transparent and accountable for its actions and benefit from the meaningful participation of the most impacted communities.

As was intended when Executive Order 12898 was first issued, this Order is designed to focus Federal attention on environmental and human health conditions in communities of color, Tribal and indigenous communities, low-income communities, and among people with disabilities to address discrimination in Federal programs substantially affecting human health and the environment, to advance justice, and to ensure opportunities for meaningful participation in, matters relating to human health or the environment. Two decades after Executive Order 12898 was issued, the Federal Government must renew its commitment not only to identifying but also addressing the legacy of discrimination and continuing inequalities. Executive Order 13985 made clear that “the Federal Government should pursue a comprehensive approach to advancing equity for all, including people of color and others who have been historically underserved, marginalized, and adversely affected by persistent poverty and inequality.” This Order now adds that affirmatively advancing equity, civil rights, racial justice, equal opportunity, and environmental justice is the responsibility of the whole of our Government. As the country faces converging economic, health, and climate crises that have exposed and exacerbated inequities, a historic movement for justice has highlighted some of the unbearable human cost of systemic racism. All children must have the chance to live, play, learn, and grow in safe, healthful, climate-resilient communities, protected from the harms of pollution, and this Order pledges to adopt policies and practices to ensure that no one in this country will be more likely to suffer adverse health effects, face greater risks, or have their life cut short simply because of their race, color, national origin, membership in a Tribe, economic status, or disability.

These are the recommendations as to Part II – Definitions:

PART II - DEFINITIONS

Sec. 201. *For purposes of this Order.* (a) The term ***“community of color”*** means a geographically distinct area in which the population of any of the following categories of individuals, individually or in combination, is higher than the average population of that category for the State in which the community is located:

(i) Black;

(ii) African American;

(iii) Asian;

(iv) Pacific Islander;

(v) Other Non-White race;

(vi) Hispanic;

(vii) Latino;

(viii) Indigenous or members of a Tribe; and

(ix) Linguistically isolated.

(b) The term ***“environmental justice”*** means the just treatment and meaningful involvement of all people regardless of race, color, national origin, or income, or ability, with respect to the development, implementation, enforcement, and evaluation of laws, regulations, programs, policies, practices, and activities, that affect human health and the environment.

(c) The term ***“environmental justice community”*** means a geographic location with significant representation of persons of color, low-income persons, indigenous persons, or members of Tribal nations, where such persons experience, or are at risk of experiencing, higher or more adverse human health or environmental outcomes.

(d) The term “***Federal agency***” means any executive department, Government corporation, Government controlled corporation, or other establishment in the executive branch of the Government (including the Executive Office of the President), or any independent regulatory agency, but does not include:

(i) the Government Accountability Office;

(ii) the Federal Election Commission;

(iii) the governments of the District of Columbia and of the territories and possessions of the United States, and their various subdivisions;

(iv) courts martial and military commissions; and

(v) military authority exercised in the field in time of war or in occupied territory.

(e) The term ***“Indian Tribe”*** has the meaning give the term “Indian tribe” in section 4 of the Indian Self-Determination and Education Assistance Act (25 U.S.C. 5304).

(f) The term "**Interagency Council**" means the White House Environmental Justice Interagency Council as that body defined in Executive Order 14008.

(g) The term ***"just treatment"*** means the conduct of a program, policy, practice or activity by a Federal agency in a manner that ensures that no group of individuals (including racial, ethnic, or socioeconomic groups) experience a disproportionate burden of adverse human health or environmental outcomes resulting from such program, policy, practice, or activity, as determined through consultation with, and with the meaningful participation of, individuals from the communities affected by a program, policy, practice, or activity of a Federal agency, and to ensure that each person enjoys, at a minimum:

(i) the full degree of protection from environmental and health hazards, especially where disproportionate human health and environmental impacts are demonstrably greater;

(ii) equitable access to any Federal agency action, including decision-making processes, actions, resources, and benefits, to build and ensure healthy, culturally vibrant, sustainable, and resilient environments for all people to live, learn, work, worship, recreate, and practice their cultures;

(iii) elimination of systemic racism and other structural barriers to achieving healthy, culturally vibrant, sustainable, and resilient communities for all people, which contribute to disproportionate human health and environmental impacts on the basis of race, color, national origin, income, and disability; and

(iv) improvement in human health and environmental outcomes in communities disproportionately impacted by environmental and health hazards, including the improvement of environmental outcomes that protect cultural practices, the maintenance and restoration of cultural heritage, and the cultural bases of human health.

(h) The term ***"low-income community"*** means any census block group in which 30 percent or more of the population are individuals with an annual household income equal to, or less than, the greater of:

(i) an amount equal to 80 percent of the median income of the area in which the household is located, as reported by the Department of Housing and Urban Development; or

(ii) 200 percent of the Federal poverty line.

(i) The term ***"meaningful participation"*** means that potentially affected populations have an opportunity to participate in decisions that will affect their health or environment, that the population's contributions can influence the agency's decisions, that the viewpoints of all participants involved will be considered in the decision-making process, and that the agency will seek out and facilitate the involvement of the population potentially affected, including consultation with Tribal and indigenous communities and by providing culturally appropriate information, access for people with disabilities, and language access for persons with Limited English Proficiency (LEP), considering issue of access raised by location, transportation, and other factors affecting participation, and by making available technical assistance to build community-based capacity for participating.

(j) The term "***policies that have tribal implications***" means regulations, legislative comments or proposed legislation, and other policy statements or actions that have substantial direct effects on one or more Indian tribes, on the relationship between the Federal Government and Indian tribes, or on the distribution of power and responsibilities between the Federal Government and Indian tribes.

(k) The term ***"publish"*** means to make publicly available in a form that is:

> (i) generally accessible in culturally appropriate forms and including on the internet and in public libraries; and
>
> (ii) accessible for individuals who are limited in English proficiency, and individuals with disabilities.

(l) The term ***"Tribal and indigenous community"*** means a population of people who are members of:

> (i) a federally recognized Indian Tribe;
>
> (ii) a State-recognized Indian Tribe;
>
> (iii) an Alaska Native or Native Hawaiian community or organization; and
>
> (iv) any other community of indigenous people located in a State, including indigenous persons residing in urban communities.

(m) The term "***indigenous persons or members of Tribal nations***" means persons who are members of Tribal and indigenous communities.

These are the recommendations as to Part III – Federal Agency Responsibilities and Implementation:

PART III - FEDERAL AGENCY RESPONSIBILITIES AND IMPLEMENTATION

Sec. 301. *Agency Responsibilities*. To the maximum extent permitted by law each Federal agency must make achieving environmental justice part of its mission by identifying and addressing disproportionate adverse human health or environmental effects of its programs, policies, practices and activities on populations and communities of color, Tribal and indigenous communities, low-income communities, and people with disabilities in the United States and its territories and possessions, the District of Columbia, the Commonwealth of Puerto Rico, American Samoa, Guam, the Northern Mariana Islands, and the U.S. Virgin Islands. (a) Achieving environmental justice as part of an agency's mission requires developing, implementing, enforcing, and evaluating laws, regulations, and policies, including those related to permitting and the reissuance of permits, that affect human health and the environment to ensure that each person enjoys:

(i) the full degree of protection from environmental and health hazards, advanced through identifying, characterizing, and addressing disproportionate human health and environmental impacts and full enforcement of civil rights and environmental laws;

(ii) equitable access to decision-making processes, actions, resources, and benefits to build and ensure healthy, culturally vibrant, sustainable, and resilient environments for all people to live, learn, work, worship, play and practice their cultures;

(iii) elimination of systemic barriers to achieving healthy, culturally vibrant, sustainable, and resilient communities for all people and redress of historical inequities and policies, including those related to systemic racism, and contribute to disproportionate human health and environmental impacts; and

(iv) improvement in human health and environmental outcomes in their communities.

(b) Agencies must ensure meaningful participation in agency programs, policies, practices, and activities, and other decision-making processes, and clear, timely, and broad communication of environmental justice updates to programs, policies, practices, and activities, and, to the maximum extent practicable, ensure states, localities, and other recipients of federal assistance also ensure meaningful participation and abide to the same standards of communication.

Sec. 302. *Conduct of Programs*. Each Federal agency must:

(a) conduct each program, policy, practice and activity of the Federal agency that adversely affects, or has the potential to adversely affect, human health or the environment in a manner that ensures that each such program, policy, practice, activity, and other decision-making processes, does not have the effect of excluding any individual from participating in, denying any individual the benefits of or subjecting any individual to discrimination or disparate impact under such program, policy, practice, or activity of the Federal agency because of race, color, national origin, income level, membership in a Tribal or indigenous community, or disability, and builds healthy, culturally vibrant, sustainable, and resilient communities;

(b) as required by Title VI of the Civil Rights Act of 1964, Section 504 of the Rehabilitation Act of 1973 and the Americans with Disabilities Act and agency regulations pursuant to these laws, ensure that all programs or activities receiving Federal Financial assistance that affect human health or the environment must not directly, or through contractual or other arrangements, use criteria, methods, or practices that discriminate on the basis of race, color, or national origin;

(c) as required by the National Environmental Policy Act (NEPA) and other Federal laws, analyze the environmental effects, including human health, economic and social effects, of Federal actions, including effects on communities of color, Tribal and indigenous communities, low-income communities, and people with disabilities; and ensure to the maximum extent practicable that mitigation measures outlined or analyzed in an environmental assessment, environmental impact statement, or record of decision address significant and adverse environmental effects of proposed Federal actions on communities of color, Tribal and indigenous communities, low-income communities, and people with disabilities;

(d) as required by the National Environmental Policy Act (NEPA) and other Federal laws, ensure opportunities for meaningful participation in decision making and adequate access to public information relating to human health or environmental planning, regulations, and enforcement; and

(e) as required by Executive Order 13175, Consultation and Coordination with Indian Tribal Governments, "establish regular and meaningful consultation and collaboration with tribal officials in the development of Federal policies that have tribal implications, to strengthen the United States government-to-government relationship with Indian tribes, and to reduce the imposition of unfunded mandates upon Indian tribes."

Sec. 303. *Responsibilities of the Interagency Council.* Section 220(d) of Executive Order 14008 (Tackling the Climate Crisis at Home and Abroad) is hereby amended (a) to require that strategy developed by the Interagency Council must include concrete and measurable actions to:

(i) ensure consideration of persistent violations by applicants in permitting decisions,

(ii) reduce, prevent and eliminate emissions and releases of pollution in environmental justice communities; and

(iii) strengthen environmental and civil rights protection and enforcement in environmental justice communities

(b) To require that within one (1) year of the effective date of this Order, and every five years thereafter, the Interagency Council:

(i) review the consideration of impacts on environmental justice communities pursuant to the National Environmental Policy Act (NEPA) and report to the President with recommendations on legislative, regulatory, or policy options for advancing environmental justice through the review process pursuant to NEPA;

(ii) review enforcement of civil rights compliance by programs or activities receiving Federal Financial assistance that affect human health or the environment and report to the President with recommendations on legislative, regulatory, or policy options for advancing environmental justice through enforcement of Title VI of the Civil Rights Act of 1964, Section 504 of the Rehabilitation Act of 1973, and the Americans with Disabilities Act and agency regulations pursuant to these laws. This review must include consideration of the effectiveness of the delegation of authority under Executive Order 12250 to the Attorney General for the consistent and effective implementation of various laws prohibiting discriminatory practices and recommendations on legislative, regulatory, or policy options to improve the coordination and effectiveness of various laws prohibiting discriminatory practices by programs or activities receiving Federal financial assistance that affect human health or the environment; and

(iii) review decisions of the Environmental Appeals Board (EAB) and report to the President with recommendations on legislative, regulatory, or policy options to ensure that EAB decisions consider environmental justice in decisions to the maximum extent practicable.

(c) To establish and implement multi-agency collaborations consisting of two or more Federal agencies in coordination with state, Tribal, and local governments, additionally, multiple environmental justice community-based stakeholders to support holistic, place-based, and community-driven programmatic initiatives. The Interagency Council must provide guidance on how multiple agencies will design and implement such initiatives based on a systematic set of policies, programs, staff, resources and tools to create favorable conditions for building and ensure healthy, culturally vibrant, sustainable, and resilient communities through such holistic, place-based, and community-driven programmatic initiatives to include maximizing the use of Justice 40 resources, where practicable. The Interagency Council will consider, and incorporate lessons learned from past collaborative efforts in the design and implementation of these initiatives.

Sec. 304. *Development of Agency Strategic Plans.* Except as provided in of this Order, not later than one (1) year after the effective date of this Order and every two (2) years thereafter, each Federal agency must develop and publish an agency-wide environmental justice strategic plan. In developing the environmental justice strategic plan, each Federal agency must provide opportunities for meaningful participation, notice, and opportunity for public comment, including meaningful participation in the scope and design of the strategic plan.

Sec. 305. *Contents of Agency Strategic Plans.* Each environmental justice strategic plan developed and updated by a Federal agency must contain:

(a) an assessment that identifies programs, planning and public participation processes, policies, practices, including spending, funding and investments, and activities of the Federal agency, related to human health or the environment that have a disproportionate and adverse human health or environmental effect on environmental justice communities;

(b) legislative, regulatory, and policy strategies, as well as strategies to effect change in practices, to address disproportionate and adverse human health or environmental effects on environmental justice communities;

(c) an assessment of legal authorities relevant to the Federal agency to advance environmental justice; and

(d) strategies to accomplish the following objectives:

> (i) reduce, prevent, and eliminate pollution, legacy pollution, and cumulative impacts in environmental justice communities and to ensure that all persons have the full degree of protection from environmental and health hazards;
>
> (ii) fully implement and enforce Title VI of the Civil Rights Act of 1964, Section 504 of the Rehabilitation Act of 1973, and the Americans with Disabilities Act, and agency regulations pursuant to these laws;
>
> (iii) fully implement the National Environmental Policy Act (NEPA) of 1969, and the Robert T. Stafford Disaster Relief and Emergency Assistance Act;
>
> (iv) enforce all health and environmental laws and regulations to ensure that all persons have the same degree of protection from environmental and health effects,
>
> (v) address the lack of infrastructure and deteriorated infrastructure, the vestiges of discriminatory land use, and the effects of commercial transportation on environmental justice communities;
>
> (vi) ensure meaningful participation and due process in the development, implementation, and enforcement of Federal laws;
>
> (vii) improve direct guidance and technical assistance to environmental justice communities with respect to the communication of science, regulations, and policy related to Federal agency action on environmental justice issues;
>
> (viii) advance scientifically informed scenario planning, including the capacity to create worst case scenarios tied to chemical policy, energy, and defense, and industrial policy;
>
> (ix) improve cooperation, collaboration, and participatory decision-making with State, Tribal, and local governments to address pollution and public health burdens in environmental justice communities, and build and ensure healthy, culturally viable, sustainable, and resilient communities;
>
> (x) improve consultation, collaboration, and participatory decision-making with federally-recognized Tribes, including consultative meetings that engage the recognition and

protection of Tribal ecological knowledge, expanded funding for Tribal Historic Preservation Offices to the demands of environmental justice on and off Indian reservations, the meaning of sacred sites (E.O. 13007) and places of cultural heritage and significance, the elimination of unfunded mandates (E.O. 12875), the potential for co-management relationships on public lands, treaty rights, funding for feasibility studies, grants that are multi-year and that offer stability, consistency, and long term staff support; and

(xi) improve Federal research and data collection efforts related to:

(a) the health and environmental justice communities, including through the increased use of community-based science and recognition of Tribal ecological knowledge;

(b) climate change; and

(c) the inequitable distribution of burdens and benefits of the management and use of natural resources, including water, minerals, or land;

(e) plans to coordinate with states, county, and other units of government, including a clear statement describing how each Federal agency can support the development, implementation, and evaluation of environmental justice strategies for those units of government. Federal agency strategic plans must directly address what courses of action, including in connection with federal funding, will be taken to address environmental justice issues at state, county, or local levels of government;

(f) the identification of resources, including staffing and funding, to support implementation of the Federal agency's environmental justice strategic plan;

(g) timetables to implement strategies included in the plan;

(h) metrics to evaluate performance of the plan; and

(i) in the initial plan, not later than one (1) year after the effective date of this Order, a plan to convene an environmental justice advisory committee pursuant to the Federal Advisory Committee Act or an equivalent body to provide ongoing expertise, input and review of agency strategic plans.

Sec. 306. *Reports to the Interagency Council.* Each Federal Agency must submit to the Interagency Council:

(a) a written Report on Implementation of the Strategic Plan within one (1) year of the publication of each strategic plan. The Report must assess progress in implementing the agency-wide environmental justice strategic plan and include a comparison of strategies used to address environmental justice issue and outcomes across regions, an assessment of barriers to implementing the environmental justice strategic plan, and recommendations for addressing those barriers. Each Federal agency must ensure the opportunity for meaningful participation in the evaluation process; and

(b) additional periodic reports in writing to the Interagency Council as requested by the Interagency Council.

Sec. 307. *Reports to the President.* Within fourteen (14) months of the date of this Order, the Interagency Council shall submit to the President, through the Office of the Deputy Assistant to the President for Environmental Policy and the Office of the Assistant to the President for Domestic Policy, a report that describes the implementation of this Order, and includes the final environmental justice strategies described in Sec 305 of this Order.

These are the recommendations as to Part IV – Research, Data Collection, and Analysis:

PART IV - RESEARCH, DATA COLLECTION, AND ANALYSIS.

Sec. 401. *Human Health and Environmental Research and Analysis.* Each Federal agency, to the maximum extent permitted by applicable law, must:

(a) in conducting environmental, public access, or human health research, include diverse segments of the population in epidemiological and clinical studies, including segments at high risk from environmental hazards, such as populations of color, members of Tribal and indigenous communities, low-income populations, people with disabilities, and workers who may be exposed to substantial environmental hazards;

(b) identify multiple and cumulative exposures, including potentially exacerbated risks and impacts due to current and future climate impacts; and

(c) actively encourage and solicit community-based science and Tribal ecological knowledge, and provide communities of color, Tribal and indigenous communities, low-income communities, and people with disabilities the opportunity for meaningful participation on the development and design of research strategies undertaken pursuant to this Order, recognizing that for some environmental justice communities, cultural practices are connected to health outcomes and can be disrupted by environmental effects/outcomes/hazards.

Sec. 402. *Human Health and Environmental Data Collection and Analysis.* To the extent permitted by existing law, including the Privacy Act, as amended (5 U.S.C. section 552a) (a) each Federal agency, to the maximum extent possible and consistent with the highest standard of ethics, must collect, maintain, and analyze information assessing and comparing environmental and human health risks borne by populations identified by race, national origin, tribal membership, or income, including to the maximum extent practicable and consistent with the highest standards of ethics, disaggregated by ethnicity and subpopulations. To the extent practical and appropriate, Federal agencies must use this information to determine whether their programs, policies, and activities have disproportionate adverse human health or environmental effects on populations of color, Tribal and indigenous populations, and low-income populations.

(b) Each Federal agency, whenever practicable and appropriate, must collect, maintain and analyze information on the race, national origin, tribal membership, income level, and other readily accessible and appropriate information for areas surrounding facilities or sites expected to have a substantial environmental, human health, or economic effect on the surrounding populations, including any designation of such areas as a land trust, when such facilities or sites become the subject of a substantial Federal environmental administrative or judicial action. Such information must be made available to the public, unless prohibited by law.

(c) Each Federal agency, whenever practicable and appropriate, must collect, maintain, and analyze information on the race, national origin, income level, and other readily accessible information for areas surrounding Federal facilities that are:

(i) subject to the reporting requirements under the Emergency Planning and Community Right-to-Know Act, 42 U.S.C. section 11001–11050 as mandated in Executive Order No. 12856; and

(ii) expected to have a substantial environmental, human health, or economic effect on surrounding populations. Such information must be made available to the public, unless prohibited by law.

(d) In carrying out the responsibilities in this section, each Federal agency, to the maximum extent practicable, must share information and eliminate unnecessary duplication of efforts through the use of existing data systems and cooperative agreements among Federal agencies and with State, local, and Tribal governments.

Sec. 403. *Environmental and Climate Justice Mapping and Screening Tool.* The Chair of the Council on Environmental Quality, in coordination with the Administrator of EPA, must make available to the public an environmental and climate justice screening tool (such as EJ Screen or the geospatial Climate and Economic Justice Screening Tool created pursuant to Executive Order 14008) that includes, at a minimum, the following features:

(i) nationally consistent data;

(ii) environmental data;

(iii) demographic data, including data relating to race, ethnicity, income, and workforce participation

(iv) data on redlining and other indicia of structural racism and other inequities;

(v) health data;

(vi) capacity to produce maps and reports by geographic area;

(vii) data on national parks and other federally protected natural, historic, and cultural sites;

(viii) an index of cumulative impacts that provides the capacity to compare the relative vulnerabilities of communities to environmental impact and climate change; and

(ix) a capacity to inform scientifically informed scenario planning, including the capacity to create worst case scenarios tied to chemical policy.

These are the recommendations as to Part V – Subsistence Consumption of and Cultural Practices Reliant on Biota, Including Fish and Wildlife:

PART V - SUBSISTENCE CONSUMPTION OF AND CULTURAL PRACTICES RELIANT ON BIOTA, INCLUDING FISH AND WILDLIFE

Sec. 501. *Consumption Patterns and Cultural Practices*. In order to assist in identifying the need for ensuring protection of communities with different patterns of subsistence consumption of biota, including fish, and wildlife, and cultural practices reliant on biota, Federal agencies, to the maximum extent practicable and appropriate and consistent with the highest standards of ethics, must collect, maintain, analyze, and consider information on subsistence consumption patterns and cultural practices of environmental justice communities. Federal agencies must communicate to the public the risks of subsistence consumption and culture practices. The design of such communications must provide information on healthy alternatives and must not imply, without meaningful public participation or Tribal consultation, that mitigation or restoration efforts to address the adverse environmental effect are unnecessary.

Sec. 502. *Guidance.* Federal agencies, to the maximum extent practicable, must work in a coordinated manner to publish and revise guidance reflecting the latest scientific information available concerning methods for evaluating the human health risks associated with the consumption of pollutant-bearing fish or wildlife. Agencies shall consider such guidance in developing their policies and rules.

These are the recommendations as to Part VI – Public Participation and Access to Information:
These are the recommendations as to Part VI – Public Participation and Access to Information:

PART VI - PUBLIC PARTICIPATION AND ACCESS TO INFORMATION.

Sec. 601. *The public may submit recommendations.* The public may submit recommendations to Federal agencies relating to the incorporation of environmental justice principles into Federal agency programs or policies. (a) Each Federal and state agency shall convey such recommendations to the Interagency Council.

(b) Each Federal and state agency, consistent with
Executive Order No.13166, must provide translation and interpretation of public documents, notices, and at any hearings relating to an action of the Federal agency as appropriate for the affected population, specifically in any case in which a population with LEP may be disproportionately affected by that action.

(c) Each Federal and state agency must work to ensure that public documents, notices, and hearings relating to human health or the environment are concise, understandable, and readily accessible to the public.

(d) The Interagency Council must hold public meetings, as appropriate, for the purpose of fact-finding, receiving public comments, and conducting inquiries concerning environmental justice. The Interagency Council must prepare, for public review, a summary of the comments and recommendations discussed at the public meetings.

These are the recommendations as to Part VII – General Provisions:

PART VII - GENERAL PROVISIONS.

Sec. 701. *Responsibility for Agency Implementation.* The head of each
Federal and State agency must be responsible for ensuring compliance with this Order.
Each Federal agency must conduct internal reviews and take such other steps as may be necessary to monitor compliance with this Order.

Sec. 702. *Executive Order No. 12250*. This Executive Order is intended to supplement but not supersede Executive Order No. 12250, which requires consistent and effective implementation of various laws prohibiting discriminatory practices in programs receiving Federal financial assistance. Nothing herein, will limit the effect or mandate of Executive Order No. 12250.

Sec. 703. *Executive Order No. 12875.* This Executive Order is not intended to limit the effect or mandate of Executive Order No. 12875.

Sec. 704. *Executive Order No. 13175*. Consultation and Coordination with Indian Tribal Governments sets action items for `regular and meaningful consultation and collaboration' with federally recognized Indian tribes.

Sec. 704. *Executive Order 13985*. This Executive Order is intended to supplement but not supersede Executive Order 13985.

Sec. 705. *Executive Order 14008*. This Executive Order is intended to supplement but not supersede Executive Order 14008.

Sec. 706. *Petitions for Exemptions*. The head of a Federal agency may petition the President for an exemption from the requirements of this Order on the grounds that all or some of the petitioning agency's programs or activities should not be subject to the requirements of this Order.

Sec. 707. *Native American Programs pertaining to federally recognized Indian Tribes*. Each Federal agency responsibility set forth under this Order must apply equally to Native American programs pertaining to federally recognized Indian Tribes. In addition, the Department of the Interior, in coordination with the Working Group, and, after consultation with tribal leaders, must coordinate steps to be taken pursuant to this Order that address Federally recognized Indian Tribes. Such steps must clarify how this Order will operate within the domain of Indian Tribes' inherent sovereignty and their government-to-government relationship with the U.S. federal government.

Sec. 708. *Federal agencies will determine procedures.* Federal agency must address health and environmental risks affecting Indigenous peoples not included in Sec 707, including Native Hawaiians, Indigenous peoples of islands and territories, members of state-recognized and un-recognized Indian Tribes, and indigenous persons living in urban centers. Indigenous peoples must not suffer adverse health and environmental outcomes or additional barriers to participation in programs, practices, policies, and decisions owing to their not being federally recognized Indian Tribes or to their not residing on reservations.

Sec. 709. *Costs.* Unless otherwise provided by law, Federal agencies must assume the financial costs of complying with this Order.

Sec. 710. *General.* Federal agencies must implement this Order consistent with, and to the extent permitted by, existing law.

Sec. 711. *Judicial Review*. This Order is intended only to improve the internal management of the executive branch and is not intended to, nor does it create any right, benefit, or trust responsibility, substantive or procedural, enforceable at law or equity by a party against the United States, its agencies, its officers, or any person. This Order must not be construed to create any right to judicial review involving the compliance or noncompliance of the United States, its agencies, its officers, or any other person with this Order.

Earthquake triggering and large-scale geologic storage of carbon dioxide

Mark D. Zoback[a,1] **and Steven M. Gorelick**[b]

Departments of [a]*Geophysics and* [b]*Environmental Earth System Science, Stanford University, Stanford, CA 94305*

Edited by Pamela A. Matson, Stanford University, Stanford, CA, and approved May 4, 2012 (received for review March 27, 2012)

Despite its enormous cost, large-scale carbon capture and storage (CCS) is considered a viable strategy for significantly reducing CO_2 emissions associated with coal-based electrical power generation and other industrial sources of CO_2 [Intergovernmental Panel on Climate Change (2005) IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change, eds Metz B, et al. (Cambridge Univ Press, Cambridge, UK); Szulczewski ML, et al. (2012) *Proc Natl Acad Sci USA* 109:5185–5189]. We argue here that there is a high probability that earthquakes will be triggered by injection of large volumes of CO_2 into the brittle rocks commonly found in continental interiors. Because even small- to moderate-sized earthquakes threaten the seal integrity of CO_2 repositories, in this context, large-scale CCS is a risky, and likely unsuccessful, strategy for significantly reducing greenhouse gas emissions.

carbon sequestration | climate change | triggered earthquakes

The combustion of coal for electrical power generation in the United States generates approximately 2.1 billion metric tons of CO_2 per year, ∼36% of all US emissions. In 2011, China generated more than three times that much CO_2 by burning coal for electricity, which accounted for ∼80% of its total emissions. (According to the Energy Information Agency of the US Department of Energy, total CO_2 emissions in China were 8.38 billion metric tonnes in 2011, with 6.95 billion tons from coal burning, nearly all of which is used electrical power generation.) From a global perspective, if large-scale carbon capture and storage (CCS) is to significantly contribute to reducing the accumulation of greenhouse gases, it must operate at a massive scale, on the order of 3.5 billion tons (1) of CO_2 per year, a volume roughly equivalent (2) to the ∼27 billion barrels of oil currently produced annually around the world. (Under reservoir conditions, one billion tons of CO_2 occupies a volume of ∼1.3 billion cubic meters, equivalent to 8.18 billion barrels. Thus, 3.5 billion tons of carbon dioxide would correspond to a volume of approximately 28.6 billion barrels. There are currently ∼850,000 wells producing oil around the world.) Moreover, a leak rate from underground CO_2 storage reservoirs of less than 1% per thousand years is required for CCS to achieve the same climate benefits as renewable energy sources (3).

Before embarking on projects to inject enormous volumes of CO_2 at numerous sites around the world, it is important to note that over time periods of just a few decades, modern seismic networks have shown that earthquakes occur nearly everywhere in continental interiors. Fig. 1, *Upper* shows instrumentally recorded earthquakes in the central and eastern United States and southeastern Canada. Fig. 1, *Lower* shows instrumentally recorded intraplate earthquakes in south and east Asia (4). The seismicity catalogs are complete to magnitude (M) 3. The occurrence of these earthquakes means that nearly everywhere in continental interiors a subset of the preexisting faults in the crust is potentially active in the current stress field (5, 6). This is sometimes referred to as the *critically stressed* nature of the brittle crust (7). It should also be noted that despite the overall low rate of earthquake occurrence in continental interiors, some of the most devastating earthquakes in history occurred in these regions. In eastern China, the M 7.8, 1976 Tangshan earthquake, approximately 200 km east of Beijing, killed several hundred thousand people. In the central United States, three M 7+ earthquakes in 1811 and 1812 occurred in the New Madrid seismic zone in southeast Missouri.

Because of the critically stressed nature of the crust, fluid injection in deep wells can trigger earthquakes when the injection increases pore pressure in the vicinity of preexisting potentially active faults. The increased pore pressure reduces the frictional resistance to fault slip, allowing elastic energy already stored in the surrounding rocks to be released in earthquakes that would occur someday as the result of natural geologic processes (8). This effect was first documented in the 1960s in Denver, Colorado when injection into a 3-km-deep well at the nearby Rocky Mountain Arsenal triggered earthquakes (9). Soon thereafter it was shown experimentally (10) at the Rangely oil field in western Colorado that earthquakes could be turned on and off by varying the rate at which water was injected and thus modulating reservoir pressure. In 2011 alone, a number of small to moderate earthquakes in the United States seem to have been triggered by injection of wastewater (11). These include earthquakes near Guy, Arkansas that occurred in February and March, where the largest earthquake was M 4.7. In the Trinidad/Raton area near the border of Colorado and New Mexico, injection of produced water associated with coalbed methane production seems to have triggered a number of earthquakes, the largest being a M 5.3 event that occurred in August. Earthquakes seem to have been triggered by wastewater injection near Youngstown, Ohio on Christmas Eve and New Year's Eve, the largest of which was M 4.0. Although the risks associated with wastewater injection are minimal and can be reduced even further with proper planning (11), the situation would be far more problematic if similar-sized earthquakes were triggered in formations intended to sequester CO_2 for hundreds to thousands of years.

Deep borehole stress measurements confirm the critically stressed nature of the crust in continental interiors (12), in some cases at sites directly relevant to the feasibility of large-scale CCS. For example, deep borehole stress measurements at the Mountaineer coal-burning power plant on the Ohio River in West Virginia indicate a severe limitation on the rate at which CO_2 could be injected without the resulting pressure build-up initiating slip on preexisting faults (13). Because of the low permeability of the formations at depth, pore pressure increases would be expected to trigger slip on preexisting faults if CO_2 injection rates exceed approximately 1% of the 7 million tons of CO_2 emitted by the Mountaineer plant each year. Similarly, stress measurements at Teapot Dome, Wyoming, the US government-owned oil field where pilot CO_2

Author contributions: M.D.Z. and S.M.G. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

[1]To whom correspondence should be addressed. E-mail: zoback@stanford.edu.

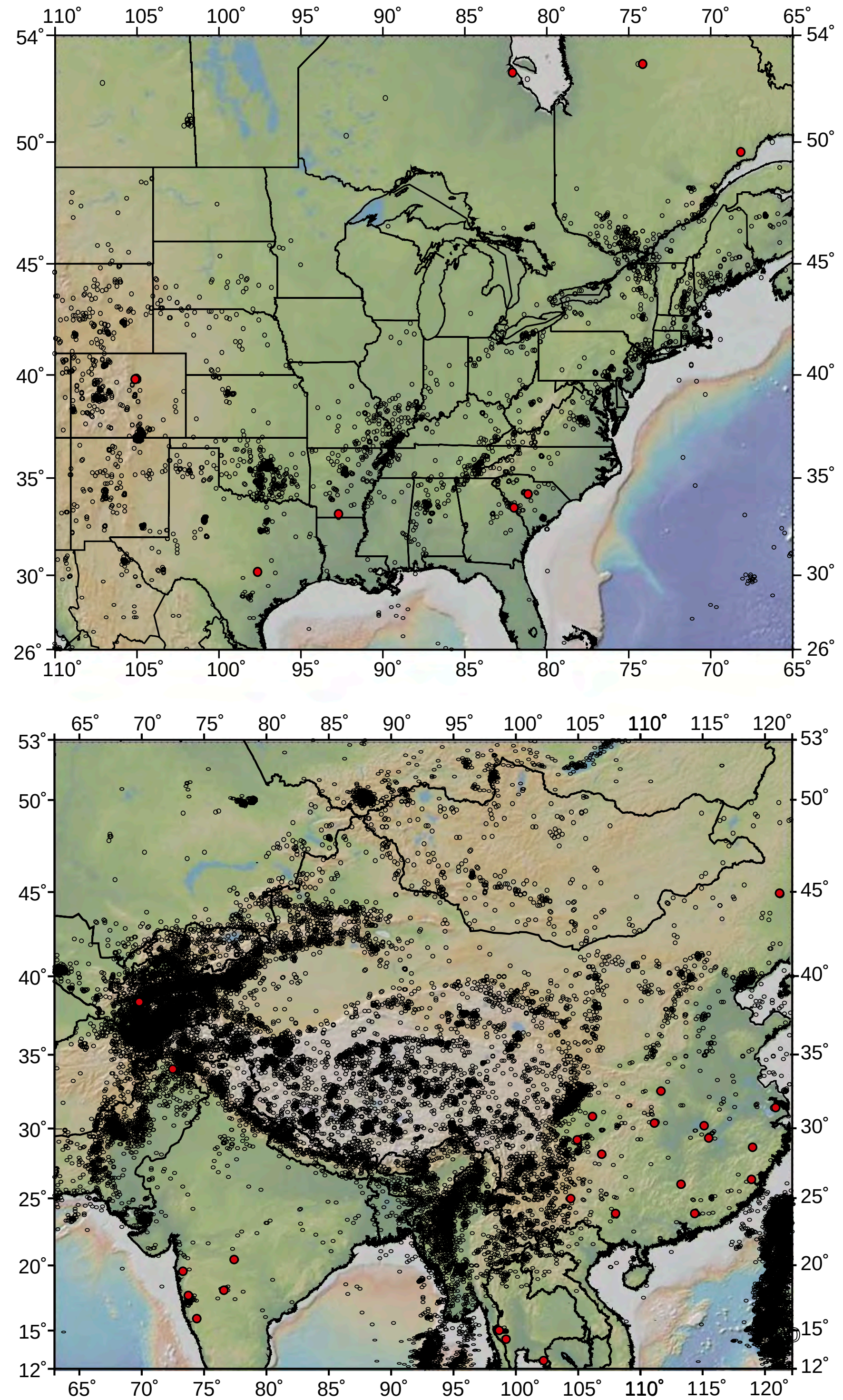


Fig. 1. *Upper*: Instrumentally recorded seismicity and damaging historical earthquakes in the central and eastern United States and southeastern Canada. Red dots indicate sites of reservoir-induced seismicity. *Lower*: Seismicity of south and east Asia and sites of reservoir-induced seismicity. Both data sets are available from the US Geological Survey (4).

injection projects have been considered, show that very small pressure buildups are capable of triggering slip on some preexisting faults (14).

Dam construction and water reservoir impoundment produce much smaller pore pressure changes at depth than are likely to occur with CO_2 sequestration, but many have triggered earthquakes at various sites around the world (15) (red dots in Fig. 1). Except for the much smaller pore pressure increases at depth, reservoir-triggered earthquakes are a good analog for the potential for seismicity to be triggered by CO_2 injection. Both activities cause pore pressure increases that act over large areas and are persistent for long periods. Three reservoir impoundments in eastern Canada (located in the ancient, stable core of the North American continent) triggered earthquakes as large as M 4.1 and M 5 at the two sites (Fig. 1), despite the fact that the pore pressure increases at depth were extremely small.

Triggered Earthquakes and Seal Integrity

Our principal concern is not that injection associated with CCS projects is likely to trigger large earthquakes; the problem is that even small to moderate earthquakes threaten the seal integrity of a CO_2 repository. In parts of the world with good construction practices, it is unusual for earthquakes smaller than approximately M 6 to cause significant human harm or property damage. Fig. 2 uses well-established seismological relationships to show how the magnitude of an earthquake is related to the size of the fault that slipped and the amount of fault slip that occurred (16). As shown, faults capable of producing M ∼6 earthquakes are at least tens of kilometers in extent. (The fault size indicated along the abscissa is a lower bound of fault size as it refers to the size of the fault segment that slips in a given earthquake. The fault on which an earthquake occurs is larger than the part of the fault that slips in an individual event.) In most cases, such faults should be easily identified during geophysical site characterization studies and thus should be avoided at any site chosen for a CO_2 repository. (Faults in crystalline basement rocks might be difficult to recognize in geophysical data. We assume, however, that any site chosen as a potential CO_2 repository would be carefully selected, avoiding the possibility of pressure changes in the CO_2 repository from affecting faults in crystalline basement.) The problem is that site characterization studies can easily miss the much smaller faults associated with small to moderate earthquakes.

Although the ground shaking from small- to moderate-sized earthquakes is inconsequential, their impact on a CO_2 repository would not be. Most of the geologic formations to be used for long-term storage of CO_2 are likely to be at depths of approximately 2 km—deep enough for there to be adequate sealing formations to isolate the CO_2 from the biosphere but not so deep as to encounter formations with very low permeability. Given large volumes of CO_2 injected into selected formations for many decades, if a small to moderate earth-

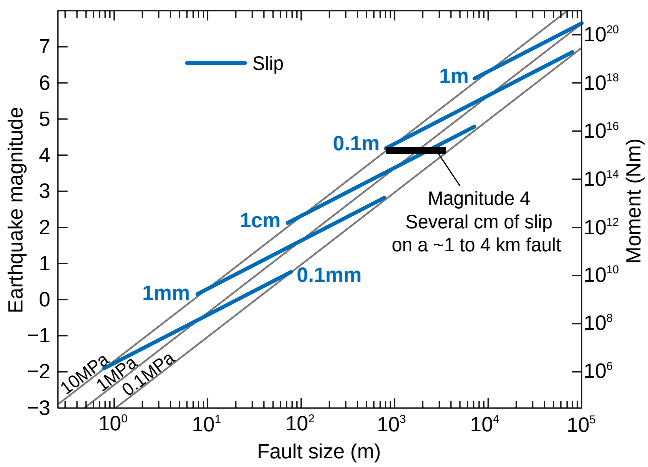


Fig. 2. Relationships among various scaling parameters for earthquakes. The larger the earthquake, the larger the fault and amount of slip, depending on the stress drop in a particular earthquake. Observational data indicate that earthquake stress drops range between 0.1 and 10 MPa.

quake were to be triggered in a geologic formation at approximately 2 km depth, it could jeopardize the seal integrity of the storage formation. For example, if a M ~4 earthquake were to be triggered by CO_2 sequestration (17)—an event that would be widely felt in a populated area but for which shaking would be unlikely to cause harm or damage—it would be associated with several centimeters of slip on a fault several kilometers in size. Because laboratory studies show that just a few millimeters of shear displacement are capable of enhancing fracture and joint permeability (18), several centimeters of slip would be capable of creating a permeable hydraulic pathway that could compromise the seal integrity of the CO_2 reservoir and potentially reach the near surface.

Safe Sequestration

It is important to emphasize that CCS can be valuable and useful for reducing greenhouse gas emissions in specific situations. A good example is the injection of CO_2 into the Utsira formation (19) at the Sleipner gas field in the North Sea, where a significant amount of CO_2 is coproduced with natural gas. After separating the CO_2 from the produced gas, approximately 1 million tons of CO_2 per year has been injected over the past 15 y without triggering seismicity. Assuming isolation from the near surface, injection into highly porous and permeable reservoirs that are laterally extensive would produce small increases in pressure in response to CO_2 injection. Moreover, weak, poorly cemented sandstones are expected to deform slowly in response to applied geologic forces. In such reservoirs, the stresses *relax* over time, and such formations are not prone to faulting (20). In this regard, the Utsira formation is ideal for CO_2 sequestration. It is isolated from vertical migration by impermeable shale formations, and it is highly porous, permeable, laterally extensive, and weakly cemented.

To contribute significantly to greenhouse gas emission reductions (2), roughly 3,500 sites similar to the Utsira formation would have to be found at convenient locations around the world, assuming comparable injection rates of approximately 1 million tons of CO_2 per year. In fact, it would take approximately 85 such sites coming on line each year to reach a goal of storing approximately 1 billion tons of CO_2 by midcentury. Clearly this is an extraordinarily difficult, if not impossible, task if only highly porous and permeable and weakly cemented formations are to be used.

Of course, rather than using potentially problematic geologic formations close to coal-burning power plants for sequestration (as illustrated by the Mountaineer case study cited above), relatively ideal formations for CO_2 storage could be sought on a regional basis to accommodate emissions from a number of plants. One example of this is the potential use of the Mt. Simon sandstone in the Illinois basin. The Mt. Simon is porous, permeable, and regionally extensive. However, models of injection of 100 million tons of CO_2 per year for 40 y predicts (21) increases in pore pressure of several megapascals over a region of ~40,000 km^2. The approximate area of significantly increased pore pressure resulting from injection is shown as the blue-shaded area in Fig. 3, essentially adjacent to the Wabash fault zone, where a series of moderate natural earthquakes occurred in the spring of 2008, the largest being M 5.2. Paleoseismic data indicate the occurrence of much larger nearby earthquakes (some greater than M ~7) in the recent geologic past (22). Importantly, the 100 million ton annual CO_2 injection rate used in the

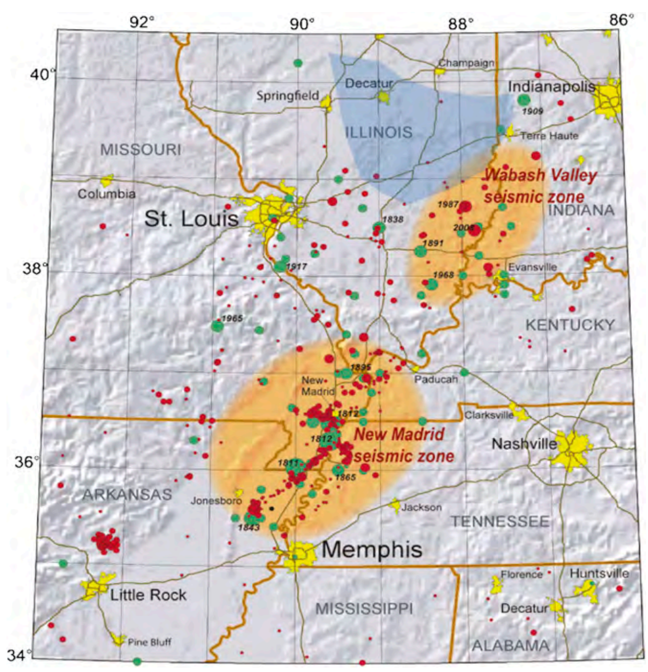


Fig. 3. Instrumentally recorded seismicity in the New Madrid and Wabash Valley seismic zones (modified from ref. 23). Red circles indicate earthquakes that occurred from 1974 to 2002 with magnitudes larger than 2.5 located using modern instruments. Green circles denote earthquakes that occurred before 1974. Larger earthquakes are represented by larger circles. The area shown in blue corresponds to the area where a pressure increase of several megapascals would result from injecting 100 million tons per year of CO_2 into the Mt. Simon sandstone in the Illinois Basin for 40 y (19).

modeling only represents approximately one seventh of the CO_2 generated by the coal-burning power plants in the Ohio River Valley alone.

Because of the need to carefully monitor CO_2 repositories with observation wells, geophysical and geochemical monitoring systems, etc., it is likely that most sites will have to be located on land or very near shore. Otherwise, highly porous reservoirs located offshore, like those adjacent to salt domes along the US Gulf Coast, would be relatively ideal sites because salt formations are known to be excellent seals for hydrocarbons.

Depleted oil and gas reservoirs are potentially suitable for CO_2 storage for a variety of reasons—an infrastructure of wells and pipelines exist, and there is a great deal of geologic and subsurface property data available to characterize the subsurface from decades of study. In addition, from an earthquake-triggering perspective, depleted reservoirs are attractive because at the time injection of CO_2 might start, the pore pressure would be below the value that existed before petroleum production. Thus, there could be significant injection of CO_2 before pressures increase to preproduction values, thereby reducing the potential for triggering earthquakes.

There are a number of potential issues to consider before using depleted oil and gas reservoirs for CO_2 storage, the most important of which are capacity and geographic distribution. The reasons that there is such interest in using saline aquifers for CO_2 storage is that they are potentially well distributed with respect to likely sources of CO_2, and they could presumably accommodate the enormous volumes of CO_2 that need to be stored. If one were only to consider the United States, storing the 2.1 billion tons of CO_2 currently generated annually by coal-burning power plants in depleted oil and gas reservoirs would require injection of CO_2 at a rate of approximately 17 billion barrels per year; a rate equivalent to eight times current US annual oil production and more than four times US peak annual oil production that occurred in the early 1970s. In addition, it is important to make sure that production-related activities, such as water flooding during secondary recovery, did not compromise the seal capacity of the reservoirs. There also needs to be careful study of the wells in the depleted oil or gas field to make sure that poorly cemented well casings, especially in older wells, will not be pathways for release of stored CO_2 (23). Finally, there are likely to be complicated legal questions concerning ownership and liability that will need to be worked out on a case-by-case basis.

Although enhanced oil recovery (EOR) using CO_2 (in which CO_2 is injected to dissolve in oil and reduce its viscosity) would be a beneficial use of CO_2, it is important not to confuse this with CCS. In CCS the goal is to inject large quantities of CO_2 into available pore space and store it there for hundreds to thousands of years. When CO_2 is used for EOR, the CO_2 dissolved in the oil is separated and captured from produced oil and then reinjected. Thus, smaller volumes of CO_2 are used, and the long-term storage capacity of the reservoir is not an issue.

Many CCS research projects are currently underway around the world. Much of this work involves characterization and testing of potential storage formations and includes a number of small-scale pilot injection projects. Because the storage capacity/pressure build-up issue is critical to assess the potential for triggered seismicity, small-scale pilot injection projects do not reflect how pressures are likely to change (increase) once full-scale injection is implemented. Moreover, even though limitations on pressure build-up are among the many factors that are evaluated when potential formations are considered as sequestration sites, this is usually done in the context of not allowing pressures to exceed the pressure at which hydraulic fractures would be initiated in the storage formation or caprock. In the context of a critically stressed crust, slip on preexisting, unidentified faults could trigger small- to moderate-sized earthquakes at pressures far below that at which hydraulic fractures would form.

As mentioned above, sequences of small to moderate earthquakes were apparently induced by injection of waste water near Guy, Arkansas, Trinidad, Colorado, and Youngstown, Ohio in 2011 and on the Dallas-Ft. Worth airport, Texas. Although these earthquakes were widely felt, they caused no injury, and only the Trinidad earthquake resulted in any significant damage. However, had similar earthquakes been triggered at sites where CO_2 was being injected, the impacts would have raised pressing and important questions: Had the seal been breached? Was it still safe to leave previously injected CO_2 in place?

In summary, multiple lines of evidence indicate that preexisting faults found in brittle rocks almost everywhere in the earth's crust are subject to failure, often in response to very small increases in pore pressure. In light of the risk posed to a CO_2 repository by even small- to moderate-sized earthquakes, formations suitable for large-scale injection of CO_2 must be carefully chosen. In addition to being well sealed by impermeable overlaying strata, they should also be weakly cemented (so as not to fail through brittle faulting) and porous, permeable, and laterally extensive to accommodate large volumes of CO_2 with minimal pressure increases. Thus, the issue is not whether CO_2 can be safely stored at a given site; the issue is whether the capacity exists for sufficient volumes of CO_2 to be stored geologically for it to have the desired beneficial effect on climate change. In this context, it must be recognized that large-scale CCS will be an extremely expensive and risky strategy for achieving significant reductions in greenhouse gas emissions.

ACKNOWLEDGMENTS. We thank Owen Hurd and Randi Walters for their help in preparation of the figures, and Mary Lou Zoback, Greg Beroza, Doug Arent, Sally Benson, Franklin Orr, John Bredehoeft, and Larry Goulder for their helpful comments.

1. Pacala S, Socolow R (2004) Stabilization wedges: Solving the climate problem for the next 50 years with current technologies. *Science* 305:968–972.
2. Snieder R, Young R (2009) Facing major challenges in carbon capture and sequestration. *GSA Today* 19:36–37.
3. Shaffer G (2010) Long-term effectiveness and consequences of carbon dioxide sequestration. *Nat Geosci* 3:464–467.
4. US Geological Survey (2011) Rectangular area earthquake search. Available at: http://earthquake.usgs.gov/earthquakes/eqarchives/epic/epic_rect.php. Accessed March 8, 2011.
5. Zoback ML, Zoback MD (1980) State of stress in the coterminous United States. *J Geophys Res* 85:6113–6156.
6. Zoback ML (1992) First- and second-order patterns of stress in the lithosphere: The world stress map project. *J Geophys Res* 97(B8):11,703–11,728.
7. Zoback MD, Townend J, Grollimund B (2002) Steady-state failure equilibrium and deformation of intraplate lithosphere. *Int Geol Rev* 44:383–401.
8. McGarr A, Simpson D, Seeber L (2002) Case histories of induced and triggered seismicity. *Int Handb Earthq Eng Seismol* 81A:647–661.
9. Healy JH, Rubey WW, Griggs DT, Raleigh CB (1968) The Denver earthquakes. *Science* 161:1301–1310.
10. Raleigh CB, Healy JH, Bredehoeft JD (1976) An experiment in earthquake control at rangely, colorado. *Science* 191:1230–1237.
11. Zoback MD (2012) Managing risk associated with earthquakes triggered by fluid injection. *Earth (Waukesha)* 38–43.
12. Townend J, Zoback MD (2008) How faulting keeps the crust strong. *Geology* 28:399–402.
13. Lucier AM, Zoback MD, Gupta N, Ramakrishnan TS (2006) Geomechanical aspects of CO_2 sequestration in a deep saline reservoir in the Ohio River Valley region. *Environ Geol* 13:85–103.
14. Chiaramonte L, Zoback MD, Friedmann J, Stamp V (2008) Seal integrity and feasibility of CO2 sequestration in the Teapot Dome EOR pilot: Geomechanical site characterization. *Environ Geol* 54:1667–1675.
15. Talwani P, Chen L, Gahalaut K (2007) Seismogenic permeability, k_s. *J Geophys Res* 112:B07309.
16. Stein S, Wysession M (2003) *An Introduction to Seismology, Earthquakes and Earth Structure* (Blackwell, Oxford).
17. Cappa F, Rutqvist J (2011) Impact of CO2 geological sequestration on the nucleation of seismic fault ruptures. *Am Rock Mechanics Assoc* 11:paper 471.
18. Chen Z, Narayan SP, Yang Z, Rahman SS (2000) An experimental investigation of hydraulic behaviour of fractures and joints in granitic rock. *Int J Rock Mech Min Sci* 37:1061–1071.

19. Chadwick RA, et al. (2004) Geological reservoir characterization of a CO_2 storage site: The Utsira Sand, Sleipner, northern North Sea. *Energy* 29:1371–1381.
20. Hagin P, Zoback MD (2004) Viscous deformation of unconsolidated sands—Part 1: Time-dependent deformation, frequency dispersion, and attenuation. *Geophysics* 69:731–741.
21. Zhou Q, Birkholzer JT, Mehnert E, Lin YF, Zhang K (2010) Modeling basin- and plume-scale processes of CO2 storage for full-scale deployment. *Ground Water* 48:494–514, 10.1111/j.1745-6584.2009.00657.x.
22. Pond EC, Martin JR (1997) Estimated magnitudes and accelerations of pre-historic earthquakes in the Wabash Valley region of the central United States. *Seismol Res Lett* 68:611–623.
23. Bohnhoff M, Zoback MD (2010) Oscillation of fluid-filled cracks triggered by degassing of CO_2 due to leakage along wellbores. *J Geophys Res* 115:B1130510.1029/2010JB000848.