California Air Resources Board

Workshop Comments

Carbon Neutrality: Scenarios for Deep Decarbonization

August 2019

Contents

Introduction to the Global Carbon Capture and Storage Institute

The Global Carbon Capture and Storage Institute (the Institute) is an international think tank, backed by governments, businesses and NGOs. Our mission is to accelerate the deployment of carbon capture and storage (CCS) within an energy transition that reduces emissions to net-zero by mid-century in an effort to prevent potentially dangerous climate change. The Institute is headquartered in Melbourne, Australia, with offices in Washington DC, London, Brussels, Beijing, Calgary, and Tokyo. The Institute is a specialist global organization with deep expertise in all aspects of CCS including capture technology, geological storage, policy, law and regulation, economics, and public engagement.

Structure of this submission

The Institute congratulates the Air Resources Board (ARB) on its recent amendment of the Low Carbon Fuel Standard (LCFS) with a CCS Protocol, as well as its efforts to understand the implications of meeting California's carbon neutrality goals. We welcome the opportunity to comment on the recent Public Workshop *Carbon Neutrality: Scenarios for Deep Decarbonization*. In this submission, the Institute has provided responses with regards to comments made during the workshop and seeks to provide general information on CCS to inform the decarbonization discussions.

Introduction

CCS is an essential suite of technologies for achieving climate change mitigation goals at the lowest possible cost. In the International Energy Agency's (IEA) Sustainable Development Scenario[1], in which Paris Agreement climate targets as well as all energy-related Sustainable Development Goals are met, CCS contributes 7% of cumulative emissions reductions to 2040. Roughly half of these reductions through CCS are expected to be delivered in the industrial sector, and half in the power sector. The scenario implies a scale-up of from roughly 35 million tonnes per annum (Mtpa) of CO_2 being captured today, to roughly 2300 Mtpa in 2040. The essential role of CCS in meeting climate targets has been emphasized by the International Energy Agency (IEA) Executive Director Fatih Birol, who said in November of 2018: "Without CCUS as part of the solution, reaching our climate goals is practically impossible"[2].

CCS technologies' role in climate mitigation was also confirmed by the Intergovernmental Panel on Climate Change's (IPCC) 2018 Report on 1.5°C, that noted: "…removing BECCS and CCS from the portfolio of available options significantly raises modelled mitigation costs"[3]. Note that BECCS can also be interpreted as representative of negative emissions technologies more broadly, such as direct air capture (DAC), which are expected to be crucial to reduce the stock of CO_2 already in the atmosphere.

CCS is the only feasible and currently available technology that can deliver deep emissions reductions in many industrial processes that are vital to the global economy, such as steel and cement. In its 2018 report[4], the Energy Transitions Commission argued that CCS will "have a crucial role to play in industrial decarbonization". Lord Nicholas Stern of the London School of Economics stated in 2018 that "More and more, people are seeing the practicality and importance in deploying the one technology proven to decarbonise 'difficult' sectors such as cement and steel and "locked-in" fossil fuel-based infrastructure" [5].

Carbon Capture in the California Context

CCS technologies are critical to California's ambitious carbon-neutrality goals. As noted by Melanie Kenderdine, Principal, Energy Futures Initiative (EFI), during the workshop, in EFI's analysis, CCS provides the largest emissions reductions potential considering California's 2030 goals, in both the industrial and electricity sector.

The Institute has welcomed California's ambition to achieve climate-neutrality and 100 per cent zero-carbon energy, along with ARB's decision to amend the LCFS with a CCS protocol, which can be regarded as an acknowledgement of the necessity of CCS to reach a carbon-neutral economy as well as the need to commercialize the technology in the near-term.

In general, CCS technologies will be relevant to California from two perspectives, addressing the stock-flow problem of CO_2 emissions in the atmosphere enabling a carbon-neutral economy.

1) **The CO_2 Flow Problem**
    - With existing infrastructure such as power plants, the industry, and internal combustion engine vehicles continuing to emit CO_2 into the atmosphere, CCS can help mitigate this flow of CO_2 by successfully capturing the CO_2 from power plants and industrial facilities, and storing it securely underground.
2) **The CO_2 Stock Problem**
    - A carbon-neutral economy implies full decarbonization. CCS can support negative emissions either through bio-energy carbon capture, or through direct air capture, enabling the ability to offset hard to abate sectors including the industrial sector, transport and most critically emission produced from agriculture.

The importance of CCS rises with climate ambition. For example, the IEA has shown that when moving from a 2°C scenario to a Beyond 2°C scenario – more aligned with 1.5°C scenario – CCS provides 32 per cent of additional emissions reduction[6]. This is due to the fact that for the time being, CCS is the only technology available to support the full decarbonization of cement and steel production. There are also sectors such as aviation which may never be able to be decarbonized, necessitating negative emissions.

California, thanks to aggressive clean energy deployment, has been able to reach a laudable level of decarbonization of the electricity sector which accounted for about 15 per cent of total emissions in 2017, after a year-on-year drop of 9 per cent. Nonetheless, the transportation and industrial sector emissions remained relatively stagnant, demonstrating the rigidity of these sectors, and emphasizing the need for stronger engagement, as well as a diversity of solutions[7].

California's industrial sector accounted for 21 per cent of emissions in 2017, and more than one-third of these emissions stem from refining and hydrogen production, in which CCS can contribute to reducing emissions. In addition, the cement sector, in which CCS is currently seen as a key technology to deeply decarbonize process emissions, accounts for 1.8 per cent of total emissions[8].

Furthermore, the application of CCS to gas-fired power plants can provide dispatchable generation capacity to complement the increased deployment of intermittent renewables while guaranteeing energy security and affordability. CCS coupled with natural gas steam-methane reforming (SMR) can also support the production of low emissions hydrogen for heat and transport.

California also possesses suitable geological CO_2 storage resources. Notwithstanding the State´s history of climate change legislation and the recent development of the CCS Protocol under the LCFS, however, California does not have CCS-specific laws and regulations of the type found in other states.

In 2017, California's total emissions amounted to 424 Million tonnes per annum (Mtpa). The scale of emissions reductions from CCS is often underestimated. A single CCS facility can deliver the large-scale, step-change emissions abatement necessary to rapidly reduce greenhouse gas emissions. Currently, there are 19 large-scale CCS facilities in operation globally. Twelve have an annual CO_2 capture capacity equal to or exceeding 1 Mtpa[9]. The largest, the Century Plant natural gas processing facility in Texas, has a capacity to capture 8.4 Million tonnes of CO_2 per annum. Appendix 1 contains a summary of commercial CCS facilities currently operating and Appendix 2 contains a summary of facilities under construction.

California is regarded as a global leader in developing innovative policy solutions to address climate. In many cases, it has inspired other states and even countries to follow its lead and replicate its policies. Its emissions profile is similar to that of other advanced economies[10], placing it in an ideal position to lead a group of climate ambitious countries and entities to higher-levels of decarbonization through developing and deploying new incentive structures and technologies. CCS is a deployment-ready technology and most models laying out pathways to a net-zero global economy anticipate the technologies' contribution to emissions reductions to commence over the next decade. CCS can support California's carbon-neutrality and decarbonization ambitions if its implementation aided by government support and market signals is supported in the near-term. As such, successful CCS deployment in California could bolster California's global climate leadership position.

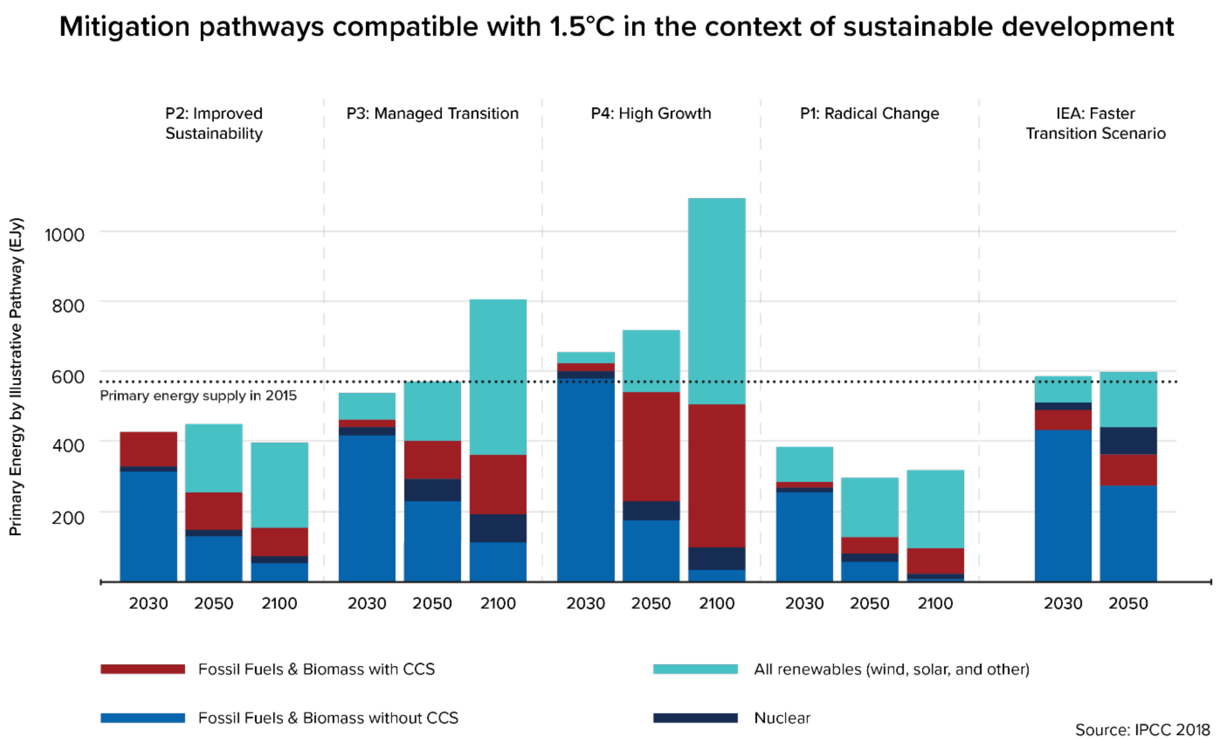
CCS in the IPCC special report on 1.5 degrees Celsius

The Institute welcomes the references to the IPCC special report on 1.5 degrees Celsius (°C) during the workshop. This authoritative report, and the detailed analysis that underpins it, demonstrates that there are a range of possible futures which all achieve a 1.5°C outcome. The IPCC presents four "Illustrative Pathways" to represent that range of futures.

CCS was acknowledged in three of the four illustrative pathways IPCC authors used to reach 1.5°C and was singled out for its ability to: "play 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."[3] Specifically:

- Three of the four pathways require very significant deployment of CCS to meet abatement requirements.
- The pathway that includes no CCS requires the most radical changes in human behavior, consumption and lifestyle.
- The pathway that requires the most CCS relies to the greatest extent on technological solutions to deliver abatement and relatively minimal changes to patterns of behavior, lifestyle and consumption.

It is reasonable to assume that the actual, optimal, pathway towards deep decarbonization lies somewhere between these two extremes and that CCS is expected to play a significant role in meeting emission targets. An illustrative comparison of pathways can be found below. That is certainly the conclusion one would draw from the many previous authoritative studies by the IPCC, IEA, the UK Committee on Climate Change, and the Energy Transitions Commission. Moreover, the IPCC's report which contributed to revised climate ambitions has also inspired a renewed discussion about CCS technologies globally. It is also worth noting that nine of 12 long-term strategies submitted to the UNFCCC following the Paris Agreement mention CCS, signaling the acknowledgment that CCS is needed to deliver emissions reductions within the energy and industrial transition[11].



California, the world's fifth largest economy, represents a microcosm of the global economy examined in these studies and there is every reason to believe that their conclusions will also generally apply to California. Most importantly, California, as one of the most climate ambitious entities in the world and an economic powerhouse open to innovation, is in an optimal position to demonstrate the IPCC's recommendations can be turned into policy and incentive structures; enabling an inclusive and all-of-the-above approach to decarbonizing the entire economy in the most cost effective way.

CCS technologies are proven and working today

CCS technologies are a proven emissions reduction solution, they are working around the world, are ready to deploy at large-scale and are vital to achieving climate targets. The world's 19 large-scale facilities are already capturing almost 35 Mtpa of CO_2, and a total of over 230 Mt of CO_2 has been safely injected underground to date[5]. A further four large scale CCS facilities are in construction and at least another 20 in planning.

CCS has the distinct advantage of being applicable to a broad range of industrial sources of carbon dioxide. For example, it is capturing and storing CO_2 emissions at commercial scale from:

- Biofuel production, hydrogen production, fertilizer production, coal power generation, natural gas processing and petcoke gasification in the USA
- Hydrogen production and coal power generation in Canada
- Natural gas processing in China
- Natural gas processing in Europe
- Natural gas processing in Australia
- Steel production and natural gas processing in the Middle East

This versatility of application has led to progressive countries such as the Netherlands, Norway, and the UK undertaking 'hub and cluster' studies where CCS is deployed across a number of emissions intense industries in a region, and economies of scale arising from this co-location reduce the cost of abatement. California also possesses multiple industrial clusters that are located near potential CO_2 storage sites[12]. It is notable that California leads the global deployment of hydrogen-fueled vehicles and provides a progressive framework for deploying hydrogen as the clean energy vector of the future[13].

CCS Cost

It is often argued, and was also put forward during the workshop, that CCS is *expensive*. It was also mentioned that CCS will make the transition to a carbon neutral economy more expensive. This statement is simply incorrect. There are several problems with a broad statement that CCS is *expensive*:

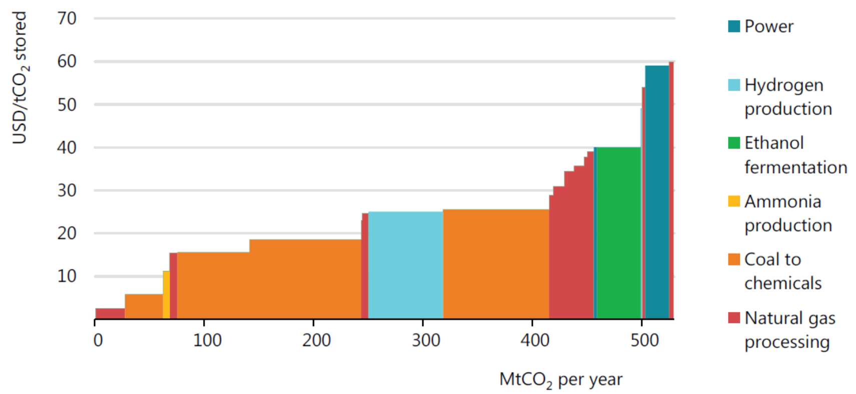
- **The Intergovernmental Panel on Climate Change (IPCC) has estimated that total decarbonization cost could more than double if CCS is not deployed at scale[14].** The IEA released an analysis recently that investigates a limited CO_2 storage scenario (LCS) which results in 80% less carbon captured than in a climate scenario consistent with the Paris Agreement, also known as Clean Technology Scenario (CTS). The study was developed to better understand the value of CCS in climate portfolios and shows that the LCS would result in higher costs and significantly higher electricity demand, which bears full decarbonization challenges on its own. It follows, that limiting the availability of CO2 storage would result in the marginal abatement costs for the industrial sector doubling in 2060 relative to the CTS, from around \$250 t/CO_2 to \$500 t/CO_2, due to increased reliance on more expensive and nascent technology options. In the power sector, the marginal abatement costs in 2060 would increase from around \$250 t/CO2 in the CTS to \$450 t/CO2. The study also concludes that "beyond 2060, continued constraints on CO_2 storage are unlikely to be consistent with climate goals given the role of CO_2 storage in carbon removal and negative emissions."[15]

- **CCS is criticized as being high cost compared to other clean energy technologies because the comparison uses the levelized cost of electricity (LCOE) as its measure.** This is an incomplete and inaccurate comparison. LCOE comparisons only address the cost of generation, which means what it costs to produce electricity from a specific resource. What matters most is the total cost of delivered electricity which includes transmission, distribution, system reliability, and resilience. LCOE fails to reflect values provided by different sources of energy such as ancillary services and capacity, which will become more valuable with the increasing penetration of intermittent sources. To illustrate, in 2015 Australian generation costs comprised only 28 per of the total cost of a typical eastern Australia Electricity System (the National Electricity Market) electricity bill. Hence, it follows that LCOE does not include the full system costs notably the remaining 72 per cent of electricity costs. Studies taking these aspects into account have shown that in the electricity sector, a portfolio including firm low-carbon resources such as nuclear and natural gas with CCS can reduce system cost between 10 and 62 per cent[16].
- **The cost of CCS depends on the purity of the CO_2 waste stream of the respective CCS facility**, which is lower for those plants that emit pure streams of CO_2, such as for example ethanol plants, where break even capture costs are around \$15/tCO_2[17]. Other cost drivers include:
    - the distance to and quality of the storage reservoir;
    - the cost of capital and labor in the location where the plant is being constructed.
- **The familiar process of cost reductions with increasing deployment that is observed in all technologies is also being observed in CCS**. In a recent paper[18], the Institute assumed a learning rate[*] of 15 per cent, an estimate consistent with other clean energy technologies, which means that cost would halve with large-scale deployment. One current example is the Allam cycle which has been proven at the 30MW (electrical output) scale and is about to be scaled up to 300MW by 2022 and seeks to become competitive with conventional combined cycle plants. Industries where the addition of CCS adds relatively higher incremental costs, such as power, steel and cement, are also industries in which capture techniques and technologies are developing. For these industries, the potential future cost reductions are likely to be relatively larger. For example, data from the United States demonstrates that the deployment of technologies still in development can reduce the cost of applying CCS by up to approximately 30 per cent in the power sector, 17 per cent in iron and steel, and 16 per cent in cement production[19].

[*] The percentage by which the cost reduce every time the number of facilities doubles.

- **A value on greenhouse gas (GHG) emissions reflecting the externalities of pollution provides a business case for CCS.** There are different ways to provide such a value on carbon. The International Energy Agency argues that as much as 450 Mt of CO_2 could be captured, utilized and storage globally with a commercial incentive as low as US$40 per tonne of CO_2[20]. Next to California's LCFS, the federal 45Q tax credit, which can be stacked with the LCFS, provides such value on carbon for CCS. Under the current arrangements, 45Q provides tax credits worth $18/t$CO_2$ for CO2 used for EOR and $29/t$CO_2$ for CO_2 stored through dedicated geological storage, rising linearly to $35/t$CO_2$ and $50/t$CO_2$ by 2026 respectively.

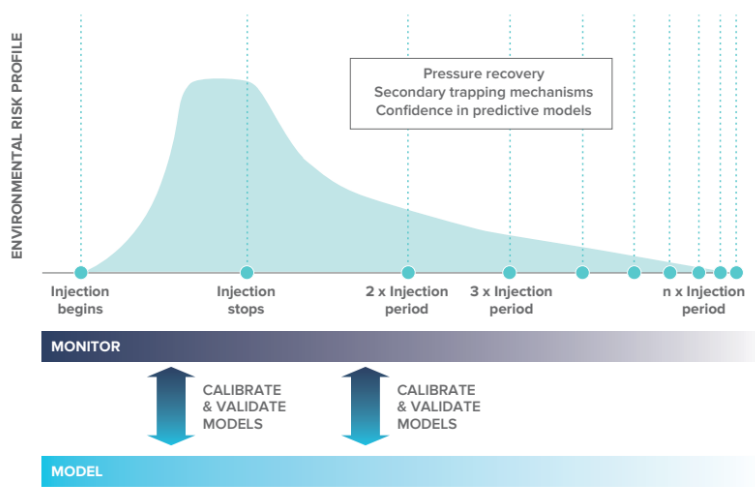
Figure 39. Break-even costs for CO_2 capture and storage by application



Source: IEA (2019). All rights reserved.

Safety of CCS

Figure 1: Life-cycle risk profile for CO_2 Storage[1]



[1] Model reproduced from Benson, S., Carbon Capture and Storage: Research Pathways, Progress and Potential, GCEP Annual Symposium, Stanford University, 2007.

CCS is a mature technology, that has been in use for more than 45 years. This provides a long history of successful CO_2 capture, transport and storage, while the understanding of CO2 permanence, storage site performance and monitoring technologies have evolved over time. Advances in the development of law and regulation, as well as project-level experience, has resulted in significant improvements in the characterization and quantification of risks associated with CCS[21]. The IPCC in a Special Report argues that[22] "observations from engineered and natural analogues as well as models suggest that the fraction retained in appropriately selected and managed geological reservoirs is very likely to exceed 99% over 100 years and is likely to exceed 99% over 1,000 years."

CCS and other carbon dioxide removal options

Throughout the workshop the need for negative emissions was mentioned. As referenced above, it is anticipated that negative emissions technologies will be needed to reduce the stock of CO_2 in the atmosphere. The different pathways to achieving a 1.5°C outcome, and the role of negative emissions technologies, are presented within the Interim Report and detailed in Box 5.2. The following quote is taken from page 51-52:

> *"Options for removing carbon dioxide from the atmosphere include large-scale afforestation and reforestation, bioenergy with CCS, enhancing natural weathering of silicates or carbonates, and direct air capture machines. Most are at very early stages of development, and many are not currently considered to be economically viable."*

Carbon dioxide removal options such as bioenergy with carbon capture and storage (BECCS) and direct air capture (DAC) technologies are proven emissions reductions solutions. While BECCS has been deployed at scale, DAC has proven to work at a smaller scale.

The individual technologies to utilize biomass to produce energy or fuel, as well as the capture, transport and storage of CO_2, are all mature and active in commercial facilities around the world using a variety of feedstocks for the production of ethanol, biodiesel, methane and other products[23]. Currently, five facilities around the world are actively using BECCS technologies and are collectively capturing approximately 1.5 Mtpa of CO_2 [23].

The largest, the Illinois Industrial CCS facility, captures up to 1 Mtpa of CO_2. This facility produces ethanol from corn at its Decatur plant, producing CO_2 as part of the fermentation process. The CO_2 is stored in a dedicated geological storage site deep underneath the facility. The remaining four BECCS facilities operating today are small-scale ethanol production plants, using most of the CO_2 for enhanced oil recovery (EOR). Additional projects are currently in the planning stages in Japan, the UK and Norway[23].

There are three notable DAC facilities in operation: Zurich based Climeworks; Canadian-based Carbon Engineering (CE) maintains that DAC technology can be built to capture one million tonnes of CO_2 per year and potentially achieve costs of $100-150 per ton of CO_2 and; New York based Global Thermostat whose technology allows the capture of CO_2 in conjunction with heavy industrial processes such as metal smelting, cement production, and petrochemical refining.

Globally unique and extremely forward-looking, California's LCFS[24] creates a significant financial incentive for the deployment of direct air capture (DAC) anywhere in the world, as well as ethanol facilities which have reduced their lifecycle emissions with CCS and contribute to emissions reductions in the California fuels market.

CCS technologies and the opportunities for emissions reduction

Authoritative analyses of pathways to climate stabilization by the IPCC, IEA and others (as previously noted), all identify the need for a broad portfolio of technologies, including CCS, to deliver emissions reductions at lowest cost, as referenced above.

There is no doubt that technological advances will present opportunities for lower cost abatement in the future. However, we cannot delay action to significantly reduce emissions in the hope of new technologies emerging. While California is on a promising path, delivering additional emissions reductions will become more difficult, and to achieve a carbon-neutral economy, a fundamental transformation needs to happen. Along these lines, the Institute welcomes California's efforts to amend the LCFS with a CCS protocol, as this is a very timely action. Nonetheless, the focus must now continue to support developing an enabling policy framework, as well as working with industry on near-term implementation. 45Q, while pending implementation, is seen as the most progressive CCS-specific incentive globally and provides a supportive tool to accelerate the deployment of carbon capture technologies in California.

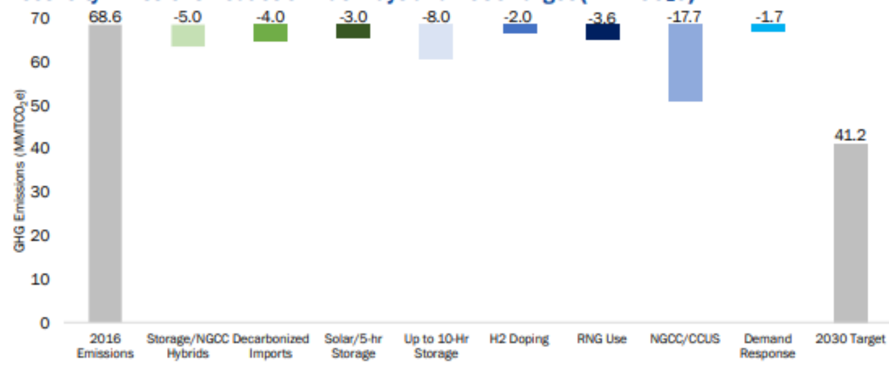
Driving the rapid change needed to reach net-zero will require very large investments from the private sector. This investment will only be available, and flow, to proven technologies. There is always a lag between technological development and deployment at large industrial scale, requiring large capital investments, as operators and investors become confident in the technology and are prepared to accept the additional risk associated with being a first mover in return for the expected benefits of better performance/lower cost etc. Therefore, the time between the development of a new large industrial technology and it achieving significant market share may be measured in decades – time that California, and the world, does not have. This is why we need to deploy proven CCS technologies that have been operating at commercial scale for decades, now.

Suggested priorities for deploying CCS vis-à-vis California's decarbonization goals

Electricity supply

While CCS is not regarded as necessary for reaching deep decarbonization levels in the electricity sector in California, there is large potential for CCS to deliver significant emissions reductions throughout California's electricity supply in harmony with renewables and energy efficiency. In addition, it is important to point out that CCS should not be seen as competing with other sources of clean energy, but can complement other clean energy technologies to enable higher levels of decarbonization in the most cost-efficient manner. Currently about 15 per cent of California's emissions stem from electricity generation, and California has demonstrated a successful timeline of decarbonization of the sector. Aided by the federal 45Q tax credit, CCS on natural gas facilities can contribute to optionality and flexibility, and the availability of low-carbon resources can limit cost, as pointed out above. In fact, the EFI, as discussed during the workshop, showed in a recent report that CCS holds the largest emissions reductions potential with regards to the 2030 emissions target. However, while CCS has been demonstrated on two coal facilities, it has yet to be applied to a natural gas power plant as a retrofit. California could become home to the first natural gas retrofit, providing an important milestone on the path to full decarbonization of the natural gas sector and emerging as a world leader. Nonetheless, at this point it needs to be emphasized that urgency is necessary vis-à-vis increasing pressure to decarbonize and deploy CCS at scale. Plants also need to commence construction by 2024 to become eligible for the 45Q tax credit.

Figure 2-46
Electricity Emissions Reduction Pathways and 2030 Target ($MMTCO_2e$)



Emissions reductions from eight decarbonization pathways could enable the Electricity sector to exceed a 40 percent reduction from 2016 levels by 2030. Source: EFI, 2019.

Industry

There are limited to no alternatives to CCS for full decarbonization of certain industrial processes. California's industrial sector accounts for 21 per cent of total emissions and has reduced its overall emissions only by 8.2 per cent since 2000. More than 65 per cent of California's industrial sector CO_2 emissions stems from natural gas processing, cement production, refining, as well as hydrogen production – sectors amenable to CCS deployment, some of which even at low cost. Ten of the 19 large-scale CCS facilities in operation are actually in natural gas processing, while the Norwegian government, as well as the EU, are supporting the development CCS projects in the cement sector, which also accounts for around eight per cent of global emissions. California is the second-largest cement producing state in the US after Texas, and cement production is anticipated to increase. In 2017, cement production accounted for 1.8 per cent of total emission alone. A recent report estimated that California's nine cement plants produced about 7.9 Mt of CO_2 in 2015, though 59% of emissions are process-related emissions, stating that energy efficiency and fuel switching are unable to deliver decarbonization on its own. "Clinker substitution and CCUS are a must in order to achieve near zero emissions in cement production[25]". A value on carbon that covers the industrial sector, in addition to 45Q and those processes not covered by the LCFS, could support technology deployment. One option would be to attach the CCS protocol to California's cap-and-trade market. Another could be developing demand side policies that specify procurement lifecycle emissions caps for industrial products.

Transport

Approximately 40 per cent of California's emissions come from the transport sector. Deep emission reductions in the transport sector are available through a shift from conventional fossil fueled vehicles to a mix of plug-in electric vehicles, hydrogen fuel cell vehicles, and biofuel. Plug in electric vehicles will increase demand for low emission electricity. CCS on power generation and biofuel production can help meet that demand.

Air pollution also remains a significant challenge in California adversely affecting communities. BEVs, FCEVs and hydrogen fuel cell vehicles have no exhaust emissions and hence have no adverse effects on air pollution.

Hydrogen

California is already a leader in hydrogen, and governments should support the clean production of hydrogen from gas with CCS and electrolysis with renewables. The LCFS already provides incentives for hydrogen production with CCS, while also supporting the roll-out of hydrogen-fueling capacity – thus eliminating one of the barriers to adoption. The LCFS also interacts with other policies such as the Zero Emissions Vehicle mandate, the cap-and-trade system, and infrastructure funding as well as tax credits. Thanks to some of these policies, California has helped the US become the world leader in hydrogen fuel cell vehicle deployment. Beyond decarbonizing the transportation sector, clean hydrogen can be used for:

- Domestic heating by replacing methane in reticulated gas (note: greater than 5-10 per cent hydrogen requires conversion of appliances)
- To generate electricity; providing dispatchable, near zero-emissions power (H2 turbine or fuel cells)
- The establishment of a sustainable new energy economy for the State.

Commercial scale clean hydrogen production from fossil fuels with CCS

Hydrogen production from fossil fuels with CCS is the lowest cost source of clean hydrogen and is operating at full commercial scale today (e.g. the Quest Hydrogen production facility with CCS, see Appendix 1). In fact, 98 per cent of hydrogen globally is produced from fossil fuels, producing as many emissions as the UK and Indonesia combined[26]. Only two per cent is being produced from electrolysis.

For hydrogen to make a meaningful contribution to global greenhouse gas emission reductions, it will need to be produced – in a low-carbon manner – in very large quantities to displace a significant proportion of current fossil fuel demand. The Australian Government estimates global hydrogen demand at 530 million tonnes per annum (Mtpa) by 2050, up from roughly 70 mtpa today.

Industrial scale production of hydrogen with CCS has been proved at scale. The necessary inputs (natural gas, pore space for CO_2 storage) are plentiful, and the technology is proven at large scale to be the lowest cost source of clean hydrogen. Today there are four facilities in operation and two under construction, that produce clean hydrogen from fossil fuels with CCS at large scale (200 to 1,300 tonnes hydrogen/day) utilizing local resources:

- Great Plains Synfuel Plant in North Dakota, United States, commenced operation in 2000, produces approximately 1,300 tonnes of hydrogen per day in the form of hydrogen rich syngas from brown coal gasification with CCS[27]

- Air Products Steam Methane Reformer for Valero Refinery with CCS in Texas, United States, commenced operation in 2013, produces approximately 500 tonnes of hydrogen per day from natural gas reforming with CCS[28]
- Coffeyville Gasification Plant in Kansas, United States, commenced operation in 2013, produces approximately 200 tonnes of hydrogen per day from petroleum coke gasification with CCS[29]
- Quest CCS in Alberta, Canada, commenced operation in 2015, produces approximately 900 tonnes of hydrogen per day from natural gas reforming with CCS[30]
- Alberta Carbon Trunk Line (ACTL)[9] in Alberta, Canada, is in construction. ACTL will enable clean hydrogen production in two projects, the Alberta Sturgeon Refinery, producing more than 240 tonnes of hydrogen per day via asphaltene residue gasification with CCS and Agrium fertiliser, producing more than 800 tonnes of hydrogen per day via natural gas reforming with CCS.

Hydrogen for domestic use in California

In California, clean hydrogen could be used in domestic heating (and possibly cooling) by replacing methane in reticulated gas. Reducing the emissions intensity of reticulated natural gas supply is a significant, immediate and low-cost opportunity. In California 90 per cent of commercial and residential emissions, which account for almost ten per cent of total emissions, stem from natural gas use[31]. Where suitable, hydrogen could be co-blended with natural gas, which between five per cent and ten per cent blending does not require infrastructure upgrades. This would deliver commensurate emission reductions. Over time, the gas network and end-user appliances can be modified to accept 100 per cent hydrogen, completely decarbonizing domestic heating.

The potential of hydrogen for domestic heating utilizing existing gas reticulation infrastructure has been demonstrated by the UK city of Leeds in a 2016 detailed economic and technical feasibility study[32]. The study confirmed the opportunity to decarbonize domestic heating with hydrogen by converting the existing natural gas network with minimal new energy infrastructure required.

CASE STUDIES: HyNet and H21 facilities in the UK: Examples of CCS equipped hydrogen production facilities

The HyNet North West project is a CCUS-equipped hydrogen production and distribution network developed by the UK gas distribution company Cadent together with Progressive Energy and ENI. The facility will produce hydrogen from natural gas that will then be supplied to industrial sites, to households for heat supply and serve as transport fuel. The project has the potential to serve more than 2 million homes and businesses.

The H21 North of England project aims to decarbonize power, heat and transport across the North of England. It will convert the UK gas grid from natural gas to CCS decarbonized hydrogen, converting 3.7 million-meter points across Leeds, Bradford, Manchester, Liverpool, Hull, York, Teesside and Newcastle. The clean hydrogen will be produced from large-scale production plants with 12.15 GW capacity, with integrated CO_2 capture processes to capture up to 20 Mtpa CO_2 by 2035 in several phases. CO_2 storage is planned to be in saline aquifers and depleted gas fields in the Southern North Sea, which can potentially facilitate the advantages of the UK's growing CCS capacity and a CCS trade with Europe.

These facilities are exemplary for Victoria, as the HESC project can also be similarly instrumental in decarbonising the power, heat and transport sectors across Victoria.

Geologic Storage

California has significant CO_2 storage resources ranging from 33 billion tonnes of CO_2 with high confidence, and 423 billion tonnes of CO_2 with low-confidence. The vast majority of this storage resource would be hosted in saline formations, however between three and six billion tonnes of CO_2 can be stored in depleted oil and gas fields[33]. Suitable potential storage basins are close (50-150 mi), and in places, adjacent to large (1 million tonnes per annum) industrial facilities. Based on current knowledge, estimates predict that storage basins could hold more than 300 years of California's current emissions.

Policies needed to drive CCS deployment

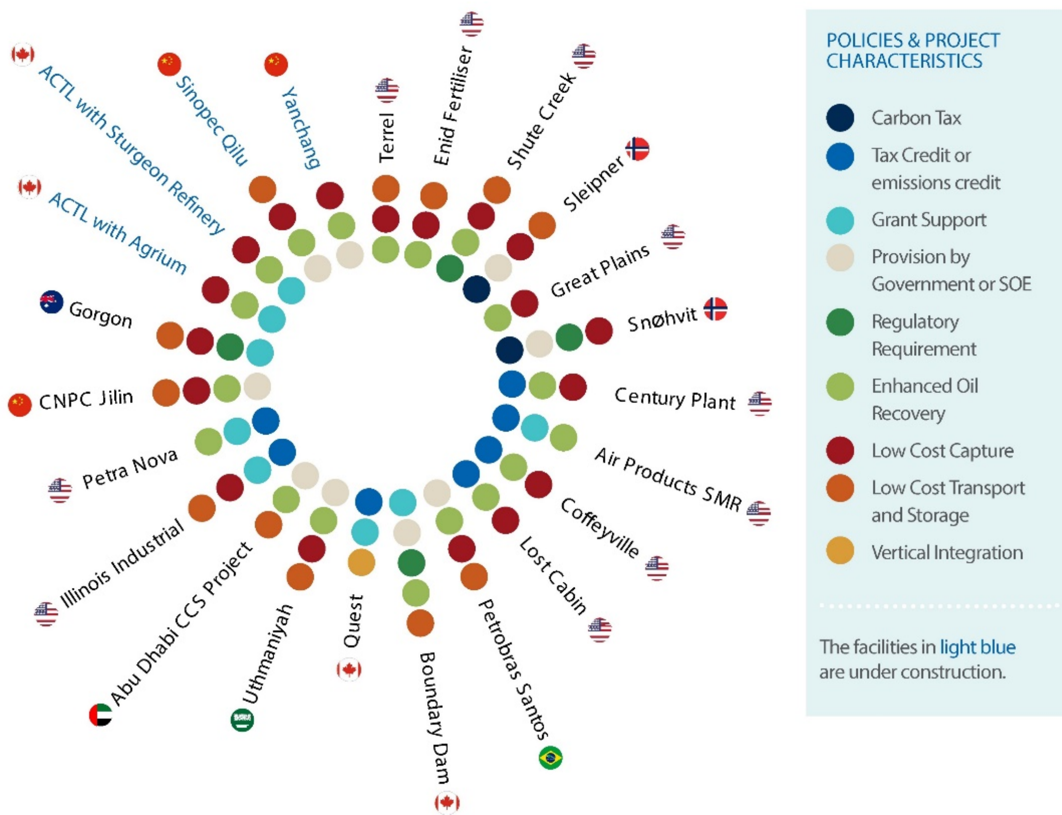
Government alone cannot solve the challenge of climate change. The solutions will be developed, commercialized and deployed by the private sector which has enormous resources and capabilities. Government policy should create incentives for large private sector investments in climate solutions. In summary, government policy should align private and public good investment incentives to drive capital towards delivering emissions abatement. Some examples of policies that have been developed recently, are listed below, and include California's LCFS.

Policy Framework

Analyzing the 23 large-scale operating and under construction CCS facilities[34], particularly their incentive and capital structures, alongside other enabling mechanisms provides a policy priorities framework to enable the commercialization of the technology.

1. A value on carbon

A value on carbon provides a clear price signal and incentive to reduce emissions along with the notion that governments are committed to moving to a lower-carbon world. 22 of 23 facilities were built in an environment that provided some value on carbon, either reflecting the externalities created by pollution through an emissions credit, a carbon tax or a tax credit, or its value to oil producers for enhanced oil recovery (EOR). For example, two projects in Norway were built as the result of a carbon tax on offshore natural gas production. Australia's Gorgon project, which is the largest geologic project globally, was solely a result of a regulatory requirement.



2. A framework enabling investment

Most CCS projects have been enabled through high proportions of grant funding, with little to no debt financing. To deploy CCS at scale, private sector investment must increase with banks providing debt financing at feasible interest rates. Currently project risks are perceived by banks as too high, and the cost of capital has a substantial implication for the sanction of CCS projects. As the number of CCS facilities increase debt finance will become available for CCS projects, thereby reducing the cost of capital. However, in the meantime, governments have an important role by providing further grant funding, accelerated depreciation, concessional loans, loan guarantees and other mechanisms to attract private capital. Such instruments rewards early investments for the knowledge first-movers create that is available to future project developers. Government investment in public goods such as clean air is important, even if these investments do not generate a financial but a societal return.

3. Infrastructure Access and Storage

Most projects that have been successfully started so far had access to well-developed and characterized storage sites and had low-cost options to build and access CO_2 transportation and storage. It is therefore an imperative for countries to map and understand their CO2 storage capacity, and aid the private-sector in the identification of suitable sites.

Policy Examples: A value on carbon

The introduction of credits in the US have provided an incentive for the geological storage of CO_2. This has been widely recognized as an important enabler of the six large-scale facilities in the US that have come on stream since 2011, including some in higher cost capture sectors such as coal fired power generation e.g. Petra Nova (see Appendix 1). Tax credits have the benefit of being well established in the context of climate change mitigation in the region, having been used to drive significant investment in renewables over the past two decades. Two of the most notable examples, from the United States, are:

"45Q" Tax Credit

This tax credit, known as 45Q in reference to the relevant section of US tax code, was extended and increased in February 2018. Under the current arrangements, 45Q provides tax credits worth \$18/tCO_2 for CO_2 used for EOR and \$29/tCO_2 for CO_2 stored through dedicated geological storage, rising linearly to \$35/tCO_2 and \$50/tCO_2 by 2026 respectively.

The credits can be used to reduce a company's tax liability or, if they have no tax liability, transferred to the company that disposes of the CO_2 or traded on the tax equity market.

Low Carbon Fuel Standard

California's Low Carbon Fuel Standard (LCFS) places lifecycle carbon intensity targets on all transportation fuels sold in California, with the aim of diversifying the State's fuel mix, reducing petroleum dependency, and reducing GHG emissions and other air pollutants. Fuels that have a lower carbon intensity than the carbon intensity target generate credits and fuels with a higher carbon intensity than the target generate deficits.

In 2018, the LCFS was amended to enable CCS projects that reduce emissions associated with the production of transport fuels sold in California, and projects that directly capture CO_2 from the air, to generate LCFS credits. These changes came into effect in January 2019. To qualify, projects need to meet the requirements of the CCS Protocol which is subordinate to the LCFS Regulation Order. The changes have attracted attention from policymakers in other jurisdictions and CCS project developers keen to understand the program, particularly given the credits have been trading on average between \$122/tCO_2 and \$190/tCO_2 in the past 12 months to February 2019[24].

Carbon Pricing

An alternative approach to placing a value on emissions reduction would be to introduce a cost for emitting. A carbon tax introduced in Norway in 1991 has been successful in incentivizing the development of the Sleipner and Snøhvit CCS projects. At \$17/tCO_2, the cost of injecting and storing CO_2 for the Sleipner project was much less than the \$50/tCO_2 tax penalty at the time for CO_2 vented to the atmosphere[35]. This was complemented by a commercial need to separate the CO_2 from natural gas to meet market requirements and provided a clear business case to invest in CCS. The current level of the tax is higher than the level when it was introduced, making the business case for CCS at Sleipner even stronger[36]. There are several cap-and-trade markets that currently recognize CCS such as for example the European Emissions Trading System. Including CCS in California's carbon market could cover more sectors amenable to CCS and provide an additional value on carbon.

Procurement Standards

Procurement standards and commitments have successfully contributed to the deployment of renewable energy. However, there is significant room to expand these types of policies to zero-carbon electricity, as well as aiming to encourage the procurement of products including cement and steel with the smallest lifecycle CO_2 emissions. The Buy Clean California Act which was enacted in 2018, establishes carbon intensity procurement standards for state infrastructure projects. Structural steel is an example of a material that is covered.

Policy Examples: A framework enabling investment and infrastructure

Capital Support

In the early stages of deployment, capital support from government is likely to be necessary to mobilize private capital in the majority of cases. This strategy has been very effective in accelerating the global deployment of renewables. Capital support may take the form of grants, tax credits, concessional loans, or accelerated depreciation on CCS assets. Direct equity investment in CCS facilities is another option that may be considered by government. Over time, as the value (explicit or implicit) on CO_2 increases, and the cost of CCS decreases, the requirement for capital support will reduce until the business case for investment in CCS is created by normal market forces. Until that time, to deliver the public good of a stable climate, government can enable private investment in CCS by providing capital support where required. This has proven effective for commercial scale facilities in the North America which have typically received capital grants of around \$200 million each.

Regulation of emissions

Regulation has also played a role in supporting the deployment of CCS by placing an implicit value on emissions. For example, a mandatory condition for the approval of the Gorgon project in Australia was the capture of CO_2 released by the gas processing operations.

Launched recently, the project is the world's largest dedicated geological CO_2 storage facility with the ability to store up to 4 Mtpa of CO_2[37]. The expectation of a future tax on carbon has also been raised as a reason for CCS being adopted for the Gorgon project. This highlights an important point, that it is not just current policies but also expected future policies that determine an investor's decision to support a CCS project.

State ownership of CCS facilities

Some governments have overcome the barriers to private sector investment by supporting the construction of CCS facilities through State Owned Enterprises (SOEs). Stable governments can borrow at very low interest rates, helping to bring down the effective cost of capital of projects. Some elements of CCS also lend themselves well to state ownership due to their natural monopoly characteristics, such as the development of carbon dioxide transport and storage infrastructure.

For example, government could make the initial investment establishing transport and storage infrastructure for an anchor customer and then expand the network to service growing demand. This hub would attract further investment from other emissions intense industries seeking to establish operations in precincts that offer carbon dioxide storage services. In this way, Government can kickstart a hub and cluster development with the option of privatizing the business after it has recruited sufficient customers (CO_2 emitters requiring CO_2 transport and storage services) to deliver sound financial performance.

Initial government investment could represent any level of equity up to 100 per cent. The determining factor should be the minimum public sector investment necessary to establish and operate the infrastructure. This model of government making the initial investment in infrastructure followed by later privatization is proven in other sectors such as road and rail transport, power generation and transmission and telecommunication.

Role of government in CCS investment

In the context of government's role in providing for the public good, and the definition of a stable climate as a public good, government support of CCS and other climate mitigation technologies is justified. It also introduces the concept of government support being an investment which delivers returns in the form of public goods, rather than financial profits. This is an important concept with respect to opportunities for government to attract private sector investments in CCS by taking on certain costs and risks during the early stages of deployment.

Another important concept to recognize is that government alone will not solve the challenge of climate change. The solutions (and there are many) will be developed, commercialized and deployed by the private sector which has enormous resources and capabilities. All that is required are the incentives to mobilize private capital, and the creation of those incentives is entirely within purview of government.

Barriers to deploying CCS in California

The greatest barriers to the deployment of CCS as an essential emissions reduction solution in California is the lack of business case, and the policies required to support such a business case. The Institute welcomes the LCFS as a step in the right direction to incentivize carbon capture projects in the US and globally.

The scaling up of CCS deployment will only be achieved if there is a clear commercial case to invest in CCS. Governments have a pivotal role to play, by providing a clear, stable and supportive policy framework. While the policy landscape has improved in recent years, there remain gaps that are holding back investment in CCS, and therefore preventing the achievement of global climate targets.

Investments in large-scale CCS facilities around the world have predominantly relied on supportive policies, revenue from enhanced oil recovery and low-cost capture, transport and storage opportunities. This coincidence of circumstances has enabled a positive financial investment decision on 23 large scale facilities to date which has proven the technology over almost five decades of operational experience[38].

However, for CCS to be deployed at the rate required to meet emissions reductions targets, governments must implement policy frameworks that align private and public good investment incentives to drive private capital into CCS at a much greater scale.

Policy must not only support the business case for investment in CCS, it must win the confidence of investors, because once policy confidence is in place, long-term capital investments can be made and the virtuous cycle of investment and cost reduction will accelerate.

Conclusion

The Institute welcomes California's climate ambition and leadership, as well as efforts to engage and understand scenarios and decarbonization pathways. First steps to accelerate the deployment of CCS technologies have been taken with California's LCFS protocol, but the initiative should now be expanded to support CCS deployment in other sectors, particularly industry, through targeted measures providing further policy confidence. The Institute sees significant potential for California to affirm its position as a global leader on climate action and the development and deployment of CCS technologies alike.

Appendix 1: Large scale CCS Facilities in operation

Title	Country	Operation Date	Industry	Capture Capacity	Capture Type	Storage Type
Terrell Natural Gas Processing Plant (formerly Val Verde Natural Gas Plants)	United States	1972	Natural Gas Processing	0.4 – 0.5	Industrial separation	Enhanced Oil Recovery
Enid Fertilizer	United States	1982	Fertiliser Production	0.7	Industrial separation	Enhanced Oil Recovery
Shute Creek Gas Processing Plant	United States	1986	Natural Gas Processing	7.0	Industrial separation	Enhanced Oil Recovery
Sleipner CO2 Storage	Norway	1996	Natural Gas Processing	1.0	Industrial separation	Dedicated Geological Storage
Great Plains Synfuels Plant and Weyburn-Midale	Canada	2000	Synthetic Natural Gas	3.0	Industrial separation	Enhanced Oil Recovery
Snøhvit CO2 Storage	Norway	2008	Natural Gas Processing	0.7	Industrial separation	Dedicated Geological Storage
Century Plant	United States	2010	Natural Gas Processing	8.4	Industrial separation	Enhanced Oil Recovery
Coffeyville Gasification Plant	United States	2013	Fertiliser Production	1.0	Industrial separation	Enhanced Oil Recovery
Air Products Steam Methane Reformer	United States	2013	Hydrogen Production	1.0	Industrial separation	Enhanced Oil Recovery
Lost Cabin Gas Plant	United States	2013	Natural Gas Processing	0.9	Industrial separation	Enhanced Oil Recovery
Petrobras Santos Basin Pre-Salt Oil Field CCS	Brazil	2013	Natural Gas Processing	1.0	Industrial separation	Enhanced Oil Recovery
Boundary Dam Carbon Capture and Storage	Canada	2014	Power Generation	1.0	Post-combustion capture	Enhanced Oil Recovery

Quest	Canada	2015	Hydrogen Production	1.0	Industrial separation	Dedicated Geological Storage
Uthmaniyah CO2-EOR Demonstration	Saudi Arabia	2015	Natural Gas Processing	0.8	Industrial separation	Enhanced Oil Recovery
Abu Dhabi CCS (Phase 1 being Emirates Steel Industries)	United Arab Emirates	2016	Iron and Steel Production	0.8	Industrial separation	Enhanced Oil Recovery
Illinois Industrial Carbon Capture and Storage	United States	2017	Ethanol Production	1.0	Industrial separation	Dedicated Geological Storage
Petra Nova Carbon Capture	United States	2017	Power Generation	1.4	Post-combustion capture	Enhanced Oil Recovery
Jilin Oil Field CO2-EOR	China	2018	Natural Gas Processing	0.6	Industrial separation	Enhanced Oil Recovery
Gorgon Carbon Dioxide Injection	Australia	2019	Natural Gas Processing	3.4 - 4.0	Industrial separation	Dedicated Geological Storage

Appendix 2: Large scale CCS Facilities in construction and advanced development

Title	Status	Country	Operation Date	Industry	Capture Capacity	Capture Type	Storage Type
Alberta Carbon Trunk Line ("ACTL") with North West Redwater Partnership's Sturgeon Refinery CO2 Stream	In Construction	Canada	2019	Oil Refining	1.2 - 1.4	Industrial separation	Enhanced Oil Recovery
Alberta Carbon Trunk Line ("ACTL") with Agrium CO2 Stream	In Construction	Canada	2019	Fertiliser Production	0.3 - 0.6	Industrial separation	Enhanced Oil Recovery
Sinopec Qilu Petrochemical CCS	In Construction	China	2019	Chemical Production	0.4	Industrial separation	Enhanced Oil Recovery
Yanchang Integrated Carbon Capture and Storage Demonstration	In Construction	China	2020 - 2021	Chemical Production	0.4	Industrial separation	Enhanced Oil Recovery
Norway Full Chain CCS	Advanced development	Norway	2023-2024	Cement production and waste-to-energy	0.8	Various	Dedicated Geological Storage

CarbonNet	Advanced development	Australia	2020's	Under evaluation	3.0	Under Evaluation	Dedicated Geological Storage
Lake Charles Methanol	Advanced development	United States	2022 (Institute estimate)	Chemical production	4.2	Industrial separation	Enhanced oil recovery
Port of Rotterdam CCUS Backbone Initiative (Porthos)	Advanced development	Netherlands	2021	Various	2.0 -5.0	Various	Dedicated Geological Storage

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