Institute for Policy Integrity
NEW YORK UNIVERSITY SCHOOL OF LAW

December 16, 2016

California Air Resources Board
VIA ELECTRONIC SUBMISSION

Subject: Comments on Discussion Draft, 2030 Target Scoping Plan Update (Dec. 2, 2016)

The Institute for Policy Integrity at New York University School of Law[1] ("Policy Integrity") respectfully submits the following comments[2] on the California Air Resource Board's ("ARB") Discussion Draft of its 2030 Target Scoping Plan Update.[3] Policy Integrity is a non-partisan think tank dedicated to improving the quality of government decisionmaking through advocacy and scholarship in the fields of administrative law, economics, and public policy. Policy Integrity regularly conducts economic and legal analysis on the appropriate use of the social cost of carbon, among other environmental and economic topics.

California recently extended its greenhouse gas emissions reduction program to 2030 with two bills, Senate Bill 32 ("SB 32") and Assembly Bill 197 ("AB 197"). These bills also modify how ARB shall assess and prioritize goals in designing regulations. Accordingly, ARB is drafting a new scoping plan for how to achieve the 2030 targets. ARB staff released a "discussion draft" of the updated scoping plan and has invited public comments on this initial draft. These comments make recommendations on how to structure the plan's economic analysis to best achieve the goals laid out in ARB's new statutory mandate.

Among other provisions, AB 197 requires ARB to consider the social cost of greenhouse gas emissions and the avoided social costs of proposed compliance measures.[4] In order to comply with the statute and consider the full range of effects of the policy options in the updated scoping plan, ARB should:

- Use the federal social costs of carbon, methane and nitrous oxide, as most recently updated in August 2016, subject to further updates that are consistent with the best available science and economics; and

- Use cost-benefit analysis, in addition to its usual cost-effectiveness analysis.

[1] No part of this document purports to present New York University School of Law's views, if any.
[2] These comments incorporate by reference into the record all of the documents cited herein.
[3] Cal. Air Res. Bd., 2030 Target Scoping Plan, Discussion Draft. (Dec. 2, 2016) [hereinafter "Discussion Draft"].
[4] Cal. Health & Safety Code §§ 38562.5 & 38562.7.

I. In its economic analysis, ARB should use the federal social cost of carbon, social cost of methane and social cost of nitrous oxide, which are the best available estimates of the damages associated with the emissions of each additional ton of these greenhouse gases[5]

AB 197 requires ARB to "consider the social costs of the emissions of greenhouse gases" when it is "adopting rules and regulations" to reduce greenhouse gases below 1990 levels.[6] The statute defines "social costs" as:

> an estimate of the economic damages, including, but not limited to, changes in net agricultural productivity; impacts to public health; climate adaptation impacts, such as property damages from increased flood risk; and changes in energy system costs, per metric ton of greenhouse gas emission per year.[7]

In selecting the appropriate metric to use for the "social costs of the emissions of greenhouse gases," ARB should choose a value that reflects the best available science and economics and has been developed through a transparent process. The August 2016 updated federal Interagency Working Group on Social Cost of Greenhouse Gases ("IWG") reports[8] reflect the best available estimates of the damages associated with the emission of each additional ton of carbon dioxide, methane, and nitrous oxide, through the federal social cost of carbon ("SC-CO_2"), federal social cost of methane ("SC-CH_4"), and federal social cost of nitrous oxide ("SC-N_2O").[9]

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[5] These comments draw from coalition comments on the social cost of carbon and social cost of methane, filed jointly in major federal rulemakings by Policy Integrity, the Environmental Defense Fund, the Natural Resource Defense Council, and the Union of Concerned Scientists. *See* Environmental Defense Fund, Institute for Policy Integrity at New York University School of Law, Natural Resources Defense Council, and Union of Concerned Scientists, Comments on Energy Conservation Standards for WICF Refrigeration Systems & Energy Conservation Standards for Residential Furnaces (Nov. 17, 2016) [hereinafter "Joint SC-CO_2 Comments"] (most recent version of these joint comments) (attached as Exhibit A).

[6] Cal. Health & Safety Code § 38562.5.

[7] Cal. Health & Safety Code § 38506.

[8] INTERAGENCY WORKING GROUP ON SOCIAL COST OF GREENHOUSE GASES, UNITED STATES GOVERNMENT, TECHNICAL SUPPORT DOCUMENT: TECHNICAL UPDATE OF THE SOCIAL COST OF CARBON FOR REGULATORY IMPACT ANALYSIS UNDER EXECUTIVE ORDER 12866 (2016) [hereinafter "2016 TSD"], *available at* https://www.whitehouse.gov/sites/default/files/omb/inforeg/scc_tsd_final_clean_8_26_16.pdf; INTERAGENCY WORKING GROUP ON SOCIAL COST OF GREENHOUSE GASES, UNITED STATES GOVERNMENT, ADDENDUM TO TECHNICAL SUPPORT DOCUMENT ON SOCIAL COST OF CARBON FOR REGULATORY IMPACT ANALYSIS UNDER EXECUTIVE ORDER 12866: APPLICATION OF THE METHODOLOGY TO ESTIMATE THE SOCIAL COST OF METHANE AND THE SOCIAL COST OF NITROUS OXIDE (2016) [hereinafter "2016 TSD ADDENDUM"], *available at* https://www.whitehouse.gov/sites/default/files/omb/inforeg/august_2016_sc_ch4_sc_n2o_addendum_final_8_26_16.pdf.

[9] These comments will use the terms "SC-CO_2," "SC-CH_4," and "SC-N_2O" to refer to the general concept of the valuation of a social cost of a ton of emission of the specified greenhouse gas, and will use the terms "federal SC-CO_2," "federal SC-CH_4," and "federal SC-N_2O" to refer to the specific sets of consensus valuations developed by the Interagency Working Group.

In response to a Ninth Circuit Court of Appeals decision that required the government to account for the economic effects of climate change in a regulatory impact analysis of fuel efficiency standards,[10] the federal government convened the IWG to develop a SC-CO_2 value for use in federal regulatory analysis. Prior to the formation of the IWG, agencies used a range of values for the economic harm caused by one additional metric ton of carbon dioxide emissions.[11] The consistent use of the IWG estimates in federal rulemaking allows agencies to harmonize their approach to conducting regulatory impact analyses and conserve agency resources to avoid duplication of modeling effort. The IWG has met several times to update its modeling based on updated scientific literature, with the most recent update in 2016, reflecting recommendations on SC-CO_2 from the National Academy of Sciences and expanding the analysis to include additional greenhouse gases, specifically methane and nitrous oxide.[12]

The IWG's August 2016 central estimate[13] of $41 in 2016 dollars per ton of carbon dioxide emissions is based on the best available science.[14] As ARB's Discussion Draft notes,[15] this value is likely an underestimate because some forms of damage, like catastrophic risks, are omitted from present calculations due to data limitations and scientific uncertainty.[16] Nonetheless, the federal SC-CO_2 is the best available estimate of climate damages and has been used in almost one hundred federal regulations and a number of state proceedings.[17] Additionally, the Seventh Circuit Court of Appeals recently approved the federal SC-CO_2's

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[10] Ctr. for Biological Diversity v. Nat'l Highway Traffic Safety Admin., 538 F.3d 1172 (9th Cir. 2008).

[11] INTERAGENCY WORKING GROUP ON SOCIAL COST OF GREENHOUSE GASES, UNITED STATES GOVERNMENT, TECHNICAL SUPPORT DOCUMENT: SOCIAL COST OF CARBON FOR REGULATORY IMPACT ANALYSIS UNDER EXECUTIVE ORDER 12866, at II-3 (2010) [hereinafter "2010 TSD"], *available at* https://www.whitehouse.gov/sites/default/files/omb/inforeg/for-agencies/Social-Cost-of-Carbon-for-RIA.pdf.

[12] *See* 2016 TSD, *supra* note 8; INTERAGENCY WORKING GROUP ON SOCIAL COST OF CARBON, TECHNICAL SUPPORT DOCUMENT: TECHNICAL UPDATE OF THE SOCIAL COST OF CARBON FOR REGULATORY IMPACT ANALYSIS UNDER EXECUTIVE ORDER 12866 (2015), *available at* https://www.whitehouse.gov/sites/default/files/omb/inforeg/scc-tsd-final-july-2015.pdf; INTERAGENCY WORKING GROUP ON THE SOCIAL COST OF CARBON, TECHNICAL SUPPORT DOCUMENT: TECHNICAL UPDATE OF THE SOCIAL COST OF CARBON FOR REGULATORY IMPACT ANALYSIS UNDER EXECUTIVE ORDER 12866 (2013) [hereinafter "2013 TSD"], *available at* https://www.whitehouse.gov/sites/default/files/omb/inforeg/social_cost_of_carbon_for_ria_2013_update.pdf; 2010 TSD, *supra* note 11.

[13] As discussed further in Section I.C, the IWG produced a range of social cost of carbon estimates, reflecting a 5-percent discount rate, a 3-percent discount rate, a 2.5-percent discount rate, and a 95th percentile estimate. This $41 per ton figure corresponds to the "central" 3-percent discount rate.

[14] 2016 TSD, *supra* note 8, at 4, tbl.ES-1 (showing a value of $36 in 2007 dollars, which yields $41 in 2016 dollars when updated using a Consumer Price Index Inflation Calculator, http://data.bls.gov/cgi-bin/cpicalc.pl).

[15] Discussion Draft, *supra* note 3, at 113.

[16] *See* Richard L. Revesz et al., *Improve Economic Models of Climate Change*, 508 NATURE 173 (2014) (co-authored with Nobel Laureate Kenneth Arrow, among others) (attached as Exhibit B); 2010 TSD, *supra* note 11; PETER HOWARD, OMITTED DAMAGES: WHAT'S MISSING FROM THE SOCIAL COST OF CARBON (2014) [hereinafter "OMITTED DAMAGES"] (attached as Exhibit C); Peter Howard, Flammable Planet: Wildfires and the Social Cost of Carbon (2014); The Cost of Carbon Pollution, http://costofcarbon.org/.

[17] JANE A. LEGGETT, CONGRESSIONAL RESEARCH SERVICE, FEDERAL CITATIONS TO THE SOCIAL COST OF GREENHOUSE GASES (2016); see discussion of state proceedings in Section I.D below.

use by a federal agency.[18] The federal SC-CH_4 and federal SC-N_2O have been developed more recently, but are also based upon a similarly rigorous IWG process.[19]

These federal SC-CO_2, SC-CH_4, and SC-N_2O estimates are firmly grounded in peer-reviewed science and economics. Furthermore, they have been developed through a transparent and ongoing process coordinated by experts and incorporating public comment. In order to reflect the best available science and economics and not duplicate efforts, ARB should use these values in its economic analysis, subject to updates over time to continue reflecting the best available science and economics.

A. The federal social cost of carbon is based on rigorous and peer-reviewed science and economics[20]

The SC-CO_2 was developed with robust academic rigor, including peer review of the estimates underlying the models and other inputs used by the IWG. The SC-CO_2 values were developed using the three most widely cited climate economic impact models that link physical impacts to the economic damages of CO_2 emissions. All of these integrated assessment models—known as DICE, FUND, and PAGE[21]—have been extensively peer reviewed in the economic literature.[22] The newest versions of the models were also published in peer-reviewed literature.[23] Each model translates emissions into changes in atmospheric carbon concentrations, atmospheric concentrations into temperature changes, and temperature changes into economic damages.[24] The IWG gives each model equal weight in developing the SC-CO_2 values.[25] The IWG also used peer-reviewed inputs to run these models.[26] The IWG conducted an "extensive review of the literature . . . to select three sets of input parameters for these models: climate sensitivity, socio-economic and emissions trajectories, and discount rates."[27] For example, to derive socioeconomic and emissions pathways, the IWG used results from the Stanford Energy Modeling Forum, all of which were peer-reviewed, published, and publicly available.[28] For each parameter, the

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[18] Zero Zone, Inc. v. U.S. Dep't of Energy, Case No. 14-2147 (slip op. at 39-45) (7th Cir. Aug. 8, 2016) (attached as Exhibit D).
[19] *See* 2016 TSD ADDENDUM, *supra* note 8.
[20] This subsection and the following subsection are based on Policy Integrity's amicus brief to the Seventh Circuit Court of Appeals in Zero Zone, Inc. v. U.S. Dep't of Energy, Case No. 14-2147 (7th Cir. July 29, 2016) (attached as Exhibit E).
[21] More specifically: DICE (Dynamic Integrated Climate and Economy), developed by William Nordhaus (more information available at http://www.econ.yale.edu/~nordhaus/); PAGE (Policy Analysis of the Greenhouse Effect), developed by Chris Hope; and FUND (Climate Framework for Uncertainty, Negotiation, and Distribution), developed by Richard Tol (more information available at http://www.fund-model.org/). *See* 2010 TSD, *supra* note 11, at 5 n.2.
[22] *See* 2010 TSD, *supra* note 11, at 4-5.
[23] *See* 2016 TSD, *supra* note 8, at 6; *see also* William Nordhaus, *Estimates of the Social Cost of Carbon: Concepts and Results from the DICE-2013R Model and Alternative Approaches*, 1 J. ASS'N ENVTL. & RESOURCE ECONOMISTS 273 (2014).
[24] 2010 TSD, *supra* note 11, at 5.
[25] *Id* at 5.
[26] *Id.* at 5-29.
[27] *Id*. at 6.
[28] *Id*. at 15; *see also* Symposium, *International, U.S. and E.U. Climate Change Control Scenarios: Results from EMF 22*, 31 ENERGY ECON. S63 (2009).

IWG documented the inputs it used, all of which are based on peer-reviewed literature.[29] The analytical methods that the IWG applied to its inputs were also peer-reviewed, and the IWG's methods have been extensively discussed in academic journals.[30]

Throughout their development process, the federal SC-CO_2 estimates have been based on rigorous and peer-reviewed science and economics, making these values a good basis for thoughtful policy analysis, and indeed, the best available estimates of the economic costs of carbon dioxide emissions.

B. The social cost of carbon values were derived through a transparent and open interagency process that is designed to be updated over time to reflect new information

The IWG's analytical process in developing the SC-CO_2 was transparent and open, designed to solicit public comment and incorporate the most recent scientific analysis.

First, the process was transparent. Beginning in 2009, the Office of Management and Budget and the Council of Economic Advisers established the IWG, composed of scientific and economic experts from the White House, Environmental Protection Agency, and Departments of Agriculture, Commerce, Energy, Transportation, and Treasury, to develop a rigorous method of valuing carbon dioxide reductions resulting from regulations.[31] In February 2010, the IWG released estimated SC-CO_2 values, developed using the three most widely cited climate economic impact models (known as integrated assessment models). These models were each developed by outside experts, and published and extensively discussed in peer-reviewed literature.[32] An accompanying Technical Support Document released by the IWG discussed the models, their inputs, and the assumptions used in generating the SC-CO_2 estimates.[33] In May 2013, after all three underlying models had been updated and used in peer-reviewed literature, the IWG released revised SC-CO_2 values, with an accompanying Technical Support Document.[34] The U.S. Government Accountability Office examined the IWG's 2010 and 2013 processes, and found that these processes were consensus-based, relied on academic literature and modeling, disclosed relevant limitations, and incorporated new information via public comments and updated research.[35]

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[29] *See* 2010 TSD, *supra* note 11, at 12 to 23.

[30] *See, e.g.*, Michael Greenstone et al., *Developing a Social Cost of Carbon for U.S. Regulatory Analysis: A Methodology and Interpretation*, 7 REV. ENVTL. ECON. & POL'Y 23 (2013); Frank Ackerman & Elizabeth Stanton, *Climate Risks and Carbon Prices: Revising the Social Cost of Carbon*, ECON.: THE OPEN-ACCESS, OPEN-ASSESSMENT E-JOURNAL, Apr. 2012, at 6 (reviewing the IWG's methods and stating, "[T]he Working Group analysis is impressively thorough.").

[31] 2010 TSD, *supra* note 11, at 2-3.

[32] *See id.* at 12 to 23.

[33] *See generally id.*

[34] *See* 2013 TSD, *supra* note 12.

[35] GOV'T ACCOUNTABILITY OFFICE, REGULATORY IMPACT ANALYSIS: DEVELOPMENT OF SOCIAL COST OF CARBON ESTIMATES (2014).

The IWG requested that the National Academies of Sciences undertake a review of the latest research on modeling the economic aspects of climate change to help the IWG assess the technical merits and challenges of potential approaches for future updates to the SC-CO_2.[36] In mid-2016, the National Academies of Sciences issued an interim report to the IWG that recommended against conducting an update to the SC-CO_2 estimates in the near-term, but which included recommendations about enhancing the presentation and discussion of uncertainty regarding particular estimates.[37] The IWG responded to these recommendations in its most recent Technical Support Document from 2016,[38] which included an addendum on the SC-CH_4 and SC-N_2O.[39] The National Academies of Sciences are expected to issue a report sometime between December 2016 and February 2017 that will contain a roadmap for how SC-CO_2 estimates should be updated.[40]

The SC-CO_2 estimates will need to be updated over time to reflect the best-available science and changing economic conditions. ARB properly anticipates this possibility in its Discussion Draft, noting, "The State shall continue to monitor and engage in discussions related to any updates to U.S. EPA's SC-CO_2 methods and values."[41] If the federal government's estimates continue to reflect the best available science and economics, California should continue to use those values.

If the federal government's numbers are no longer updated to reflect the best available research, are no longer calculated based on a sound, transparent methodology that can be widely endorsed by economists, or are no longer consistent with other countries' estimates, California should undertake to update its own SC-CO_2 over time. In so doing, ARB should create an open and transparent process that involves reviewing the forthcoming National Academies of Sciences roadmap document, consulting with economists, considering peer-reviewed studies, and opening the process for public comment. The factors that California should consider in such an effort include the appropriate discount rate (discussed in section I.C. below), the extent of omitted damages (discussed in section I.C.), and the global nature of the damages associated with climate change.[42]

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[36] *See* 2016 TSD, *supra* note 8, at 2.
[37] NATIONAL ACADEMIES OF SCIENCES, ENGINEERING AND MEDICINE, ASSESSMENT OF APPROACHES TO UPDATING THE SOCIAL COST OF CARBON: PHASE 1 REPORT ON A NEAR-TERM UPDATE (2016) (attached as Exhibit F).
[38] 2016 TSD, *supra* note 8.
[39] 2016 TSD ADDENDUM, *supra* note 8.
[40] The National Academy of Sciences accepted public comment during its review process. Policy Integrity submitted comments during that process. Institute for Policy Integrity, Recommendations for Changes to the Final Phase 1 Report on the Social Cost of Carbon, and Recommendations in Anticipation of the Phase 2 Report on the Social Cost of Carbon (Apr. 29, 2016) [hereinafter "Policy Integrity NAS comments"] (attached as Exhibit G).
[41] Discussion Draft, *supra* note 3, at 114.
[42] The IWG and other commentators have concluded that the SC-CO_2 should reflect global climate damages for numerous reasons, including the global nature of the harm and the need to encourage international coordination to address climate change. *E.g.*, Peter Howard & Jason Schwartz, *Think Global: International Reciprocity as Justification for a Global Social Cost of Carbon* (Institute for Policy Integrity at NYU School of Law Working Paper, 2016) (forthcoming in COLUMBIA J. ENVTL. L.) (attached as Exhibit H); Michael Greenstone et al., *Developing a Social Cost of Carbon for U.S. Regulatory Analysis: A Methodology and Interpretation*, 7 REV. ENVTL. ECON. & POL'Y 23 (2013) (reviewing the policy justifications for a global value and the practical

At present, however, the federal SC-CO_2 values have been developed through an open and transparent process, with significant public input, using the best science and economic methods available. It is sensible for ARB to use the federal SC-CO_2, rather than developing its own social-cost values from the ground up.

C. California should consider the appropriate discount rate and extent of omitted damages in deciding which values to use for the social cost of carbon from within the range of federal values

The federal SC-CO_2 estimates are not a single number, but instead are a range of four estimates, based on three discount rates, plus a 95th percentile estimate.[43] Higher discount rates reduce the value of future streams of benefits, resulting in a lower SC-CO_2, as compared to lower discount rates. The discount rates used by the IWG are 5, 3, and 2.5 percent. The fourth value, which represents low-probability catastrophic situations, takes the 95th percentile of the SC-CO_2 from each model, using a 3-percent discount rate.[44]

The models used in calculating the SC-CO_2 estimate the damages resulting from the emission of a ton of carbon starting at the present time and continuing into the future, typically to the year 2300. The models then discount the value of those future damages over the entire timeframe, back to the present value, and add up the full effects over this time, to arrive at the SC-CO_2 figure.[45] The discount rate accounts for the fact that "[b]enefits or costs that occur sooner are generally more valuable."[46] The further in the future the effects are, the "more they should be discounted" before considering them in the cost-benefit analysis.[47]

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complications of a domestic-only value); Frank Ackerman & Elizabeth A. Stanton, *Climate Risks and Carbon Prices: Revising the Social Cost of Carbon,* 6 ECONOMICS E-JOURNAL 1 (2012)("The analysis by the federal Interagency Working Group is significant . . . for its recognition that policy should be based on global, rather than domestic, impacts."); Laurie Johnson & Chris Hope, *The Social Cost of Carbon in U.S. Regulatory Impact Analyses: an Introduction and Critique*, 2 J. ENVTL. STUD. SCI. 205, 208 (2012)("Empirical, theoretical, and ethical arguments strongly support the use of a global value."); William Pizer et al., *Using and Improving the Social Cost of Carbon*, 346 SCIENCE 1189, 1190 (2014) ("[T]he moral, ethical, and security issues . . . [and the] strategic foreign relations question . . . are compelling reasons to focus on a global SCC [social cost of carbon]."); Robert Kopp & Bryan Mignone, *Circumspection, Reciprocity, and Optimal Carbon Prices*, 120 CLIMATIC CHANGE 831, 831 (2013) ("[T]he domestically optimal price approaches the global cooperative optimum linearly with increasing circumspection and reciprocity"); Celine Guivarch, et al., *Letter: Social Cost of Carbon: Global Duty*, 351 SCIENCE 1160 (2016).

43 2010 TSD, *supra* note 11; 2013 TSD, *supra* note 12; 2016 TSD, *supra* note 8.

44 *See* Environmental Defense Fund, Institute for Policy Integrity at New York University School of Law, Natural Resources Defense Council, and Union of Concerned Scientists, Comments on Proposed Exception to the Colorado Roadless Rule and Supplemental Draft Environmental Impact Statement 9-10 (Jan. 15, 2016) (describing the importance of the 95th percentile value), *available at* http://policyintegrity.org/documents/Forest_Service_SDEIS_comments.pdf.

45 2016 TSD, *supra* note 8.

46 OFFICE OF MGMT. & BUDGET, CIRCULAR A-4 at 32 (2003) (laying out economic best practices for cost-benefit analysis) [hereinafter "CIRCULAR A-4"], *available at* https://www.whitehouse.gov/sites/default/files/omb/assets/omb/circulars/a004/a-4.pdf.

47 *Id.*

Choosing the correct discount rate is crucial to obtaining the best SC-CO_2 estimate. Frequently, agencies will conduct their economic analyses using a range of SC-CO_2 values, reflecting the range of estimates.[48] Other analyses will focus on a "central" estimate of the SC-CO_2.[49] Frequently, the SC-CO_2 estimate using the 3-percent discount rate is considered to be the central estimate.[50] Some jurisdictions, like Washington State, have chosen to use a SC-CO_2 estimate based upon a 2.5-percent discount rate, due to the high level of uncertainty of forecasting climate change and its impacts.[51] Using a 2.5-percent rate as the basis for the estimate will result in a higher SC-CO_2 value than using a 3-percent discount rate.

A number of factors might result in a jurisdiction using a SC-CO_2 value that is higher than the estimate based on a 3-percent discount rate. Recent research has shown that the appropriate discount rate for intergenerational analysis may be even lower than that reflected in the SC-CO_2 analysis, which would result in a higher SC-CO_2.[52] A jurisdiction might decide that the uncertainty associated with climate damages warrants using a discount rate that declines over time, which would increase the SC-CO_2.[53] Furthermore, as ARB's Discussion Draft notes,[54] a number of types of damage from climate change are missing or poorly quantified in the federal SC-CO_2 estimates, meaning that the federal SC-CO_2 estimate associated with a 3-percent discount rate should be interpreted as a lower bound on the central estimate.[55] Omitted damages include the effects of climate change on fisheries; the effects of increased pest, disease, and fire pressures on agriculture and forests; and resource scarcity due to migration. Additionally, these models omit the effects of climate change on economic growth and the rise in the future value of environmental

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[48] *See, e.g.*, Energy Conservation Program: Energy Conservation Standards for Miscellaneous Refrigeration Products, 81 Fed. Reg. 75,194 (Oct. 26, 2016); Cross-State Air Pollution Rule Update for the 2008 Ozone NAAQS, 81 Fed. Reg. 74,504 (Oct. 26, 2016).

[49] *See, e.g.*, Proceeding on Motion of the Commission in Regard to Reforming the Energy Vision, Order Establishing the Benefit Cost Analysis Framework, New York Public Service Comm'n Case No. 14-M-0101 (Jan. 21, 2016) [hereinafter "BCA Order"].

[50] According to the 2010 TSD, the 3% discount rate estimate is considered the central estimate because it uses the central (i.e., middle) discount rate and is based on an average, rather than worse-than-expected, climate outcome; the average climate outcome is the standard assumption made by the IWG. 2010 TSD, *supra* note 11, at 25.

[51] WASHINGTON STATE DEPARTMENT OF COMMERCE, SOCIAL COST OF CARBON: WASHINGTON STATE ENERGY OFFICE RECOMMENDATION FOR STANDARDIZING THE SOCIAL COST OF CARBON WHEN USED FOR PUBLIC DECISION-MAKING PROCESSES 3-5 (2014).

[52] Proceeding on Motion of the Commission in Regard to Reforming the Energy Vision, New York Public Service Commission Case No. 14-M-0101, Institute for Policy Integrity Comments on Staff White Paper on Benefit-Cost Analysis in the Reforming Energy Vision Proceeding, Filing No. 447, at 8 (Aug. 21, 2015).

[53] *See* Martin L. Weitzman, *Gamma Discounting*, 91 AM. ECON. REV. 260, 270 (2001); Kenneth J. Arrow et al., *Determining Benefits and Costs for Future Generations*, 341 SCIENCE 349 (2013); Kenneth J. Arrow et al., *Should Governments Use a Declining Discount Rate in Project Analysis?*, 8 REV ENVTL. ECON. & POLICY 1 (2014); Maureen L. Cropper et al., *Declining Discount Rates*, 104 AM. ECON. REV. 538 (2014); Christian Gollier & Martin L. Weitzman, *How Should the Distant Future Be Discounted When Discount Rates Are Uncertain?* 107 ECONOMICS LETTERS 3 (2010). Policy Integrity further explores the use of declining discount rates in its recent comments to the National Academies of Sciences. Policy Integrity NAS Comments, *supra* note 40, at 13-16.

[54] Discussion Draft, *supra* note 3, at 113.

[55] *See* OMITTED DAMAGES, *supra* note 16; Richard L. Revesz et al., *Global Warming: Improve Economic Models of Climate Change*, 508 NATURE 173 (2014) (co-authored with Nobel laureate Kenneth Arrow).

services due to increased scarcity. Some of these omitted damages have particular relevance to California, including wildfires and agricultural damage. In the past few years alone, Californians have experienced severe drought and wildfires, which have threatened lives and livelihoods throughout the state.

California should weigh these factors, including the appropriate discount rate and omitted damages, in deciding which values to use for the SC-CO_2 out of the range of federal SC-CO_2 estimates, choosing a central value (or range of values resulting in a projection) that is at least as high as the $41 per ton value associated with a 3-percent discount rate.

D. California can draw support and lessons from other states that use the federal social cost of carbon in their rulemaking

It may be helpful for ARB to understand how other states' agencies have used the SC-CO_2, in order to decide how to structure its own approach. Leading states, including Minnesota, Maine, New York and Washington have all begun using the federal SC-CO_2 in energy-related cost-benefit analysis, recognizing that the SC-CO_2 is the best available estimate of the marginal economic impact of carbon emission reductions.[56] Several states and municipalities have used the SC-CO_2 in the context of renewable energy decisionmaking, and New York State has used the SC-CO_2 to assess the value of keeping some of the state's nuclear power plants operational.

Minnesota

Minnesota Statute 216B.2422, subdivision 3 states, "The [Public Utilities] commission shall, to the extent practicable, quantify and establish a range of environmental costs associated with each method of electricity generation. A utility shall use the values established by the commission in conjunction with other external factors, including socioeconomic costs, when evaluating and selecting resource options in all proceedings before the commission, including resource plan and certificate of need proceedings."[57] Between 1993, when 216B.2422 was enacted, and 2014, Minnesota used its own methodology to determine the costs of $PM_{2.5}$, SO_2, NO_x, and CO_2.[58] In 2014, after environmental advocacy groups filed a motion requesting that the Minnesota Public Utility Commission update these figures, the commission referred the issue to the Office of Administrative Hearings to assess whether the state should use the federal SC-CO_2 and how to value externalities.[59]

The Administrative Judge who reviewed the matter of the Further Investigation into Environmental and Socioeconomic Costs Under Minnesota Statutes Section 216B.2422,

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[56] *See* Proceeding on Motion of the Commission in Regard to Reforming the Energy Vision, New York Public Service Commission Case No. 14-M-0101, Institute for Policy Integrity Comments on Staff White Paper on Benefit-Cost Analysis in the Reforming Energy Vision Proceeding, Filing No. 447, at 22 (Aug. 21, 2015).

[57] 2016 Minnesota Stat. § 216B.2422 subd. 3.

[58] State of Minnesota, Office of Administrative Hearings, *In the Matter of the Further Investigation into Environmental and Socioeconomic Costs Under Minnesota Statutes Section 216B.2422, Subdivision 3*, Docket No. OAH 80-2500-31888, MPUC E-999/CI-14-643, Findings of Fact, Conclusions, and Recommendations: Carbon Dioxide Values 2-3 (Apr. 15, 2016).

[59] *Id* at 4.

Subdivision 3 recommended that "the Commission adopt the Federal Social Cost of Carbon as reasonable and the best available measure to determine the environmental cost of CO_2, establishing a range of values including the 2.5 percent, 3.0 percent, and 5 percent discount rates . . . ."[60]

Maine[61]

Maine enacted the Act to Support Solar Energy Development in Maine during its 2014 legislative session.[62] Section 1 of the Act states that it is "in the public interest is to develop renewable energy resources, including solar energy, in a manner that protects and improves the health and well-being of the citizens and natural environment of the State while also providing economic benefits to communities, ratepayers and the overall economy of the State."[63] Section 2 of the Act instructs the Public Utilities Commission to determine the value of distributed solar energy generation in the State, evaluate implementation options, and deliver a report to the Legislature. Maine has a statute that calls for calculating "the societal value of the reduced environmental impacts of the energy."[64] Maine uses the federal SC-CO_2, as well as other monetized costs and benefits, to make this calculation. Because carbon costs are already partially embedded in existing energy valuation because of carbon emissions caps under the Regional Greenhouse Gas Initiative ("RGGI"), the net SC-CO_2 is calculated by subtracting the embedded carbon allowance costs from the total SC-CO_2. The Maine Public Utilities Commission uses the federal SC-CO_2, with a central 3-percent discount rate estimate.

Similar to California's AB 32, Maine's statute requires the PUC to assess how to maximize social welfare in its policy options. Maine addresses this requirement by weighing market costs and benefits with the monetized values of societal benefits in a cost-benefit analysis.[65]

New York

New York's Clean Energy Standard and accompanying Zero Emissions Credit ("ZEC") take into account the SC-CO_2 in calculating the value of using emission-free nuclear power, rather than carbon-emitting fossil fuel power. The New York Public Service Commission's program is designed to compensate nuclear plants based directly on the value of the carbon-free attributes of their generation.[66]

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[60] *Id.* at 123.
[61] For more details, see Maine Public Utilities Commission, Maine Distributed Solar Valuation Study (2015) [hereinafter "MPUC Distributed Solar Valuation Study"], *available at* http://www.maine.gov/mpuc/electricity/elect_generation/documents/MainePUCVOS-FullRevisedReport_4_15_15.pdf .
[62] Maine P.L ch. 562 (Apr. 24, 2014) (codified at 35-A M.R.S.A. §§ 3471-3474).
[63] *Id* at § 3472(1).
[64] *Id.* at § 2(1).
[65] MPUC Distributed Solar Valuation Study at 4.
[66] Denise Grab & Burcin Unel, New York's Clean Energy Standard Is a Key Step Toward Pricing Carbon Pollution Fairly, UTILITY DIVE (Aug.18, 2016), *available at* http://www.utilitydive.com/news/new-yorks-clean-energy-standard-is-a-key-step-toward-pricing-carbon-pollut/424741/.

The commission recognized that the federal SC-CO_2 is the "best available estimate of the marginal external damage of carbon emissions."[67] It then designed the ZEC based upon the difference between the average April 2017 through March 2019 projected SC-CO_2, as published by the IWG in July 2015 and a fixed baseline portion of the cost that is already captured in the market revenues received by the eligible nuclear facilities under RGGI.[68] The New York Public Service Commission uses the federal SC-CO_2, with a central 3-percent discount rate estimate.[69]

Washington

Executive Order 14-04 on Washington Carbon Pollution Reduction and Clear Energy Action requires the state's agencies to "[e]nsure the cost-benefit tests for energy-efficiency improvements include full accounting for the external cost of greenhouse gas emissions."[70] With these requirements in mind, the Washington State Energy Office, in consultation with the Washington State Department of Ecology, recommended that all state agencies use the federal SC-CO_2 estimates.

The Energy Office noted that the federal SC-CO_2 estimates do not capture the total cost of emitting carbon dioxide into the atmosphere (total future climate damages), and because of omitted damages and uncertainty about the full scope of the consequences of climate change, the Office recommended using the lower 2.5-percent discount rate.[71]

The Energy Office supports using the 2.5-percent discount rate for a number of reasons.[72] First, the 2.5-percent discount most closely matches with the existing Office of Financial Management real discount rate of 0.9 percent. Second, the IWG models focus only on the damages of climate change that can be easily monetized and since the trend seems to be that additional impacts are monetized with each federal SC-CO_2 update, Washington can stay ahead of this trend by choosing the lowest IWG discount rate. Third, because the discount rate applied to greenhouse gas emissions is an "intergenerational" discount rate applied to society as a whole, the discount rate used in this context should be substantially lower than private sector discount rates. Fourth, there is a higher risk associated with underestimating the SC-CO_2 than with overestimating it. Fifth, Washington State wants to lead on climate issues, so it makes sense for the Energy Office to put forth the higher associated SC-CO_2.

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[67] Proceeding on Motion of the Commission to Implement a Large-Scale Renewable Program and a Clean Energy Standard, New York Public Service Comm'n Case No. 15-E-0302, Order Establishing a Clean Energy Standard 131, (Aug. 1, 2016).
[68] *Id.* at 129.
[69] BCA Order, *supra* note 49, at appx. C.
[70] State of Washington, Executive Order 14-04 at 6, *available at* http://www.governor.wa.gov/sites/default/files/exe_order/eo_14-04.pdf.
[71] WASHINGTON STATE DEPARTMENT OF COMMERCE, SOCIAL COST OF CARBON: WASHINGTON STATE ENERGY OFFICE RECOMMENDATION FOR STANDARDIZING THE SOCIAL COST OF CARBON WHEN USED FOR PUBLIC DECISION-MAKING PROCESSES 3 (2014).
[72] *Id.* at 3-5.

Washington state agencies have begun following the recommendation of the state's energy office and using a 2.5-percent discount rate for their economic analyses involving greenhouse gas emissions.[73]

Washington and the other states' experiences in applying the federal SC-CO_2 can be instructive for California's ARB as it decides how to integrate the "social costs of the emissions of greenhouse gases" into its decisionmaking.

E. How ARB should use the social cost of carbon

Once ARB has selected a value to use for the SC-CO_2 (or SC-CH_4 or SC-N_2O), it can use those figures to calculate the expected monetized benefits of avoided emissions. In order to conduct this analysis properly, it is necessary to understand how timing factors into the analysis of the social cost of greenhouse gases.

Timing plays into the economic analysis surrounding the SC-CO_2 in at least three ways. First, as discussed in Section I.C, the values of the SC-CO_2 in the IWG analysis were calculated by adding up the streams of future effects from a ton of emissions in the year of anticipated release, with discount rates reflecting the passage of time between the anticipated release and the future effects.

Second, the federal SC-CO_2 values that have come out of that process represent the damages associated with each additional ton of carbon dioxide emissions released *from the perspective of the year of emission*. Thus, it is necessary when conducting a policy analysis *at the present time* about policies that affect greenhouse gas releases *in the future* to make sure that the SC-CO_2 values are translated into the *perspective of the year of the policy decision*. The proper way to accomplish this translation is by using the discount rate to convert the effects of emissions from the year of release into the present value.

Third, entirely separate from the discounting considerations, which reflect the resource tradeoffs facing the actors in the relevant year of action, currency tends to inflate over time. The IWG's calculations for the SC-CO_2 are based upon 2007 dollars, but the purchasing power of the dollar has gone down since then, meaning that $1 in 2007 is worth $1.16 in 2016.[74] It is important to ensure that the analysis is consistent across time frames and makes sense to decisionmakers. Thus, before any calculations are done, the analysts should account for inflation by converting all of the SC-CO_2 values from 2007 dollars into dollars for the year the analysis is taking place (currently, 2016).

Understanding these timing considerations, once ARB has selected a value to use for the SC-CO_2 (or SC-CH_4 or SC-N_2O), it can use those figures to calculate the expected monetized benefits of avoided emissions. To make this calculation, the SC-CO_2 figure should be

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[73] *See, e.g.*, STATE OF WASHINGTON, DEPARTMENT OF ECOLOGY, PRELIMINARY COST-BENEFIT AND LEAST-BURDENSOME ALTERNATIVE ANALYSIS: CHAPTER 173-442 WAC CLEAN AIR RULE & CHAPTER 173-441 WAC REPORTING OF EMISSIONS OF GREENHOUSE GASES 38 (2016), *available at* https://fortress.wa.gov/ecy/publications/documents/1602008.pdf.

[74] *See* CPI Inflation Calculator, http://data.bls.gov/cgi-bin/cpicalc.pl?cost1=1&year1=2007&year2=2016

multiplied by the projected avoided emissions to provide a figure for the monetized benefits of the scoping plan's avoided greenhouse gas emissions. ARB can look to federal rulemakings for guidance on how to conduct this analysis.[75] Specifically, ARB should:

1. Convert the SC-CO_2 values from 2007 dollars to the year of analysis, using a consumer price index inflation calculator[76] (if the values have not yet been converted);
2. Determine the avoided emissions for each Year X between the plan's effective date and the plan's end date of 2030;
3. Multiply the quantity of avoided emissions in Year X by the corresponding SC-CO_2 (or SC-CH_4 or SC-N_2O) in Year X,[77] to calculate the monetary value of damages avoided by avoiding emissions in Year X ;[78]
4. Apply the same discount rate used to calculate the SC-CO_2 to calculate the present value of future effects of emissions from Year X;[79]
5. Sum these values for all relevant years between the plan's effective date and the plan's end date of 2030 to arrive at the total monetized climate benefits of the plan's avoided emissions;[80] and
6. Qualitatively describe in the final discussion of the climate benefits all of the other damages that have been omitted from the SC-CO_2.

The ARB could conduct these calculations with a single, central discount rate for the SC-CO_2, or the agency could conduct the analysis several times, using a range of discount rates for the SC-CO_2, being sure to use the selected discount rate in step 4 for each different iteration.

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[75] *See, e.g.*, Energy Conservation Program: Energy Conservation Standards for Commercial Refrigeration Equipment 79 Fed. Reg. 17,726, at 17,728, 17,773, 17,779, 17,811 (Mar. 28, 2014); U.S. DEPARTMENT OF ENERGY, TECHNICAL SUPPORT DOCUMENT: ENERGY EFFICIENCY PROGRAM FOR CONSUMER PRODUCTS AND COMMERCIAL AND INDUSTRIAL EQUIPMENT 12-22, 13-4 to 13-5, 14-2 (2014).

[76] *See* CPI Inflation Calculator, http://data.bls.gov/cgi-bin/cpicalc.pl

[77] In general, the SC-CO_2 goes up over time because greenhouse gases accumulate, exacerbating the effects of climate change—and therefore the harm from each additional unit of emissions—over time. 2010 TSD, *supra* note 11, at 28.

[78] The SC-CO_2 for a given year encompasses the effects that a ton of carbon dioxide, once emitted in that year, will have stretching into the future over a 300-year time frame. 2010 TSD, *supra* note 11, at 25.

[79] Using a consistent discount rate for both the SC-CO_2 (assessed from the perspective of the actors in the year of emission) and the net present value calculation (assessed from the perspective of the decisionmaker) is important to ensure that the decisionmaker is treating emissions in each time frame similarly. The decisionmaker should not be overvaluing or undervaluing emissions in the present as compared to emissions in the future. NATIONAL ACADEMIES OF SCIENCES, ENGINEERING AND MEDICINE, ASSESSMENT OF APPROACHES TO UPDATING THE SOCIAL COST OF CARBON: PHASE 1 REPORT ON A NEAR-TERM UPDATE 49-50 (2016).

[80] Steps 4 and 5 combined are equivalent to calculating the present value of the stream of future monetary values using the same discount rate as the SC-CO_2 discount rate.

F. ARB should also use the best available estimates of the social cost of methane, the social cost of nitrous oxide, and, as they are developed, the social costs of other greenhouse gases

The IWG has also developed robust federal estimates of the social cost of methane and social cost of nitrous oxide. EPA has used the IWG's estimates for the federal SC-CH_4, but has not yet found an occasion to use the SC-N_2O.[81] California should use these federal SC-CH_4 and SC-N_2O estimates in its economic analyses when these gases are being regulated.

The SC-CH_4 and SC-N_2O methodologies build directly on the SC-CO_2 methodology. Therefore, the same rigorous, consensus-based, transparent process used for the federal SC-CO_2 has shaped the federal SC-CH_4 and federal SC-N_2O estimates. Like the SC-CO_2, the SC-CH_4's emphasis on a global value and selection of discount rates is justified, and if anything the SC-CH_4 is underestimated due to conservative assumptions.

EPA first developed SC-CH_4 estimates based upon a recent peer-reviewed article: Marten et al.[82] The IWG has now similarly endorsed the Marten et al. approach.[83] Marten et al. takes a reasonable (although conservative) approach to estimating the SC-CH_4 and currently constitutes "the best available science" to inform agency regulation. The Marten et al. study maintains the same three integrated assessment models, five socioeconomic-emissions scenarios, equilibrium climate sensitivity distribution, three constant discount rates, and aggregation approach that were agreed upon by the IWG. Consequently, many of the key assumptions underlying the federal SC-CH_4 estimates have already gone through a transparent, consensus-driven, publically reviewed, regularly updated process, as they were borrowed from the IWG's thoroughly vetted methodology.

The IWG's SC-CH_4 and SC-N_2O estimates improve upon an approach that simply adjusts the SC-CO_2 by these other gases' warming potentials because these gas-specific estimates take into account specific characteristics of the gases involved, making the estimates more accurate. For example, the federal SC-CH_4 estimates directly account for the quicker time horizon of methane's effects compared to carbon dioxide, include the indirect effects of methane on radiative forcing, and reflect the complex, nonlinear linkages along the pathway from methane emissions to monetized damages.

Just as the federal SC-CO_2 likely underestimates the true social cost of carbon, the federal SC-CH_4 and SC-N_2O are likely to underestimate the true social cost of methane due to omitted damages and uncertainties regarding the appropriateness of the model.[84]

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[81] *See* Oil and Natural Gas Sector: Emission Standards for New, Reconstructed, and Modified Sources, 81 Fed. Reg. 35,823 (June 3, 2016); Standards of Performance for Municipal Solid Waste Landfills, 81 Fed. Reg. 59,331 (Aug. 29, 2016); Emission Guidelines and Compliance Times for Municipal Solid Waste Landfills, 81 Fed. Reg. 59,275 (Aug. 29, 2016).

[82] Alex L. Marten et al., *Incremental CH_4 and N_2O Mitigation Benefits Consistent With the US Government's SC-CO_2 Estimates*, 15 CLIMATE POLICY 272 (2014).

[83] 2016 TSD ADDENDUM, *supra* note 8.

[84] Alex L. Marten et al., *Incremental CH_4 and N_2O Mitigation Benefits Consistent with the U.S. Government's SC-CO_2 Estimates*, 15 CLIMATE POLICY 272, 277, 292 (2014); Joint SC-CO_2 Comments, *supra* note 5, at 19-20.

Nonetheless, the federal SC-CH_4 and SC-N_2O are the best available estimates of the social costs associated with the emission of one ton of each of these greenhouse gases.

II. ARB should conduct both cost-effectiveness analysis and cost-benefit analysis, in order to satisfy its new statutory requirements

ARB has traditionally used cost-effectiveness analysis for its emissions reduction programs, although the statutory language warrants the agency's use of cost-benefit analysis in addition to cost-effectiveness analysis. AB 32 specifies that "[t]he regulations adopted by the state board pursuant to this section shall achieve the maximum technologically feasible and cost-effective reductions in greenhouse gas emissions from those sources or categories of sources, in furtherance of achieving the statewide greenhouse gas emissions limit."[85] The act defines "cost-effective" as "the cost per unit of reduced emissions of greenhouse gases adjusted for its global warming potential."[86]

Courts have interpreted ARB's authority to interpret this language broadly, but not without limit. In *Association of Irritated Residents v. California Air Resources Board*, the plaintiffs argued that ARB's economic analysis in the 2008 scoping plan was inadequate because, among other factors, it did not create and apply a standard criteria for cost-effectiveness and did not directly compare the environmental and public health effects of different possible measures for compliance. The court refused to strike down the scoping plan on these grounds. Part of the court's holding relied on the agency's assertion that "[t]he limitations of the available modeling tools . . . prevent a comparison between market-based approaches and alternative strategies, such as one that relies only on direct regulation," as well as the fact that the statute at that time did not require comparison of the effects of individual measures, but only of the whole plan.[87] The court deferred to the agency in part because "[d]etermining the best means of identifying and implementing the most cost-effective and feasible measures to maximize greenhouse gas emissions reductions involves numerous highly technical and novel scientific, technical and economic issues."[88]

However, both the statute and the availability of additional modeling techniques have changed since the AB 32 plan was proposed. The statute now explicitly calls for the agency to identify the pollution and health effects of each proposed emission reduction measure.[89] And the economic models used to monetize pollution effects have grown ever more robust. EPA has developed a thorough and standardized method for monetizing the benefits of a whole range of pollutants, including particulate matter, NOx, SO_2, and ozone. In light of these changes since *AIR* was decided, ARB should conduct a thorough, monetized analysis of the full range of significant externalities associated with the compliance alternatives.

[85] Cal. Health & Safety Code § 38560.
[86] Cal. Health & Safety Code § 38505(d).
[87] Ass'n of Irritated Residents v. State Air Resources Bd., 206 Cal. App. 4th 1487, 1501 (2012).
[88] *Id.* at 1502.
[89] Cal. Health & Safety Code § 38562.7.

A. ARB should use a cost-benefit analysis, in addition to its traditional cost-effectiveness analysis, in order to meet the mandate set out in AB 197

AB 197 instructs ARB to "consider the social cost of the emissions of greenhouse gases" in future emissions reduction rules.[90] While ARB has conducted cost-effectiveness and other economic analyses in the past,[91] it should use a cost-benefit analysis for comparing combinations of possible compliance mechanisms, as set out in California Health & Safety Code section 38562.7. That section reads:

> Each scoping plan update developed pursuant to Section 38561 shall identify for each emissions reduction measure, including each alternative compliance mechanism, market-based compliance mechanism, and potential monetary and nonmonetary incentive the following information:
>
> (a) The range of projected greenhouse gas emissions reductions that result from the measure.
>
> (b) The range of projected air pollution reductions that result from the measure.
>
> (c) The cost-effectiveness, including avoided social costs, of the measure.

The advantages of cost-benefit analysis as compared to cost-effectiveness analysis alone are detailed below. While ARB is still required to conduct cost-effectiveness analysis of proposed measures,[92] using cost-benefit analysis to quantify and monetize the benefits of each proposed alternative in the new scoping plan will allow the ARB to best fulfill the mandate set out in section 38562.7. Monetizing, or pricing, benefits is important because it is the most effective way to aggregate information (in this case, the costs and benefits), and determine how to allocate scarce resources to produce the greatest societal benefit.[93]

B. Cost-benefit analysis is better than cost-effectiveness analysis for maximizing social welfare

In accordance with statutory requirements, ARB conducted cost-effectiveness analysis for the rules and regulations it promulgated under AB 32. There are a number of reasons why ARB should use cost-benefit analysis in addition to cost-effectiveness analysis in order to fulfill its statutory mandate, as revised under AB 197.

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[90] Cal. Health & Safety Code § 38562.5.

[91] *See* CALIFORNIA AIR RESOURCES BOARD, CLIMATE CHANGE SCOPING PLAN: A FRAMEWORK FOR CHANGE 84-85 (2008); *see generally* CALIFORNIA AIR RESOURCES BOARD, UPDATED ECONOMIC ANALYSIS OF CALIFORNIA'S CLIMATE CHANGE SCOPING PLAN: STAFF REPORT TO THE AIR RESOURCES BOARD (Mar. 24, 2010).

[92] Cal. Health & Safety Code § 38562.5.

[93] RICHARD L. REVESZ & MICHAEL A. LIVERMORE, RETAKING RATIONALITY: HOW COST-BENEFIT ANALYSIS CAN BETTER PROTECT THE ENVIRONMENT AND OUR HEALTH 13 (2008).

A cost-effectiveness analysis assesses how to achieve a given policy goal most cheaply and does not allow for easy comparison of distinct policy options that provide multiple types of benefits to society.[94] In contrast, cost-benefit analysis assesses a number of potential policy options to determine which combination of the options will result in the greatest net benefits (that is, total benefits, minus total costs) to society, including producers, consumers, and third parties.[95] Cost-benefit analysis allows regulators to select the most effective policy options in a resource-constrained world.

Cost-benefit analysis is a systematic method of calculating and comparing the costs and benefits of different policy approaches, in order to choose the option that maximizes net benefits for society. A cost-benefit analysis involves several steps. First, decisionmakers identify costs and benefits associated with each policy alternative. Because the goal is to select the alternative that maximizes net social welfare, it is essential to account for any costs or benefits that could affect the ultimate decision, including any externalities.[96] An externality is the uncompensated benefit or cost imposed on third parties by a transaction: in other words, an effect whose cost or benefit is not internalized by the acting party. Pollution, like the hazardous chemicals and particulate matter released from power plants or refineries, is one classic example of an externality.[97] Once all significant impacts are cataloged, analysts quantify, and then monetize each effect, to the extent possible, using a common metric (like dollars) to allow comparison between various policies.[98] Established economic methodologies exist for weighing various effects, including impacts to health, safety, and the environment.[99] Once all effects are translated to a common metric, the analyst subtracts costs from benefits to find the net benefits of each approach. The decisionmaker can then select the policy options that generate the greatest net benefits to society.[100] Because cost-benefit analysis involves a detailed assessment of the anticipated outcomes of alternatives, it also assists decisionmakers in communicating to the public and stakeholders why a particular outcome was selected.

In its cost-benefit analysis, ARB should take into account the significant indirect benefits, also known as ancillary or co-benefits, of regulating greenhouse gas emissions. Co-benefits of greenhouse gas regulation include reductions of other pollutants that occur together with greenhouse gases, including criteria pollutants, like particulate matter, and air toxics. Reducing these co-pollutants may improve air quality and lessen some of the adverse public health consequences of air pollution. Consideration of ancillary consequences of ARB's rulemaking is consistent with the statutory mandate set out in AB 32 which tasks ARB with designing greenhouse gas emissions reduction measures that maximize "additional environmental and economic co-benefits for California, and complements the

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[94] *See* CIRCULAR A-4, *supra* note 46, at 9-12. *See also* Denise A. Grab, *Balancing on the Grid Edge: Regulating for Economic Efficiency in the Wake of* FERC v. EPSA, 40 HARV. ENVTL. L. REV. F. 32, 36 (2016).
[95] CIRCULAR A-4, *supra* note 46, at 9-12.
[96] *Id.* at 2-3.
[97] *Cf. id*. at 4.
[98] Where quantification is not possible, the analysis should describe the likely effects qualitatively, and the decisionmaker should still consider those factors in her analysis.
[99] *See* CIRCULAR A-4, *supra* note 46, at 18-26.
[100] Decisionmakers may also balance economic efficiency with other goals, like distributional fairness.

state's efforts to improve air quality."[101] Consideration of co-benefits is also consistent with AB 197, which requires ARB to identify both the "range of projected greenhouse gas emissions reductions that result from the measure" and the "range of projected air pollution reductions that result from the measure."[102] Using comprehensive cost-benefit analysis that accounts for the monetized value of co-benefits enhances ARB's ability to determine which policy options would maximize social welfare. ARB notes that the SC-CO_2 is incomplete because it "does not account for impacts related to changes in criteria pollutants or toxics resulting from GHG focused policies and programs."[103] ARB should address this weakness by using cost-benefit analysis to weigh co-benefits in its economic analysis.

Cost-benefit analysis is the most effective way to fulfill ARB's mandate to "[d]esign the regulations . . . in a manner that . . . seeks to minimize costs and maximize the total benefits to California"[104] and also to "[c]onsider overall societal benefits, including reductions in other air pollutants, diversification of energy sources, and other benefits to the economy, environment, and public health."[105] Without understanding the full range of benefits and costs, it will be difficult, if not impossible, for ARB to appropriately consider overall societal benefits and to maximize benefits (minus costs) to California.

Furthermore, a cost-benefit analysis that quantifies and monetizes, to the extent feasible, the health benefits associated with co-benefit reductions associated with different combinations of emission reduction measures will help decisionmakers and communities to understand the full scope of the effects of pollution that can be avoided under different reduction approaches. In order to "consider the social costs of the emissions of greenhouse gases" and to "prioritize . . . [e]mission reduction rules and regulations that result in direct reductions,"[106] it will be necessary to understand the true extent and impact of those direct reductions. Without quantifying and monetizing these co-benefits in a comprehensive cost-benefit analysis, there is a risk that these co-benefits might be undervalued, especially if a dollar value is put on the greenhouse gas reductions through the requirement to consider the social costs of the greenhouse gas emissions. The same argument applies to the requirement for the scoping plans to identify for each possible compliance measure the range of projected greenhouse gas emission reductions, the range of projected air pollution reductions, and the cost effectiveness, including avoided social costs.[107] To monetize the greenhouse gas reductions with an avoided social cost analysis, without also monetizing the projected air pollution reductions, would undervalue the co-benefits from the air pollution reductions. Cost-benefit analysis can also aid ARB in transparently communicating the significant effects of their policy decisions to the public, by laying out their full anticipated economic effects.

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[101] Cal Health & Safety Code § 38501(h).
[102] Cal Health & Safety Code § 38562.7.
[103] Discussion Draft, *supra* note 3, at 113.
[104] Cal. Health & Safety Code § 38562(b)(1).
[105] Cal Health & Safety Code § 38562(b)(6).
[106] Cal. Health & Safety Code § 38562.5.
[107] Cal. Health & Safety Code § 38562.7.

California can look to EPA's regulatory impact analyses to see how co-benefits have been monetized and used in cost-benefit analysis. For example, in the Clean Power Plan Final Rule regulatory impact analysis, EPA monetized societal costs and benefits such as lost work days, acute bronchitis, emergency room visits for cardiovascular effects and premature mortality based on short-term study estimates.[108] EPA's estimate of the monetized co-benefits is based on the best available science and methods and is supported by the Sciences and Advisory Board of the EPA, as well as the National Academy of Sciences.

In addition to helping ARB fulfill its statutory requirements, conducting comprehensive cost-benefit analysis that includes externalities, like pollutants affecting public health, is also consistent with California's standardized regulatory impact assessment requirements. The Department of Finance's regulations indicate that, when conducting economic impact assessments, agencies must "produce (to the extent possible) quantitative estimates of . . . [t]he benefits of the regulations, including but not limited to benefits to the health, safety, and welfare of California residents, worker safety, and the state's environment and quality of life, among any other benefits identified by the agency."[109]

In contrast to a cost-benefit analysis, the cost-effectiveness analysis historically used in California's greenhouse gas emission reduction decisions is less comprehensive in its assessment of effects, fails to compare alternatives in a way that is useful for prioritizing actions with the greatest net benefits, and cannot communicate information to the public as fully or as transparently. For example, in the 2008 initial AB 32 Scoping Plan, ARB set forth both costs and benefits of proposed greenhouse gas emissions reduction programs, but failed to monetize societal benefits in such a way that they could be directly compared to costs. In evaluating AB 32 and its subsequent regulations, ARB used a cost-effectiveness approach, as the board understood it to be required under the statute. This approach placed the focus on the costs of proposed measures to energy suppliers, other businesses, their customers, and to California's economy at-large but in doing so, did not fully monetize social externalities, including co-benefits. Cost-benefit analysis is the most analytically sound way to choose among policy options in a resource-limited world.

Should ARB choose to explore reductions beyond those that are mandated in the new 2030 targets, it should use cost-benefit analysis. Cost-benefit analysis is most effective when it can also be used to set the stringency of the standard, in addition to the selection of policy approaches to achieve the goal. While the scoping plan adopts a 40 percent reduction below 1990 levels by 2030 as the minimum target in all three of the alternative reduction measures, ARB may have the option to reduce greenhouse gases even further.[110] If considering further reductions is a possibility, ARB should use cost-benefit analysis to guide the setting of such targets.

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[108] U.S. ENVIRONMENTAL PROTECTION AGENCY, REGULATORY IMPACT ANALYSIS FOR THE CLEAN POWER PLAN FINAL RULE tbl.ES-6 at ES-12 to ES-14 (2016).
[109] 1 Cal. Code Reg. § 2003(a)(3)(F).
[110] Cal. Health & Safety Code § 38566 ("[T]he state board shall ensure that statewide greenhouse gas emissions are reduced to **at least** 40 percent below the statewide greenhouse gas emissions limit no later than December 31, 2030." (emphasis added)).

If ARB chooses to simply meet the minimum 2030 targets with the measures laid out in the proposed scoping plan, then the reduction in greenhouse gases will be consistent across different alternative scenarios (a total of 40% below 1990 levels by 2030), which means that the social value of greenhouse gas reductions are likely to remain consistent between alternatives (possibly with some variation if the makeup of the mixture of greenhouse gases reduced changes among alternatives). It is nonetheless important to use the SC-CO_2, SC-CH_4, and/or SC-N_2O in the cost-benefit analysis so that all of the costs and benefits associated with each proposed measure are transparent to the public. However, most of the difference in net benefits between the different alternatives will stem from differences in co-benefit reductions, as well as compliance costs. Once the analysis is complete, ARB will be able to determine which of the alternative compliance scenarios results in the greatest net benefits to society, and will be able to use that information in conjunction with other statutory requirements to select the optimal combination of reduction measures.

Conclusion

In brief, ARB should use the federal SC-CO_2 and SC-CH_4 based on the best available science as the value of the social cost of greenhouse gases to fulfill its mandate under AB 197. Furthermore, California should use cost-benefit analysis to evaluate policy alternatives in order to ensure that it maximizes the benefits to society of the updated program.

Respectfully submitted,

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Exhibits

Exhibit A

November 7, 2016

Attn: EERE-2015-BT-STD-0016, Energy Conservation Standards for WICF Refrigeration Systems
EERE-2014-BT-STD-0031, Energy Conservation Standards for Residential Furnaces

Comments submitted by: Environmental Defense Fund, Institute for Policy Integrity at New York University School of Law, Natural Resources Defense Council, and Union of Concerned Scientists.

Our organizations respectfully submit these comments regarding DOE's valuation of the benefits of its energy efficiency standards—specifically, the use of the Social Cost of Carbon, and the non-use of the Social Cost of Methane methodology. Our organizations may separately and independently submit other comments regarding the proposed standards themselves.

We strongly affirm that the current Social Cost of Carbon (SCC) values are sufficiently robust and accurate to continue to be the basis for regulatory analysis going forward. We further encourage DOE to monetize the benefits of other greenhouse gas reductions, such as through the Social Cost of Methane (SCM) methodology. As demonstrated below, if anything, current values are significant underestimates of the SCC and SCM. As economic and scientific research continues to develop in the future, the values should be revised, and we offer recommendations for that future revision.

Our comments are summarized in six sections:

1. Introduction: The SCC is an important policy tool.

2. The Interagency Working Group's (IWG) analytic process was science-based, open, and transparent.

3. The SCC is an important and accepted tool for regulatory policy-making, based on well-established law and fundamental economics.

4. Recommendations on further refinements to the SCC.

5. Support for the Social Cost of Methane methodology, and recommendations on refinements.

6. Conclusion: Recommendations on the use of the SCC and Social Cost of Methane in regulatory impact analyses.

1. Introduction: The SCC is an important policy tool.

The SCC estimates the economic cost of climate impacts—specifically the additional economic harm caused by one additional metric ton of carbon dioxide (CO_2) emissions. SCC calculations are important for evaluating the costs of activities that produce greenhouse gas emissions and contribute to climate change, such as burning fossil fuels to produce energy. The SCC is also important for evaluating the benefits of policies that would reduce the amount of those emissions going into the atmosphere.

As with all economic impact analyses, the exercise can only provide a partial accounting of the costs of climate change (those most easily monetized) and inevitably involves incorporating elements of uncertainty. However, accounting for the economic harms caused by climate change is a critical component of sound benefit-cost analyses of regulations that directly or indirectly limit greenhouse gases. This endeavor is important because benefit-cost analysis is a central tool of regulatory policy in the United States, first institutionalized in a 1981 executive order by President Ronald Reagan. The executive order currently in effect provides that agencies:

- "[P]ropose or adopt a regulation only upon a reasoned determination that its benefits justify its costs (recognizing that some benefits and costs are difficult to quantify); . . .
- "[S]elect, in choosing among alternative regulatory approaches, those approaches that maximize net benefits (including potential economic, environmental, public health and safety, and other advantages; distributive impacts; and equity); . . .
- "In applying these principles, each agency is directed to use the best available techniques to quantify anticipated present and future benefits and costs as accurately as possible. Where appropriate and permitted by law, each agency may consider (and discuss qualitatively) values that are difficult or impossible to quantify, including equity, human dignity, fairness, and distributive impacts."[1]

Benefit-cost analysis has long been a staple of agency rulemakings, usually conducted as part of the regulatory impact analysis associated with proposed rules. Even though the analysis is generally not able to encompass all of the effects of a policy, and it is challenging to translate impacts on health, mortality, and welfare into dollar values, benefit-cost analysis is an important economic tool to help inform decision-makers about the societal benefits of different policy choices. Of course, benefit-cost analysis cannot be the sole criterion for making regulatory decisions, especially in cases where there are overriding public health, equity, or safety imperatives.[2] And in a few instances, legal protections prohibit the consideration of benefit-cost analysis.

Without an SCC estimate, regulators would by default be using a value of zero for the benefits of reducing carbon pollution, implying that carbon pollution has no costs. That, sadly, is not the case, as evidenced by the large body of research outlining the sobering health, environmental, and economic impacts of rising temperatures, extreme weather, intensifying smog, and other climate impacts. If anything, most evidence points to the fact that current numbers significantly underestimate the SCC. It would be arbitrary for a federal agency to weigh the societal benefits and

[1] Exec. Order No. 13,563 §§ 1(b)-(c), 76 Fed. Reg. 3,821 (Jan. 18, 2011); *see also infra* on how this and subsequent orders, including Exec. Order No. 13,609, inform the use of a global SCC value.

[2] President Clinton issued Executive Order 12,866 in 1993, establishing new guidance for benefit-cost analysis and explicitly directing agencies to consider, in addition to costs and benefits for which quantitative estimates are possible, "qualitative measures of costs and benefits that are difficult to quantify, but nevertheless essential to consider." Exec. Order No. 12,866 § 1(a), 58 Fed. Reg. 51,735 (Sept. 30, 1993).

costs of a rule with significant carbon pollution effects but to assign no value at all to the considerable benefits of reducing carbon pollution.[3]

2. The IWG's analytic process was science-based, open, and transparent.

To facilitate accounting for the costs of climate impacts and the benefits of reducing carbon pollution in regulatory proceedings undertaken by different agencies, the United States government assembled an Interagency Working Group (IWG) to develop an estimate of a social cost of carbon that can be utilized in rulemakings and other pertinent settings across the federal government.[4] The IWG's estimates—first released in 2010 and updated in 2013 and 2015—have been used in numerous benefit-cost analyses related to federal rulemakings.[5] The IWG recently released an updated set of SCC estimates, centered at approximately $40 per metric ton of CO_2 for emissions in the year 2015, in 2015 dollars at a 3% discount rate.[6] The 2015 SCC estimates are higher than those

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[3] Ctr. for Biological Diversity v. Nat'l Highway Traffic Safety Admin., 538 F.3d 1172, 1199 (9th Cir. 2008) (holding unlawful NHTSA's fuel economy standards for passenger vehicles when NHTSA ascribed a value of "zero" to the benefits of mitigating carbon dioxide, reasoning that "NHTSA assigned no value to *the most significant benefit* of more stringent CAFE standards: reduction in carbon emissions" (emphasis added)).

[4] The IWG involved a large number of agencies, including the Council of Economic Advisers, Council on Environmental Quality, Department of Agriculture, Department of Commerce, Department of Transportation, Environmental Protection Agency, National Economic Council, Office of Energy and Climate Change, Office of Management and Budget, Office of Science and Technology Policy, and the Department of the Treasury. *See* INTERAGENCY WORKING GROUP ON THE SOCIAL COST OF CARBON, TECHNICAL SUPPORT DOCUMENT: SOCIAL COST OF CARBON FOR REGULATORY IMPACT ANALYSIS UNDER EXECUTIVE ORDER 12,866 (2010) [hereinafter "2010 TSD"], *available at* http://www.whitehouse.gov/sites/default/files/omb/inforeg/for-agencies/Social-Cost-of-Carbon-for-RIA.pdf.

[5] The SCC has been used in numerous notice-and-comment rulemakings by various agencies since it was published in 2010, and each of these occasions has provided opportunity for public comment on the SCC. *See, e.g.*, Energy Conservation Program: Energy Conservation Standards for Residential Clothes Washers, 77 Fed. Reg. 32,381 (May 31, 2012); Energy Conservation Program: Energy Conservation Standards for Residential Dishwashers, 77 Fed. Reg. 31,964 (May 30, 2012); Energy Conservation Program: Energy Conservation for Battery Chargers and External Power Supplies, 77 Fed. Reg. 18,478 (Mar. 27, 2012); Energy Conservation Program: Energy Conservation Standards for Standby Mode and Off Mode for Microwave Ovens, 77 Fed. Reg. 8526 (Feb. 14, 2012); Energy Conservation Program: Energy Conservation Standards for Distribution Transformers, 77 Fed. Reg. 7282 (Feb. 10, 2012); Energy Conservation Program for Certain Industrial Equipment: Energy Conservation Standards and Test Procedures for Commercial Heating, Air-Conditioning, and Water-Heating Equipment, 77 Fed. Reg. 2356 (Jan. 17, 2012); 2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards, 76 Fed. Reg. 74,854 (Dec. 1, 2011); Oil and Natural Gas Sector: New Source Performance Standards and National Emission Standards for Hazardous Air Pollutants Reviews, 76 Fed. Reg. 52,738 (Aug. 23, 2011); Energy Conservation Program: Energy Conservation Standards for Residential Furnaces and Residential Central Air Conditioners and Heat Pumps, 76 Fed. Reg. 37,549 (June 27, 2011); Energy Conservation Program: Energy Conservation Standards for Residential Clothes Dryers and Room Air Conditioners, 76 Fed. Reg. 22,324 (Apr. 21, 2011); Energy Conservation Program: Energy Conservation Standards for Fluorescent Lamp Ballasts, 76 Fed. Reg. 20,090 (Apr. 11, 2011); National Emission Standards for Hazardous Air Pollutants: Mercury Emissions from Mercury Cell Chlor-Alkali Plants, 76 Fed. Reg. 13,852 (Mar. 14, 2011); Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles, 75 Fed. Reg. 74,152 (Nov. 30, 2010); Standards of Performance for New Stationary Sources and Emission Guidelines for Existing Sources: Sewage Sludge Incineration Units, 75 Fed. Reg. 63,260 (Oct. 14, 2010); Energy Conservation Program: Energy Conservation Standards for Residential Refrigerators, Refrigerator-Freezers, and Freezers, 75 Fed. Reg. 59,470 (Sept. 27, 2010); Federal Implementation Plans to Reduce Interstate Transport of Fine Particulate Matter and Ozone, 75 Fed. Reg. 45,210 (Aug. 2, 2010). The undersigned organizations have provided comment on the SCC in a number of these proceedings.

[6] INTERAGENCY WORKING GROUP ON THE SOCIAL COST OF CARBON, TECHNICAL SUPPORT DOCUMENT: TECHNICAL UPDATE OF THE SOCIAL COST OF CARBON FOR REGULATORY IMPACT ANALYSIS UNDER EXECUTIVE ORDER 12,866 (2015); *see also* INTERAGENCY WORKING GROUP ON THE SOCIAL COST OF CARBON, TECHNICAL SUPPORT DOCUMENT: TECHNICAL UPDATE OF THE SOCIAL COST OF CARBON FOR REGULATORY IMPACT ANALYSIS UNDER EXECUTIVE ORDER 12,866 (2013) [hereinafter "2013 TSD"], *available at* http://www.whitehouse.gov/sites/default/files/omb/assets/inforeg/technical-update-social-cost-of-carbon-for-regulator-impact-analysis.pdf.

from 2010, reflecting the growing understanding of the costs that climate impacts will impose on society.

The increase in the SCC estimate is important because it reflects the growing scientific and economic research on the risks and costs of climate change, but is still very likely an underestimate of the economic cost of carbon emissions. The increase also reflects the costs of climate change that we are already experiencing, such as those associated with sea level rise and rising temperatures. Climate change is making coastal flooding, drought, and impacts from extreme weather worse. A rapidly increasing body of evidence has linked ever more recent events directly to climate change.[7]

The analytic work of the IWG has been transparent. The 2010 Technical Support Document (TSD) set out in detail the IWG's decision-making process with respect to how it assessed and employed the models.[8] Furthermore, the Government Accountability Office (GAO) found that "the working group's processes and methods reflected the following three principles: *Used consensus-based decision making, Relied on existing academic literature and models, and Took steps to disclose limitations and incorporate new information."*[9]

Because the 2013 IWG made no changes to the input assumptions and procedures for deriving its SCC estimates, the 2013 TSD discussed only how the three Integrated Assessment Models (IAMs) used in the analysis were updated in the academic literature over the three-year interim period by the independent researchers who have developed these models. The 2013 TSD also established that the increase in the SCC estimate from 2010 to 2013 resulted solely from updates to the three underlying IAMs.[10]

The 2015 TSD update provided detailed responses[11] to public comments collected through an opportunity for public participation initiated by the Office of Management and Budget (OMB).[12] Additionally, the comment period on these proposed standards is yet another opportunity for continued dialogue about areas requiring further study. Such repeated comment processes and updates demonstrate that the IWG's SCC estimates were developed—and are being used—transparently. Given their strong grounding in the best science available, nothing should prevent the current, continued use of this well-established estimate. As economic and scientific research continues to develop, future revisions will be able to further refine existing estimates based on the latest peer-reviewed literature and the latest updates to the quality of the overall modeling exercise.

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[7] *See generally* Thomas C. Peterson et al. eds., *Explaining Extreme Events of 2012 from a Climate Perspective*, 94 BULL. AMER. METEOR. SOC. S1-74 (2013), and IPCC, *Special Report: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (2012). On the scientific research connecting weather and other climate-related events to climate change, see Peter A. Stott et al., "Attribution of Weather and Climate-Related Events." In *Climate Science for Serving Society*, edited by Ghassem R. Asrar and James W. Hurrell. Netherlands: Springer s307-37 (2013).

[8] *See generally* 2010 TSD, *supra* note 4.

[9] GAO, REGULATORY IMPACT ANALYSIS: Development of Social Cost of Carbon Estimates, GAO-14-663 (2014).

[10] The 2010 and 2013 IWGs did very little to adjust the three IAMs. The main adjustment by IWG was to DICE to ensure that the IAM had an exogenous growth path that matched FUND and PAGE for the purposes of modeling various socio-economic and emission scenarios. *Id.* at 24.

[11] OMB & Interagency Working Group, Response to Comments on Social Cost of Carbon (July 2015).

[12] OMB, Notice of Availability and Request for Comments, Technical Support Documents: Social Cost of Carbon for Regulatory Impact Analysis, 78 Fed. Reg. 70,586 (Nov. 26, 2013).

3. The SCC is an important and accepted tool for regulatory policy-making based on well-established law and fundamental economics.

The legal and analytic basis for using the SCC is clear and well established. ***As a matter of law and economics, uncertainty in benefits estimates does not mean they should be excluded from regulatory impact analyses***. No benefit or cost estimates are certain. Further, the courts have explicitly rejected the argument that uncertainty in assessing the costs of climate impacts provided a basis for ignoring them in assessing the benefits and costs of regulations, and executive orders dating back as far as the Reagan administration have all issued guidelines specifying explicit consideration of benefits even if the precise size of the benefit is uncertain.

In 2008, the U.S. Court of Appeals for the Ninth Circuit determined that agencies could not assign a zero dollar value to the social costs of the impacts of climate change. It determined that *failing* to count SCC benefits would be illegal. In this case, the National Highway Traffic Safety Administration (NHTSA) had decided not to count any avoided climate damages in issuing fuel economy standards. The court concluded: "NHTSA's reasoning is arbitrary and capricious for several reasons. First while the record shows that there is a ***range of values***, the value of carbon emission reductions is certainly ***not zero*** (emphasis added)."[13]

Like the Court of Appeals, executive orders dating back to 1981 have also required agencies to assess benefits and costs even when significant uncertainty exists. Every president since (and including) Ronald Reagan has issued directives requiring that agencies conduct cost-benefit analyses of proposed regulations where permitted by statute.[14] Specifically, agencies are directed to "take into account benefits and costs, both quantitative and qualitative . . . and use the ***best available techniques*** to quantify anticipated present and future benefits and costs as accurately as possible."[15] The IWG's use of Integrated Assessment Models (IAMs) reflects the best available, peer-reviewed science to tally the benefits and costs of specific regulations with impacts on carbon dioxide emissions. While we address ways for improvement in the next section, current IAMs include benefits and costs that have been quantified to date.

The bottom line is that the IWG has properly and lawfully used the best available techniques to quantify the benefits of carbon emission reductions, basing its analysis on the peer-reviewed literature. When agencies use the IWG's estimates of the SCC to calculate the benefits of a rulemaking, they have taken, and will continue to take, comment on the SCC and the process used to derive that value. That is what the law—and good policy—requires.

The IWG Correctly Used a Global SCC Value.

To design the economically efficient policies necessary to forestall severe and potentially catastrophic climate change, all countries must use a global SCC value. Given that the United States and many other significant players in the international climate negotiations have already applied a global SCC framework in evaluating their own climate policies, the continued use of the global value in U.S. regulatory decisions may be strategically important as the United States seeks to set an example for other countries, harmonize regulatory systems, and take the lead in ongoing

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[13] Ctr. for Biological Diversity v. Nat'l Highway Traffic Safety Admin., 538 F.3d 1172, 1200 (9th Cir. 2008) (emphases added).

[14] Stuart Shapiro, *The Evolution of Cost-Benefit Analysis in U.S. Regulatory Decisionmaking*, *in* HANDBOOK ON THE POLITICS OF REGULATION 385-392 (David Levi-Faur ed., 2011).

[15] Exec. Order No. 13,563 §§ 1(a)-(c), 76 Fed. Reg. 3,821 (Jan. 18, 2011) (emphasis added).

international negotiations. Binding legal obligations, basic ethical responsibilities, and practical considerations further counsel in favor of the United States using a global SCC value.

To avoid a global "tragedy of the commons" and an economically inefficient degradation of the world's climate resources, all countries should set policy according to a global SCC value. The climate and clean air are global common resources, meaning they are free and available to all countries, but any one country's use—i.e., pollution—imposes harms on the polluting country as well as the rest of the world. Because greenhouse gases do not stay within geographic borders but rather mix in the atmosphere and affect climate worldwide, each ton of carbon pollution emitted by the United States not only creates domestic harms, but also imposes additional and large externalities on the rest of the world, including disproportionate harms to some of the least-developed nations. Conversely, each ton of carbon pollution abated in another country will benefit the United States along with the rest of the world.

If all countries set their greenhouse gas emission levels based on only their domestic costs and benefits, ignoring the large global externalities, the collective result would be substantially sub-optimal climate protections and significantly increased risks of severe harms to all nations, including to the United States. "[E]ach pursuing [only its] own best interest . . . in a commons brings ruin to all."[16] By contrast, a global SCC value would require each country to account for the full damages of its greenhouse gas pollution and so to collectively select the efficient level of worldwide emissions reductions needed to secure the planet's common climate resources.

Thus, well-established economic principles demonstrate that the United States stands to benefit greatly if all countries apply a global SCC value in their regulatory decisions. A rational tactical option in the effort to secure that economically efficient outcome is for the United States to continue using a global SCC value itself. The United States is engaged in a repeated strategic game of international negotiations and regulatory coordination, in which several significant players—including the United States—have already adopted a global SCC framework.[17] For the United States to now depart from this implicit collaborative dynamic by reverting to a domestic-only SCC estimate could undermine the country's long-term interests in future climate negotiations and could jeopardize emissions reductions underway in other countries, which are already benefiting the United States.[18] A domestic-only SCC value could be construed as a signal that the United States does not recognize or care about the effects of its policy choices on other countries, and signal that it would be acceptable for other countries to ignore the harms they cause the United States. Further, a sudden about-face could undermine the United States' credibility in negotiations. The United States has recently reasserted its desire to take a lead in both bilateral and international climate negotiations.[19] To set an example for the rest of the world, to advance its own long-term climate interests, and to secure greater cooperation toward reducing global emissions, strategic factors support the continued use a global SCC value in U.S. regulatory decisions.

Though the Constitution balances the delegation of foreign affairs power between the executive and legislative branches, "[t]he key to presidential leadership is the negotiation function. Everyone agrees that the President has the exclusive power of official communication with foreign governments."[20] The development and analysis of U.S. climate regulations are essential parts of the

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[16] Garrett Hardin, *The Tragedy of the Commons*, 162 SCIENCE 1243 (1968).

[17] *See infra* notes 26 and 32 to 35, and accompanying text, detailing use of a global SCC value by Canada, Mexico, the United Kingdom, France, Germany, and Norway.

[18] *See* ROBERT AXELROD, THE EVOLUTION OF COOPERATION 10-11 (1984) (on repeated prisoner's dilemma games).

[19] EXEC. OFFICE OF THE PRES., THE PRESIDENT'S CLIMATE ACTION PLAN 17-21 (2013).

[20] Phillip R. Trimble, *The President's Foreign Affairs Power*, 83 AM. J. OF INTL. L. 750, 755 (1989).

dialogue between the United States and foreign countries about climate change. Using a global SCC value communicates a strong signal that the United States wishes to engage in reciprocal actions to mitigate the global threat of climate change. The President is responsible for developing and executing the negotiation strategy to achieve the United States' long-term climate interests. Currently, the President has instructed federal agencies to use a global SCC value as one important step that encourages other countries to take reciprocal actions that also account for global externalities. The President's constitutional powers to negotiate international agreements would be seriously impaired if federal agencies were forced to stop relying on a global SCC value.[21]

In fact, the United States has already begun to harmonize with other countries its policies on climate change and on the valuation of regulatory benefits. The recent U.S.-China agreement is but the latest example. For instance, the United States has entered into a joint Regulatory Cooperation Council with Canada, which has adopted a work plan that commits the two countries to synchronizing "aggressive" greenhouse gas reductions, especially in the transportation sector.[22] A separate Regulatory Cooperation Council with Mexico calls generally for improving and harmonizing policy "by strengthening the analytic basis of regulations,"[23] and its work plan acknowledges the transboundary nature of environmental risks.[24] Mexico and Canada have both adopted greenhouse gas standards for vehicles that harmonize with the U.S. standards[25] and that calculate benefits according to a global SCC value.[26] Canada has also used the IWG's global SCC value in developing carbon dioxide standards for its coal-fired power plants, estimating $5.6 billion

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[21] *See* David Remnick, *The Obama Tapes*, NEW YORKER, Jan. 23, 2014, *available at* http://www.newyorker.com/online/blogs/newsdesk/2014/01/the-obama-tapes.html (quoting interview with President Obama: "[M]y goal has been to make sure that the United States can genuinely assert leadership in this issue internationally, that we are considered part of the solution rather than part of the problem. And if we are at the table in that conversation with some credibility, then it gives us the opportunity to challenge and engage the Chinese and the Indians, as long as we take into account the fact that they've still got, between the two of them, over a billion people in dire poverty. . . . This is why I'm putting a big priority on our carbon action plan here. It's not because I'm ignorant of the fact that these emerging countries are going to be a bigger problem than us. It's because it's very hard for me to get in that conversation if we're making no effort.").

[22] UNITED STATES-CANADA REGULATORY COOPERATION COUNCIL, JOINT ACTION PLAN, at 16 (2011), *available at* http://www.whitehouse.gov/sites/default/files/omb/oira/irc/us-canada_rcc_joint_action_plan.pdf.

[23] UNITED STATES-MEXICO HIGH-LEVEL REGULATORY COOPERATION COUNCIL, WORK PLAN at 3 (2012), *available at* http://www.whitehouse.gov/sites/default/files/omb/oira/irc/united-states-mexico-high-level-regulatory-cooperation-council-work-plan.pdf.

[24] *Id.* at 11 (noting that oil drilling activities in the Gulf of Mexico conducted by either country "present risks for both countries, and both countries would benefit from a common set of drilling standards").

[25] *See* INT'L COUNCIL ON CLEAN TRANSP., MEXICO LIGHT-DUTY VEHICLE CO_2 AND FUEL ECONOMY STANDARDS 4 (Policy Update, July 2013), *available at* http://www.theicct.org/sites/default/files/publications/ICCTupdate_Mexico_ LDVstandards_july2013.pdf (noting that Mexico's standards were based on the U.S. and Canadian standards).

[26] *See* Heavy-Duty Vehicle and Engine Greenhouse Gas Emission Regulations, SOR/2013-24, 147 Can. Gazette pt. II, 450, 544 (Can.), *available at* http://canadagazette.gc.ca/rp-pr/p2/2013/2013-03-13/html/sor-dors24-eng.html ("The SCC is used in the modelling of the cost-benefit analysis . . . . It represents an estimate of the economic value of avoided climate change damages *at the global level*. . . . The values used by Environment Canada are based on the extensive work of the U.S. Interagency Working Group on the Social Cost of Carbon.") (emphasis added); Instituto Nacional de Ecología, Mexico, Regulatory Impact Analysis on *PROY-NOM-163- SEMARNAT-ENER-SCFI-2012, Emisiones de bióxido de carbono (CO_2) provenientes del escape y su equivalencia en términos de rendimiento de combustible, aplicable a vehículos automotores nuevos de peso bruto vehicular de hasta 3857 kilogramos* (July 5, 2012), *available at* http://207.248.177.30/mir/formatos/defaultView.aspx?SubmitID=273026 ("[S]e obtienen beneficios ambientales por la reducción del consumo de combustible, los cuales se reflejan en beneficios a la salud de la población en el caso de contaminantes criterio, y en *beneficios globales para las emisiones evitadas de CO_2*.") (emphasis added).

(Canadian dollars) worth of global climate benefits.[27] The direct U.S. share of the net benefits from that Canadian regulation will likely total in the hundreds of millions of dollars.[28]

Further efforts at regulatory harmonization are currently underway. For example, the United States is now negotiating a Transatlantic Trade and Investment Partnership with the European Union, and a key element is regulatory coordination.[29] The European Union has already adopted an Emissions Trading Scheme (ETS) to cap its greenhouse gas emissions, and its Aviation Directive is just one of the climate policies that could be shaped by these negotiations.[30] The European Commission has indicated its willingness to further reduce its ETS cap if other major emitters make proportional commitments[31]—a result that will only occur if countries consider more than their own domestic costs and benefits from reducing greenhouse gas emissions. Moreover, several individual European nations—including the United Kingdom,[32] France,[33] Germany,[34] and Norway[35]—have adopted a global SCC value for use in their regulatory analyses. Some other European countries, such as Sweden, have adopted carbon taxes that implicitly operate as a high SCC that accounts for global externalities.[36]

As further evidence of how the United States' use of a global SCC value is already influencing other international actors to follow suit, the International Monetary Fund (IMF) applies in its policy

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[27] Reduction of Carbon Dioxide Emissions from Coal-Fired Generation of Electricity Regulations, SOR/2012-167, 146 Can. Gazette pt. II, 1951, 2000, 2044 (Can.), *available at* http://www.gazette.gc.ca/rp-pr/p2/2012/2012-09-12/html/sor-dors167-eng.html.

[28] $5.6 billion in Canadian dollars is worth $5.0 billion in U.S. dollars (using February 2014 conversion rates). Seven to twenty-three percent of $5 billion is between $350 million and $1.15 billion. *See* 2010 TSD, *supra* note 4, at 11 (provisionally calculating the direct U.S. share of a global SCC value at between 7-23%, though ultimately recommending "that using the global (rather than domestic) value . . . is the appropriate approach," for reasons consistent with these comments).

[29] *See* EUR. COMM'N, TRANSATLANTIC TRADE AND INVESTMENT PARTNERSHIP: THE REGULATORY PART (2013).

[30] *See* SIERRA CLUB, THE TRANSATLANTIC FREE TRADE AGREEMENT: WHAT'S AT STAKE FOR COMMUNITIES AND THE ENVIRONMENT at 9-10 (2013).

[31] Eur. Comm'n, Working with International Partners, http://www.e.europa.eu/clima/policies/international ("The EU is offering to step up its 2020 reduction targets to 30% if other major economies commit.").

[32] ECONOMICS GROUP, DEFRA, U.K., THE SOCIAL COST OF CARBON AND THE SHADOW PRICE OF CARBON: WHAT THEY ARE, AND HOW TO USE THEM IN ECONOMIC APPRAISAL IN THE UK 1 (2007); *see also* Ministry of Finance, Norway, Cost-Benefit Analysis: Carbon Price Paths, *available at* http://www.regjeringen.no/en/dep/fin/Documents-and-publications/official-norwegian-reports-/2012/nou-2012-16-2/10.html?id=713585 ("The United Kingdom has changed its method for the valuation of greenhouse gas emissions. Prior to 2009, the estimated global social cost of carbon was used, but one [sic] has now switched over to pricing in line with the necessary marginal cost of meeting long-term domestic emission reduction targets in conformity with the EU Climate and Energy Package.").

[33] *See* Balázs Égert, *France's Environmental Policies: Internalising Global and Local Externalities* 8-10 (OECD Economics Department Working Papers No. 859, 2011), *available at* http://dx.doi.org/10.1787/5kgdpn0n9d8v-en (discussing global impacts and France's history of calculating the SCC); Oskar Lecuyer & Philippe Quirion, funded by the European Union's Seventh Framework Programme, *Choosing Efficient Combinations of Policy Instruments for Low-Carbon Development and Innovation to Achieve Europe's 2050 Climate Targets—Country Report: France* at 8 (2013) (noting the prospects for a carbon tax in 2014-15, and explaining that "A 2009 stakeholder and expert group led by the 'Conseil d'analyse stratégique' (a public body in charge of expertise and stakeholder dialogue) set the optimal level of the carbon tax (the social cost of carbon) at € 32/tCO 2 in 2010, and rising to € 100 in 2030 and € 200 in 2050.").

[34] Testimony of Howard Shelanski, OIRA Admin., before the H. Comm. on Oversight & Gov't Reform's Subcomm. on Energy Policy, Healthcare, and Entitlements, July 18, 2013, at 3 (explaining that the global SCC value estimated by the IWG is consistent with values used by Germany and the United Kingdom).

[35] *See* Ministry of Finance, *supra* note 32 (explaining that, for projects not already covered by a binding emission limitation, the carbon price should "be based on the marginal social cost of carbon," meaning "the global cost of emitting one additional tonne of CO_2e"). Note that Norway has joined the E.U.'s trading scheme.

[36] Henrik Hammar, Thomas Sterner & S. Åkerfeldt, *Sweden's CO_2 Tax and Taxation Reform Experiences*, in REDUCING INEQUALITIES: A SUSTAINABLE DEVELOPMENT CHALLENGE (Genevey, R. et al. eds., 2013).

reviews an SCC estimate based on the IWG number.[37] Given the potential influence of the IMF on the environmental policies of developing countries,[38] the pull that the IWG's global estimate has at the IMF could be very advantageous to the United States, by motivating industrializing countries to use similar numbers in the future.

In addition to this compelling strategic argument—namely, that it is rational for the United States and other countries to continue their reciprocal use of a global SCC value to achieve the economically efficient outcome on climate change (and avoid catastrophic climate impacts)—legal obligations further prescribe using a global SCC value. A basic ethical responsibility to prevent transboundary environmental harms has been enshrined in customary international law.[39] For the United States to knowingly set pollution levels in light of only domestic harms, willfully ignoring that its pollution directly imposes environmental risks—including catastrophic risks—on other countries, would violate norms of comity among countries. The United States would be knowingly causing foreseeable harm to other countries, without compensation or just cause. Given that the nations most at risk from climate change are often the poorest countries in the world, such a policy would also violate basic and widely shared ethical beliefs about fairness and distributive justice. Indeed, taking a global approach to measuring climate benefits is consistent with the ideals of transboundary responsibility and justice that the United States commits to in other foreign affairs.[40]

Binding international agreements also require consideration and mitigation of transboundary environmental harms. Notably, the United Nations Framework Convention on Climate Change—to which the United States is a party—declares that countries' "policies and measures to deal with climate change should be cost-effective so as to ensure *global benefits* at the lowest possible cost."[41] The Convention further commits parties to evaluating global climate effects in their policy decisions, by "employ[ing] appropriate methods, for example *impact assessments* . . . with a view to minimizing adverse effects on the economy, on public health and on the quality of the environment, of projects or measures undertaken by them to mitigate or adapt to climate change."[42] The unmistakable implication of the Convention is that parties—including the United States—must account for global economic, public health, and environmental effects in their impact assessments.

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[37] *E.g.*, Benedict Clements et al., International Monetary Fund, *Energy Subsidy Reforms: Lessons and Implications* 9 (IMF Policy Paper, Jan. 28, 2013).

[38] *See* Natsu Taylor Saito, *Decolonization, Development, and Denial*, 6 FL. A & M U. L. REV. 1, 16 (2010) (quoting former IMF counsel as saying "today it is common to find these institutions [IMF and World Bank] requiring their borrowing member countries to accept and adhere to prescribed policies on environmental protection").

[39] *See* PHILIPPE SANDS, PRINCIPLES OF INTERNATIONAL ENVIRONMENTAL LAW 241 (2d ed. 2003) (noting that "the responsibility not to cause damage to the environment of other states or of areas beyond national jurisdiction has been accepted as an obligation by all states[;] . . . there can be no questions but that Principle 21 [of the Stockholm Declaration on the Human Environment] reflects a rule of customary international law").

[40] *See* Paul Baer & Ambuj Sagar, *Ethics, Rights and Responsibilities*, in CLIMATE CHANGE SCIENCE AND POLICY (Stephen Schneider et al., eds., 2009).

[41] United Nations Framework Convention on Climate Change, May 9, 1992, S. Treat Doc. No. 102-38, 1771 U.N.T.S. 107, Article 3(3) (emphasis added); *see also id.* at Article 3(1) ("The Parties should protect the climate system for the *benefit of present and future generations of humankind*, on the basis of *equity* and in accordance with their common but *differentiated responsibilities* and respective capabilities.") (emphasis added); *id.* at Article 4(2)(a) (committing developed countries to adopt policies that account for "the need for equitable and appropriate contributions by each of these Parties to the global effort").

[42] *Id.* at Article 4(1)(f) (emphasis added); *see also id.* at Article 3(2) (requiring parties to give "full consideration" to those developing countries "particularly vulnerable to the adverse effects of climate change"). *See also* North American Agreement on Environmental Cooperation (1993), 32 I.L.M. 1480, art. 10(7) (committing the United States to the development of principles for transboundary environmental impact assessments).

Similar obligations exist in domestic U.S. law as well. For example, the U.S. National Environmental Policy Act recognizes "the worldwide and long-range character of environmental problems"[43] and requires federal agencies to include reasonably foreseeable transboundary effects in their environmental impact statements.[44] While some individual statutes under which federal agencies will craft climate policies may be silent on the issue of considering extraterritorial benefits, arguably the most important statute for U.S. climate policy—the Clean Air Act—requires the control of air emissions that affect other countries and so encourages a global assessment of greenhouse gas effects. Specifically, Section 115 of the Clean Air Act directs EPA and the states to mitigate U.S. emissions that endanger foreign health and welfare.[45] The global perspective on climate costs and benefits required by that provision should inform all regulatory actions developed under the Clean Air Act, and may provide useful guidance under other statutes as well.[46]

Presidential orders on regulatory analysis also support use of a global SCC value. In 2012, President Obama issued Executive Order 13,609 on promoting international regulatory cooperation.[47] The Order built on his previous Executive Order 13,563, which in turn had affirmed its 1993 predecessor, Executive Order 12,866, in requiring benefit-cost analysis of significant federal regulations.[48] Though White House guidance published in 2003 on regulatory impact analysis under E.O. 12,866 assumed that most analyses would focus on domestic costs and benefits, it ultimately deferred to the discretion of regulatory agencies on whether to evaluate "effects beyond the borders of the United States."[49] More importantly, since the publication of that guidance, President Obama has issued his own supplemental orders on regulatory analysis, including E.O. 13,609, which clarified the importance of international cooperation to achieve U.S. regulatory

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[43] 42 U.S.C. § 4332(2)(F).

[44] COUNCIL ON ENVIRONMENTAL QUALITY, GUIDANCE ON NEPA ANALYSIS FOR TRANSBOUNDARY IMPACTS (1997), *available at* http://www.gc.noaa.gov/documents/transguide.pdf; *see also* CEQ, DRAFT NEPA GUIDANCE ON CONSIDERATION OF THE EFFECTS OF CLIMATE CHANGE AND GREENHOUSE GAS EMISSIONS at 2 (2010), *available at* http://www.whitehouse.gov/sites/default/files/microsites/ceq/20100218-nepa-consideration-effects-ghg-draft-guidance.pdf (defining climate change as a "global problem"); *see also* Exec. Order No. 12,114, *Environmental Effects Abroad of Major Federal Actions*, 44 Fed. Reg. 1957 §§ 1-1, 2-1 (Jan. 4, 1979) (applying to "major Federal actions . . . having significant effects on the environment outside the geographical borders of the United States," and enabling agency officials "to be informed of pertinent environmental considerations and to take such considerations into account . . . in making decisions regarding such actions").

[45] 42 U.S.C. § 7415.

[46] For details on the applicability of Section 115, see Petition from the Institute for Policy Integrity, to EPA, for Rulemakings and Call for Information under Section 115, Title VI, Section 111, and Title II of the Clean Air Act to Regulate Greenhouse Gas Emissions (Feb. 19, 2013); *see also* Nathan Richardson, *EPA and Global Carbon: Unnecessary Risk*, COMMON RESOURCES, Feb. 28, 2013 (explaining how Section 115 authorizes use of a global SCC value when regulating under other Clean Air Act provisions).

[47] 77 Fed. Reg. 26,413 (May 4, 2012).

[48] *Id.* § 1 (explaining the order intends to "promot[e] the goals of Executive Order 13563"); *see also* Exec. Order No. 13,563, *Improving Regulation and Regulatory Review*, § 1(b), 76 Fed. Reg. 3821 (Jan. 18, 2011) (reaffirming Exec. Order No. 12,866, 58 Fed. Reg. 51,741 (Sept. 30, 1993) and requiring benefit-cost analysis).

[49] OMB, CIRCULAR A-4, at 15 (2003). In sharp contrast to the Circular's ultimate deferral to agencies on the issue of considering transboundary efficiency effects, the Circular makes very clear that international transfers and distributional effects should be assessed as costs and benefits to the United States: "Benefit and cost estimates should reflect real resource use. Transfer payments are monetary payments from one group to another that do not affect total resources available to society. . . . However, transfers from the United States to other nations *should* be included as costs, and transfers from other nations to the United States as benefits, as long as the analysis is conducted from the United States perspective." *Id.* at 38 (emphasis original). In other words, even if federal agencies use a global SCC value to assess efficiency effects relating to their climate policies, that global valuation will not prevent the agencies from also counting international transfers or distributional effects that benefit the United States as benefits. *See* Comments from the Institute for Policy Integrity, to EPA, on Proposed Rulemaking to Establish Light-Duty Vehicle Greenhouse Gas Emission Standards, at 12-13 (Nov. 27, 2009) (explaining that, depending on the relevant statutory mandate, agencies may calculate a monopsony benefit to the United States even while using a global SCC value).

goals. This 2012 order explicitly recognizes that significant regulations can have "significant international impacts,"[50] and it calls on federal agencies to work toward "best practices for international regulatory cooperation with respect to regulatory development."[51] By employing a global SCC value in U.S. regulatory development, and by encouraging other countries to follow that best practice and account for the significant international impacts of their own climate policies, federal agencies will advance the mission of this presidential order on regulatory harmonization.

Finally, two practical considerations counsel in favor of a global SCC value. First, unlike some other significant international environmental impacts, no methodological limitations block the quantitative estimation of a global SCC value. In recent regulatory impact analyses for major environmental rules, EPA has qualitatively considered important transnational impacts that could not be quantified. For example, in the Mercury and Air Toxics Standards, EPA concluded that a reduction of mercury emissions from U.S. power plants would generate health benefits for foreign consumers of fish, both from U.S. exports and from fish sourced in foreign countries. EPA did not quantify these foreign health benefits, however, due to complexities in the scientific modeling.[52] Similarly, in the analysis of the Cross-State Air Pollution Rule, EPA noted—though could not quantify—the "substantial health and environmental benefits that are likely to occur for Canadians" as U.S. states reduce their emissions of particulate matter and ozone—pollutants that can drift long distances across geographic borders.[53] Yet where foreign costs or benefits are important and quantifiable, other federal agencies frequently include those calculations.[54] Given that sophisticated models already exist to quantify the global SCC, the global estimate is appropriate to use.

Second, a global SCC value is in the national interest because harms experienced by other countries could significantly impact the United States. Climate damages in one country could generate large spillover effects to which the United States is especially vulnerable. The mesh of the global economy is woven tightly, and disruptions in one place can have consequences around the world. As seen historically, economic disruptions in one country can cause financial crises that reverberate globally at a breakneck pace.[55] In a similar vein, national security analysts in government and academia increasingly emphasize that the geopolitical instability associated with climatic disruptions abroad poses a serious threat to the United States.[56] Due to its unique place among countries—both as the largest global economy with trade- and investment-dependent links throughout the world, and as a military superpower—the United States is particularly vulnerable to international spillover effects.

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[50] 77 Fed. Reg. at 26,414, § 3(b).

[51] 77 Fed. Reg. at 26,413, § 2(a)(ii)(B) (defining the goals of the regulatory working group).

[52] EPA, REGULATORY IMPACT ANALYSIS FOR THE FINAL MERCURY AND AIR TOXICS STANDARDS at 65 (2011) ("Reductions in domestic fish tissue concentrations can also impact the health of foreign consumers . . . [and] reductions in U.S. power plant emissions will result in a lowering of the global burden of elemental mercury . . . .").

[53] Federal Implementation Plans to Reduce Interstate Transport of Fine Particulate Matter and Ozone, 75 Fed. Reg. 45,209, 45,351 (Aug. 2, 2010).

[54] *E.g.*, Unique Device Identification System, 78 Fed. Reg. 58,786 (Sept. 24, 2013) ("[I]n our final regulatory impact analysis we include an estimate of the costs to foreign labelers."); Standards for the Growing, Harvesting, Packing, and Holding of Produce for Human Consumption, 78 Fed. Reg. 3504 (Jan. 16, 2013) (including costs to foreign farms); U.S. Customs and Border Protection Regulatory Agenda, RIN 1651-AA96 Definition of Form I-94 to Include Electronic Format (2013) (preliminarily estimating net benefits to foreign travelers and carriers).

[55] Steven L. Schwarz, *Systemic Risk*, 97 GEO. L.J. 193, 249 (2008) (observing that financial collapse in one country is inevitably felt beyond that country's borders).

[56] *See, e.g.*, Department of Defense, Climate Change Adaptation Roadmap (2014); CNA Military Board, National Security and the Accelerating Risks of Climate Change (2014).

The 2010 TSD included a rigorous examination of global versus domestic SCC estimates.[57] Consistent with the above discussion, the 2010 IWG reached the conclusion to estimate a global SCC value, citing both the global impacts of climate change and the global action needed to mitigate climate change. The IWG restated these arguments in the 2013 TSD, and refers back explicitly to its discussion in the 2010 TSD.[58] DOE should continue using a global SCC estimate in its regulatory impact analyses.

4. Recommendations on further refinements to the SCC.[59]

The IWG process uses assumptions that accord with economic and scientific theory. Economic models, and the scientific analyses they draw from, are of course improving continuously. Future updates to the SCC should build on these and go further. As further refinements better account for climate change impacts not yet incorporated into the modeling, all indications are that the estimated benefits of curbing carbon pollution will rise substantially over current estimates.

The IWG appropriately used consumption discount rates rather than returns on capital.

With respect to the **discount rate**, the IWG conducted sensitivity analysis of the results to three constant consumption discount rates: 2.5%, 3%, and 5%; for each of the discount rates, the TSDs reported the various moments and percentiles[60] of the SCC estimates.

The discount rate is one of the most important inputs in models of climate damages, with plausible assumptions easily leading to differences of an order of magnitude in the SCC. The climate impacts of present emissions will unfold over hundreds of years. When used over very long periods of time, discounting penalizes future generations heavily due to compounding effects. For example, at a rate of 1%, $1 million 300 years hence equals over $50,000 today; at 5% it equals less than 50 cents.[61] The discount rate changed by a factor of five, whereas the discounted value changed by more than five orders of magnitude. Depending on the link between climate risk and economic growth risk, even a rate of 1% may be too high.[62] Uncertainty around the correct discount rate pushes the rate lower still.[63]

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[57] 2010 TSD, *supra* note 4, at 10-11.

[58] 2013 TSD, *supra* note 6, at 14-15.

[59] The following section relies heavily on Richard L. Revesz et al., *Global Warming: Improve Economic Models of Climate Change*, 508 NATURE 173 (2014), on Gernot Wagner & Martin L. Weitzman, *Climate Shock*, Princeton University Press (2015), on Frank J. Convery & Gernot Wagner, *Reflections—Managing Uncertain Climates: Some Guidance for Policy Makers and Researchers* (forthcoming in REVIEW OF ENVIRONMENTAL ECONOMICS AND POLICY) as well as on several papers cited in footnotes throughout.

[60] The moments of a distribution (of SCC estimates in this case) are, loosely speaking, the various values that describe the distribution's shape: what value is the distribution centered around (mean); how wide is the distribution (the variance); whether the distribution is lopsided (skewness); and whether it is tall and skinny or short and fat (kurtosis). A percentile is a statistical measure of the value (the SCC value in this case) below which a specified percentage of (SCC) observations falls. The 1st percentile indicates the SCC value above which (the other) 99% of observed SCC values fall. The 99th percentile indicates the SCC value below which 99% of all observed SCC values fall.

[61] Dallas Burtraw & Thomas Sterner, *Climate Change Abatement: Not "Stern" Enough?* (Resources for the Future Policy Commentary Series, Apr. 4, 2009), *available at* http://www.rff.org/Publications/WPC/Pages/09_04_06_Climate_Change_Abatement.aspx.

[62] "If climate risk dominates economic growth risk because there are enough potential scenarios with catastrophic damages, then the appropriate discount rate for emissions investments is lower tha[n] the risk-free rate and the current price of carbon dioxide emissions should be higher. In those scenarios, the "beta" of climate risk is a large negative value and emissions mitigation investments provide insurance benefits. If, on the other hand, growth risk is always dominant because catastrophic damages are essentially impossible and minor climate damages are more likely to

The IWG correctly excluded a 7% discount rate, a typical private sector rate of return on capital, for several reasons. First, typical financial decisions, such as how much to save in a bank account or invest in stocks, focus on private decisions and utilize private rates of return. Private market participants typically have short time horizons. However, here we are concerned with social discount rates because emissions mitigation is a public good, where individual emissions choices affect public well-being broadly. Rather than evaluating an optimal outcome from the narrow perspective of investors alone, economic theory would require that we make the optimal choices based on societal preferences (and social discount rates). Second, climate change is expected to affect primarily consumption, not traditional capital investments.[64] OMB guidelines note that in this circumstance, consumption discount rates are appropriate.[65] Third, 7% is considered much too high for reasons of discount rate uncertainty and intergenerational concerns (further discussed below).

The IWG correctly adopted as one of its discount rates a value reflecting long-term interest rate uncertainty, and—as a primary extension to current results—should go further by directly implementing a declining discount rate.

The IWG was correct in choosing as one of its discount rates an estimate based upon declining discount rates (2.5%). Since the IWG undertook its initial analysis, a consensus has emerged among leading climate economists that a declining discount rate should be used for climate damages to reflect long-term uncertainty in interest rates. Arrow *et al* (2013) presents several arguments that strongly support the use of declining discount rates for long-term benefit-cost analysis.[66]

Perhaps the best reason is the simple fact that there is considerable uncertainty around which interest rate to use: uncertainty in the rate points directly to the need to use a declining rate, as the impact of the uncertainty grows exponentially over time. The uncertainty about future discount rates could stem from a number of reasons particularly salient to climate damages, including uncertainties in future economic growth, consumption, and the interest rate reaped by investments.

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occur when growth is strong, times are good, and marginal utility is low, then the "beta" of climate risk is positive, the discount rate should be higher than the risk-free rate, and the price of carbon dioxide emissions should be lower." Robert B. Litterman, *What Is the Right Price for Carbon Emissions?,* REGULATION*,* Summer 2013, at 38, 41, *available at* http://www.cato.org/sites/cato.org/files/serials/files/regulation/2013/6/regulation-v36n2-1-1.pdf

[63] See following subsection.

[64] "There are two rationales for discounting future benefits—one based on consumption and the other on investment. The consumption rate of discount reflects the rate at which society is willing to trade consumption in the future for consumption today. Basically, we discount the consumption of future generations because we assume future generations will be wealthier than we are and that the utility people receive from consumption declines as their level of consumption increases . . . . The investment approach says that, as long as the rate of return to investment is positive, we need to invest less than a dollar today to obtain a dollar of benefits in the future. Under the investment approach, the discount rate is the rate of return on investment. If there were no distortions or inefficiencies in markets, the consumption rate of discount would equal the rate of return on investment. There are, however, many reasons why the two may differ. As a result, using a consumption rather than investment approach will often lead to very different discount rates." Maureen Cropper, *How Should Benefits and Costs Be Discounted in an Intergenerational Context?*, 183 RESOURCES 30, 33.

[65] *See* CIRCULAR A-4, *supra* note 49, at 33.

[66] The arguments here are primarily based on: Kenneth J. Arrow et al., *Determining Benefits and Costs for Future Generations*, 341 SCIENCE 349 (2013); Kenneth J. Arrow et al., *Should Governments Use a Declining Discount Rate in Project Analysis?*, REV ENVIRON ECON POLICY 8 (2014); Richard G. Newell & William A. Pizer, *Discounting the Distant Future: How Much Do Uncertain Rates Increase Valuations?,* 46 J. ENVTL. ECON. & MGMT. 52 (2003); Maureen L. Cropper et al., *Declining Discount Rates*, AMERICAN ECONOMIC REVIEW: PAPERS AND PROCEEDINGS (2014); S.K. Rose, D. Turner, G. Blanford, J. Bistline, F. de la Chesnaye, and T. Wilson. *Understanding the Social Cost of Carbon: A Technical Assessment.* EPRI Report #3002004657 (2014).

A possible declining interest rate schedule for consideration by the IWG is the one proposed by Weitzman (2001).[67] It is derived from a broad survey of top economists and the profession at large in a climate change context and explicitly incorporates arguments around interest rate uncertainty. Arrow *et al* (2013, 2014), Cropper *et al* (2014), and Gollier and Weitzman (2010), among others, similarly argue for a declining interest rate schedule and lay out the fundamental logic.[68]

Moreover, the United States would not be alone in using a declining discount rate. It is standard practice for the United Kingdom and French governments, among others.[69] The U.K. schedule explicitly subtracts out an estimated time preference.[70] France's schedule is roughly similar to the United Kingdom's. Importantly, all of these discount rate schedules yield lower present values than the constant 2.5% Newell-Pizer rate, suggesting that even the lowest discount rate evaluated by the IWG is too high.[71] The consensus of leading economists is that a declining discount rate schedule should be used, consistent with the approach of other countries like the United Kingdom. Adopting such a schedule would increase the SCC substantially from the administration's central estimate, suggesting that even the high end of the range presented by the administration is likely too low.

The IWG's choice of three IAMs was fully justified but should still be revisited in its next iteration.

In its calculations of the SCC, the IWG relied on the three Integrated Assessment Models (IAMs) available at the time, all with a long record of peer-reviewed publications that link physical and economic effects: the Dynamic Integrated Model of Climate and the Economy (DICE),[72] the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND),[73] and Policy Analysis of the Greenhouse Effect (PAGE).[74] The government's first SCC estimates, published in 2010, used the then-current versions of the models; the recent update employed revised, peer-reviewed versions of the models but maintained the underlying assumptions of the 2010 IWG analysis. As stated by the 2010 IWG, "the main objective of [the 2010 IWG modeling] process was to develop a range of

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[67] Martin L. Weitzman, *Gamma Discounting*, 91 AM. ECON. REV. 260, 270 (2001). Weitzman's schedule is as follows:

1-5 years	6-25 years	26-75 years	76-300 years	300+ years
4%	3%	2%	1%	0%

[68] Arrow et al. (2013, 2014), Cropper et al. (2014), *supra* note 66. Christian Gollier & Martin L. Weitzman, *How Should the Distant Future Be Discounted When Discount Rates Are Uncertain?* 107 ECONOMICS LETTERS 3 (2010).

[69] *Id.*

[70] Joseph Lowe, H.M. Treasury, U.K., Intergenerational Wealth Transfers and Social Discounting: Supplementary Green Book Guidance 5 (2008), *available at* http://www.hm-treasury.gov.uk/d/4(5).pdf. The U.K. declining discount rate schedule that subtracts out a time preference value is as follows:

0-30 years	31-75 years	76-125 years	126-200 years	201-300 years	301+ years
3.00%	2.57%	2.14%	1.71%	1.29%	0.86%

[71] Using the IWG's 2010 SCC model, Johnson and Hope find that the U.K. and Weitzman schedules yield SCCs of \$55 and \$175 per ton of CO_2, respectively, compared to \$35 at a 2.5% discount rate. Laurie T. Johnson & Chris Hope, *The Social Cost of Carbon in U.S. Regulatory Impact Analyses: An Introduction and Critique*, 2 J. ENVTL. STUD. & SCI. 205, 214 (2012).

[72] William D. Nordhaus, *Estimates of the social cost of carbon: concepts and results from the DICE-2013R model and alternative approaches*, 1 JOURNAL OF THE ASSOCIATION OF ENVIRONMENTAL AND RESOURCE ECONOMISTS 1 (2014).

[73] David Anthoff & Richard S.J. Tol, THE CLIMATE FRAMEWORK FOR UNCERTAINTY, NEGOTIATION AND DISTRIBUTION (FUND), TECHNICAL DESCRIPTION, VERSION 3.6 (2012), *available at* http://www.fund-model.org/versions.

[74] Chris Hope, *The Marginal Impact of CO_2 from PAGE2002: An Integrated Assessment Model Incorporating the IPCC's Five Reasons for Concern*, 6 INTEGRATED ASSESSMENT J. 19 (2006).

SCC values using a defensible set of input assumptions grounded in the existing scientific and economic literatures."[75]

DICE, FUND, and PAGE are well-established, peer-reviewed models. They represent the state-of-the-art IAMs. Each of these models has been developed over decades of research, and has been subject to rigorous peer review, documented in the published literature. However, updates to the SCC should also consider other models that are similarly peer reviewed and based on the state of the art of climate-economic modeling. One such model is Climate and Regional Economics of Development (CRED); another is the World Bank's ENVironmental Impact and Sustainability Applied General Equilibrium (ENVISAGE) model.

CRED borrows its fundamental structure from William Nordhaus's DICE and RICE models but also offers significant changes. For one, it uses updated damage functions and Marginal Abatement Cost Curves (MACC). Moreover, it uses different global equity weights, and uses additional state-of-the-art methodologies.[76]

ENVISAGE represents a broader modeling effort by the World Bank, where perhaps the largest contribution is a more detailed sectoral breakdown, using 57 different sectors.[77] This level of analysis allows for a more detailed view of agriculture as well as food and energy sectors that are particularly important to any climate-economy modeling.

Moreover, the broader policy and research community at large ought to consider creating the right incentive structure within the economic and scientific community to engage many more researchers on working with the core IAMs. Doing so could speed up the process of capturing the latest research on climate damages.

No model fully captures the costs of climate impacts to society. In fact, virtually all uncertainties and current omissions point to a higher SCC value. That makes it essential to use the established IWG process, which provides for updating the SCC estimates every two to three years in order to capture the advances in physical and social sciences that have been incorporated into the models during the intervening period, in order to revisit both the choice of models and the key inputs used.[78]

The IWG should update its socio-economic assumptions to reflect the latest Shared Socio-economic Pathways (SSPs).

One key input is the use of socio-economic scenarios reflected in the choice of economic growth rates and emissions trajectories. Current IWG socio-economic and emissions scenarios were chosen from the Stanford Energy Modeling Forum exercise, EMF-22, and consist of projections for income/consumption, population, and emissions (CO_2 and non-CO_2). The IWG selected five sets of trajectories, four of which represent business as usual (BAU) trajectories (MiniCAM, MESSAGE, IMAGE, and MERGE models) and a fifth that represents a CO_2 emissions pathway with CO_2 concentrations stabilizing at 550 ppm. Given the possibility of increases in emissions above those

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[75] 2010 TSD, *supra* note 4, at 1.

[76] Frank Ackerman, Elizabeth A. Stanton & Ramón Bueno, *CRED: A New Model of Climate and Development*, 85 ECOLOGICAL ECONOMICS 166 (2013).

[77] World Bank, ENVISAGE, http://go.worldbank.org/8DTXIDMRM0 (last visited Feb. 4, 2014).

[78] 2010 TSD, *supra* note 4, at 1-3 ("The estimates are presented with an acknowledgement of the many uncertainties involved and with a clear understanding that they should be updated over time to reflect increasing knowledge of the science and economics of climate impacts . . . . Specifically, we have set a preliminary goal of revisiting the SCC values within two years or at such time as substantially updated models become available, and to continue to support research in this area.").

expressed by Business As Usual Scenarios, a high-CO_2 emissions pathway should also be considered. The assumptions used in calculating the SCC should be updated regularly to reflect the latest thinking around possible scenarios, reflecting the latest Shared Socio-economic Pathways (SSPs).[79] These SSPs represent the latest, consistent pathways, feeding, for example, into the latest IPCC report.

The current inclusion of CO_2 fertilization benefits likely overstates its effects.

The models do not reflect recent research on agricultural changes, which suggest the CO_2 fertilization is overestimated, particularly in the FUND model, and that much, if not all, of the fertilization benefits may be cancelled out by negative impacts on agriculture (e.g., extreme heat, pests, and weeds).[80] If the agency is not able to adequately model all agricultural impacts it should, at a minimum, remove CO_2 fertilization benefits.

The specific functional form assumptions in IAMs ought to be re-evaluated.

Climate damages in IAMs are assumed to affect levels of economic output rather than economic growth rates. Similarly, standard modeling assumptions assume multiplicative damage functions—i.e. substitutability across economic sectors—rather than additive functions—i.e. limited substitutability across sectors. IAMs ought to probe the impacts of both assumptions. Recent literature supports the conclusion that climate change will effect economic growth rates.[81]

Similarly, models ought to better capture the impacts of wildly heterogeneous climate damages. Each of the models used to calculate the SCC assume one representative household, going as far as to consider damages by relatively large regions. Such averaging ignores the enormously diverse effects of damages. It similarly contributes to not fully capturing the effects of extreme outcomes and tail risks. Instead, models ought to attempt to capture a much broader array of damages and climate impacts.[82]

The IWG used solid economic tools to address uncertainty and ought to go further in capturing the full extent of its implications.

The IWG was rigorous in addressing **uncertainty**. First, it conducted Monte Carlo simulations over the IAMs specifying different possible outcomes for climate sensitivity (represented by a Roe and Baker Distribution).[83] It also used five different emissions growth scenarios and three discount

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[79] Kristie L. Ebi et al., *A New Scenario Framework for Climate Change Research: Background, Process, and Future Directions*, 122 CLIMATIC CHANGE 363, 368 (2014).

[80] FRANK ACKERMAN & ELIZABETH A. STANTON, CLIMATE ECONOMICS: THE STATE OF THE ART 45-56 (2013); Wolfram Schlenker et al., *Will U.S. Agriculture Really Benefit From Global Warming? Accounting for Irrigation in the Hedonic Approach*, 95 AM. ECON. REV. 395, 395-406 (2005). See also: Fisher, Anthony C., W. Michael Hanemann, Michael J. Roberts, and Wolfram Schlenker. 2012. "The Economic Impacts of Climate Change: Evidence from Agricultural Output and Random Fluctuations in Weather: Comment." *American Economic Review*, 102(7): 3749-60. **DOI:** 10.1257/aer.102.7.3749

[81] *See* Melissa Dell et al., *Temperature shocks and economic growth: Evidence from the last half century*, 4 AMERICAN ECONOMIC JOURNAL: MACROECONOMICS 66-95 (2012); R. Bansal & M. Ochoa *Temperature, aggregate risk, and expected returns* (National Bureau of Economic Research No. w17575, 2011); E.J. Moyer et al., *Climate impacts on economic growth as drivers of uncertainty in the social cost of carbon* (University of Chicago Coase-Sandor Institute for Law & Economics Research Paper 652, 2013); S. Dietz & N. Stern, *Endogenous Growth, Convexity of Damage and Climate Risk: How Nordhaus' Framework Supports Deep Cuts in Carbon Emissions*, 125 THE ECONOMIC JOURNAL 574-620 (2015); F.C. Moore & D.B. Diaz *Temperature impacts on economic growth warrant stringent mitigation policy*, NATURE CLIMATE CHANGE (2015).

[82] See, for example, National Science Foundation-funded work by Per Krusell and Anthony A. Smith on "A Global Economy-Climate Model with High Regional Resolution" using 19,000 agents (each covering a 1 x 1° area of land).

[83] *See infra* note 95.

rates. Second, the IWG reported the various moments and percentiles[84] of the resulting SCC estimates. Third, the IWG put in place an updating process, e.g., the 2013 revision, which updates the models as new information becomes available.[85] As such, the IWG used the various tools that economists have developed over time to address the uncertainty inherent in estimating the economic cost of pollution: reporting various measures of uncertainty, using Monte Carlo simulations, and updating estimates as evolving research advances our knowledge of climate change.

The Monte Carlo framework took a step toward addressing what is the most concerning aspect of climate change, the potential for **catastrophic damages**, i.e., low probability/high damage events. These damages come from: uncertainty in the underlying parameters in IAMs,[86] including the climate sensitivity parameter; climate tipping points[87]—thresholds that, when crossed, cause rapid, often irreversible changes in ecosystem characteristics; and "black swan" events—which refer to unknown unknowns.[88]

The analysis used a right-skewed distribution of temperature (as captured in the Roe Baker climate sensitivity parameter) and an increasing, strictly convex damage function;[89] this correctly results in right-skewed distributions of damage and SCC estimates. By using the mean values of these estimates instead of the median, IWG estimates partially captured the effects of small probability, higher damages from high-level warming events.[90] To reflect uncertainty in estimates resulting from the right-skewed distribution of SCC estimates, the IWG reported the SCC value for the 95th percentile from the central 3% discount rate distribution.[91] This is done to reflect the estimation uncertainty in terms of the possibility of higher-than-expected economic impacts from climate change.

While the IAMs take different approaches to explicitly modeling tipping points, which to a great extent is lacking in current versions of FUND and DICE, the IWG improved (but in no way fixed) the representation of uncertain catastrophic damages with the Monte Carlo analysis. Still, black swan

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[84] *See supra* note 60.

[85] The federal government has committed to continuing to update SCC estimates to account for new information. The IWG stated in its 2010 TSD that "[i]t is important to emphasize that the interagency process is committed to updating these estimates as the science and economic understanding of climate change and its impacts on society improves over time. Specifically, we have set a preliminary goal of revisiting the SCC values within two years or at such time as substantially updated models become available, and to continue to support research in this area. In the meantime, we will continue to explore the issues raised in this document and consider public comments as part of the ongoing interagency process." 2010 TSD, *supra* note 4, at 3.

[86] In this case, parameters are the various characteristic that describe the underlying climate and economic systems.

[87] *See generally* Timothy M. Lenton et al., *Tipping Elements in the Earth's Climate System*, 105 PNAS 1786 (2008).

[88] Standard decision theory under uncertainty addresses "known unknowns," which are unknowns for which we can specify a probability distribution function. In the cases of "unknown unknowns," i.e., 'black swan' events, we cannot specify a probability distribution function, raising a host of additional questions. *See*, *e.g.*, Richard J. Zeckhauser, *Investing in the Unknown and Unknowable*, CAPITALISM & SOCIETY vol. 1, iss. 2, art. 5 (2006).

[89] An increasing, strictly convex climate damage function implies a damage function that is strictly increasing in temperature at an increasing rate.

[90] The point here is that we miss the big picture if we ignore the "tails" (the upper-most values in the case of the right-skewed SCC), and as a result come to the wrong conclusions. An everyday analogy is airplane safety regulation: safety is protected by guarding against the low-probability but highly dangerous events. With climate change we do not have the luxury of knowing with certainty how damaging the extremes could be or whether they will be triggered by greenhouse gases accumulating in the atmosphere; all we know is that there is a very real possibility they could occur and could be devastating.

[91] This approach partially captures catastrophic damages via tipping points through the PAGE model.

events go completely unaddressed in the IWG modeling framework, and therefore the SCC estimates do not reflect the value of preventing the occurrence of catastrophic events.[92]

In addition to choosing an appropriate discount rate and sensitivity analyses around different SSPs, another important parameter to which the SCC estimates are sensitive is Equilibrium Climate Sensitivity (ECS)—how the climate system responds to a constant radiative forcing, which is typically expressed as the temperature response to a doubling of CO_2 concentration in the atmosphere.[93] In its current iteration, the IWG conducted extensive sensitivity analyses over a range of equilibrium climate sensitivity estimates.[94] The assumptions are clearly stated in the TSD. In addition to its sensitivity analysis, the IWG conducted a Monte Carlo simulation over the climate sensitivity parameter and the other random variables specified within the three IAMs.[95]

The range for the Equilibrium Climate Sensitivity (ECS) is derived from a combination of methods that constrain the values from measurements in addition to models. These include measured ranges from paleoclimate records, observed comparisons with current climate, as well as responses to recent climate forcings. The currently agreed "likely" range for the ECS (from both the IPCC TAR and AR5) is 1.5-4.5 degrees Celsius. Physical constraints make it "extremely unlikely" that the ECS is less than 1 degree Celsius and "very unlikely" greater than 6 degrees Celsius.[96]

A host of analyses points to the costs of such uncertainty—both for values that go outside the "likely" range and for uncertainty within it: in short, the optimal SCC tends to increase with increased uncertainty, sometimes dramatically so.[97] While the current treatment of uncertainty around climate sensitivity by the IWG highlights a range of possible uncertainties, a reconsideration of the assumptions feeding into the SCC ought to take the latest advances highlighting the potentially higher costs of deep-seated uncertainty into account. Additionally, the IWG should

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[92] *See, e.g.*, Peter Howard, *Omitted Damages: What's Missing from the Social Cost of Carbon* (Cost of Carbon Project Report, 2014), and van den Bergh, J. C. J. M., and W. J. W. Botzen, *A lower bound to the social cost of CO_2 emissions*, 4 NATURE CLIMATE CHANGE 4 (2014).

[93] *See* INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, CLIMATE CHANGE 2013: THE PHYSICAL SCIENCE BASIS—SUMMARY FOR POLICYMAKERS 14 (2013).

[94] Specifying the climate sensitivity parameter as a random variable has a basis in PAGE02, which species a probability distribution function for the parameter. The IWG calibrated the Roe and Baker distribution, a right-skewed distribution, to characterize the probability distribution function of this parameter. The 2010 TSD explains the IWG's choice of the Roe and Baker distribution. The right-skewed nature of the climate sensitivity parameter's probability distribution function is independent of the IWG's choice of the Roe and Baker distribution. Rather, this skewness results from the IPCC's finding that values of the climate sensitivity parameter above 4.5 degree Celsius cannot be excluded. As a result, all of the probability distribution functions fit by the IWG for the climate sensitivity parameter were skewed to the right (see Figure 2 in the 2010 TSD), including Roe and Baker. *See* 2010 TSD, *supra* note 4, at 14, fig. 2.

[95] A Monte Carlo simulation will run an integrated assessment model thousands of times, each time randomly picking the value of uncertain parameters from a probability distribution function, i.e. a function that assigns a probability to each possible parameter value. In the case of the SCC, the IWG ran 10,000 Monte Carlo simulations for each of the three IAMs and five socio-economic scenarios, randomizing the value of climate sensitivity, i.e., the change in average global temperature associated with a doubling of CO_2, and all other uncertain parameters in the IAMs by the original authors. For each randomly drawn set of values, the IAM estimated the associated damages, with the final SCC estimate equaling the average value across all 10,000 runs, five socio-economic scenarios, and then across all three models. Therefore, each SCC estimate is calculated using 150,000 runs.

[96] IPCC, *supra* note 93, at 14.

[97] *E.g.,* Robert S. Pindyck, *Uncertain Outcomes and Climate Change Policy*, 63 J. ENVTL. ECON. & MGMT. 289 (2012); Martin L. Weitzman, *GHG Targets as Insurance Against Catastrophic Climate Damages*, 14 J. PUB. ECON. THEORY 221 (2012); Robert S. Pindyck, *The Climate Policy Dilemma*, 7 REV. ENVTL. ECON. & POL'Y 219 (2013); Gernot Wagner & Richard J. Zeckhauser, *Confronting Deep Uncertainty on Climate Sensitivity: When Good News is Bad News*, ('Beyond IPCC' Presentation, October 17, 2014).

consider whether it relies too heavily on its 95th percentile estimates as a catchall to cover for limitations in its treatment of uncertainty and catastrophic damages.

5. Support for the Social Cost of Methane methodology, and recommendations on continued improvements.

DOE acknowledges that its proposed standards will reduce significant quantifies of non-carbon dioxide greenhouse gases, including methane. DOE does not, however, include a monetary estimate of these non-carbon dioxide reductions in its net benefits calculations. By contrast, EPA and other agencies have begun using a methodology developed to specifically measure the Social Cost of Methane—namely, the Marten et al. approach[98]—in recent proposed rulemakings.[99] In their latest technical support update, the Interagency Working Group adopts the Marten methodology and includes estimates of the Social Cost of Methane and Social Cost of Nitrous Oxide for agencies to apply in their regulatory impact analyses.[100] In its final energy conservation standards, DOE should use the Social Cost of Methane metric to more accurately reflect the true benefits of the standards and to enhance the rigor and defensibility of the final rules.

EPA first developed Social Cost of Methane estimates based on one of the most recent peer-reviewed articles: Marten *et al*.[101] The Interagency Working Group has now similarly endorsed the Marten et al. approach. Marten *et al.* takes a reasonable (although conservative) approach to estimating the Social Cost of Methane and currently constitutes "the best available science" to inform agency regulation.[102] Specifically, Marten *et al*. builds on the methodology used by the Interagency Working Group to develop the SCC. The study maintains the same three integrated assessment models, five socioeconomic-emissions scenarios, equilibrium climate sensitivity distribution, three constant discount rates, and aggregation approach that were agreed upon by the Interagency Working Group. Consequently, many of the key assumptions underlying the Social Cost of Methane estimates have already gone through a transparent, consensus-driven, publically reviewed, regularly updated process, since they were borrowed from the Interagency Working Group's thoroughly vetted methodology.

Yet while sharing that carefully built framework with the SCC estimates, Marten *et al*.'s Social Cost of Methane estimates directly account for the quicker time horizon of methane's effects compared to carbon dioxide, include the indirect effects of methane on radiative forcing, and reflect the complex, nonlinear linkages along the pathway from methane emissions to monetized damages. Marten *et al*. was not only published in a peer reviewed economics journal, but EPA undertook additional internal and peer review of the approach.[103] Marten *et al*.'s estimates thus are reasonable and appropriate measurements of the Social Cost of Methane.

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[98] Marten, A.L., E.A. Kopits, C.W. Griffiths, S.C. Newbold & A. Wolverton (2014). Incremental CH4 and N2O Mitigation Benefits Consistent with the U.S. Government's SC-CO2 Estimates, Climate Policy, DOI: 10.1080/14693062.2014.912981.

[99] *See* 80 Fed. Reg. 52,099, 52,145 (Aug. 27, 2015).

[100] Interagency Working Group on the Social Cost of Greenhouse Gases, Addendum: Application of the Methodology to Estimate the Social Cost of Methane and the Social Cost of Nitrous Oxide 3 (2016) ("This addendum summarizes the Marten et al. methodology and presents the SC-CH4 and SC-N2O estimates from that study as a way for agencies to incorporate the social benefits of reducing CH4 and N2O emissions into benefit-cost analyses of regulatory actions").

[101] Alex L. Marten et al., *Incremental CH4 and N2O Mitigation Benefits Consistent With the US Government's SC-CO2 Estimates,* Climate Policy (2014).

[102] *See* Executive Order 13,563, 76 Fed. Reg. 3821 (January 18, 2011).

[103] http://www3.epa.gov/climatechange/pdfs/social%20cost%20methane%20white%20paper%20application%20and%20peer%20review.pdf

In fact, Marten *et al.*'s estimates are conservative and very likely underestimate the true Social Cost of Methane. To start, as the authors note, because their methodology followed the Interagency Working Group's approach, all limitations that apply to inputs and modelling assumptions for the SCC also apply to the Social Cost of Methane. As discussed above, omitted damages, socio-economic assumptions, the treatment of uncertainty and catastrophic damages, and so forth all suggest the Social Cost of Methane is underestimated, just as the SCC is.

Additionally, the integrated assessment models shared by both the Social Cost of Methane and the SCC include some features better suited to assessing carbon dioxide effects than methane effects, and so likely underestimate the costs of methane. For example, a countervailing benefit of carbon dioxide emissions—enhanced fertilization in the agricultural sector—is included in the underlying models used to develop both the SCC and Social Cost of Methane, yet does not apply to methane emissions.[104] Similarly, the damage functions used by the integrated assessment models assume some level of adaptation to climate change over time, but because methane is a much faster-acting climate pollutant than carbon dioxide, there is less opportunity for technological advancement or political progress to adapt to the climate damages imposed by methane emissions. Methane also has indirect but significant effects, via its contribution to surface ozone levels, on global health and agriculture, and such effects need to be included either in the Social Cost of Methane or elsewhere in the cost-benefit analysis, but currently are not.[105]

Overall, the Marten *et al*. methodology provides reasonable, direct estimates that reflect updated evidence and provide consistency with the Government's accepted methodology for estimating the SCC. DOE should use the Interagency Working Group's estimates of the Social Cost of Methane in future rulemakings, including the final version of these energy standards.

6. Conclusion: Recommendations on the use of the SCC and Social Cost of Methane in regulatory impact analyses.

DOE should use the latest estimates of the SCC and the SCM. The current estimates are biased downwards: more can and should be done to improve the estimates and to ensure, through regular

[104] Interagency Working Group on the Social Cost of Carbon, *Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis*, 12 (February 2010), available at https://www.whitehouse.gov/sites/default/files/omb/inforeg/for-agencies/Social-Cost-of-Carbon-for-RIA.pdf ("Impacts other than temperature change also vary across gases in ways that are not captured by GWP. For instance . . . damages from methane emissions are not offset by the positive effect of CO2 fertilization.").
Martin et al (2015) state that "A comparison across models further highlights the importance of CO2 fertilization impacts on the global damage potential. CO2 emissions, and the resulting increase in atmospheric concentration, have the potential to increase yields in the agriculture and forestry sector. This characteristic is not shared by other GHG emissions. Accordingly, the FUND model, which explicitly captures this effect, exerts downward pressure on the SC-CO2 that is not present for the SC-CH4 and SC-N2O, allowing for the possibility of substantially higher global damage potential estimates. The results based on the FUND model presented in this article exhibit this effect; however, the CO2 fertilization effect is not explicitly modelled in DICE and PAGE and therefore they are found to produce lower estimates of the global damage potential. For example, using the 3% discount rate, the global damage potential for CH4 as estimated by FUND ranges between 58 and 88 depending on the scenario, whereas it ranges from 19 to 28 for DICE and PAGE. As the DICE and PAGE models only consider two natural system impacts, temperature and sea level, if they do implicitly include potential CO2 fertilization benefits, they are included by using the temperature anomaly as a proxy for the increasing atmospheric CO2 concentration. Fertilization benefits would therefore be allowed to falsely accrue to perturbations of other GHG emissions besides CO2. It is not clear the degree to which these models try to incorporate CO2 fertilization effects and therefore the degree to which this issue is of concern."

[105] A study by Sarofim et al. (2015) finds that reductions in surface ozone levels from the mitigation of methane emissions would provide additional global health benefits from avoided cardiopulmonary deaths equal to 60 to 140% of climate benefits identified by Marten. Similarly, Shindell (2014) finds that the impact of methane on agriculture, via changes in surface ozone, are valued at $22 and $27 per ton, for 5% and 3% discounting respectively, in addition to his study's estimates for climate and climate-health related damages.

updates, that they reflect the latest science and economics. However, the necessary process of improving the ability of the SCC and Social Cost of Methane to fully reflect the costs of climate impacts to society cannot hold up agency rulemaking efforts. The values provide an important, if conservative, estimate of the costs of climate change and the benefits of reducing carbon pollution. To ignore these costs would be detrimental to human health and well-being and contrary to law and Presidential directives to agencies to evaluate the cost of pollution to society when considering standards to abate that pollution. In the context of agency rulemakings, the SCC and Social Cost of Methane provide the best available means to factor those costs into benefit-cost analyses.

In using the estimates in its regulatory impact analyses, however, DOE should also include a qualitative assessment of all significant climate effects that are not currently quantified in the monetized estimate. The IWG acknowledged its incomplete treatment of both catastrophic and non-catastrophic damages, and instructed agencies that "These caveats . . . are necessary to consider when interpreting and applying the SCC estimates."[106] Those instructions are consistent with Executive Orders on regulatory analysis, which tell agencies to "assess . . . qualitative measures of costs and benefits that are difficult to quantify, but nevertheless essential to consider."[107] Before the IWG published its first estimates in 2010, some agencies included a detailed chart of unquantified climate effects in their regulatory impact analyses.[108] However, most recent rulemakings only reference unquantified benefits from non-CO_2 gases and from co-pollutants, and list none of the significant, unquantified climate effects from carbon dioxide. In the final regulatory impact analysis, DOE should detail all significant, unquantified climate effects, as consistent with administration-wide policy, the IWG's instructions, past agency practices, and best economic practices.

We also suggest that DOE encourage the IWG to regularly update the SCC and Social Cost of Methane, as new economic and scientific consensus emerges. Such updates are in line with the stated intentions of the IWG, which committed to "updating these estimates as the science and economic understanding of climate change . . . improves."

Sincerely,

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* No part of this document purports to present New York University School of Law's views, if any.

[106] 2010 TSD, *supra* note 4, at 29.

[107] Exec. Order No. 12,866 § 1(a); *see also* OMB, Circular A-4.

[108] *E.g.*, EPA, 420-D-09-001, DRAFT REGULATORY IMPACT ANALYSIS:CHANGES TO RENEWABLE FUEL STANDARD PROGRAM 690 tbl. 5.3-4 (2009).

Exhibit B

NATURE | COMMENT

Global warming: Improve economic models of climate change

Richard L. Revesz, **Peter H. Howard**, **Kenneth Arrow**, **Lawrence H. Goulder**, **Robert E. Kopp**, **Michael A. Livermore**, **Michael Oppenheimer** & **Thomas Sterner**

04 April 2014

Costs of carbon emissions are being underestimated, but current estimates are still valuable for setting mitigation policy, say Richard L. Revesz and colleagues.

Subject terms: Climate sciences Economics Policy

Danny Lawson/PA Wire

Floods brought parts of Britain to a standstill earlier this year.

On 31 March, the Intergovernmental Panel on Climate Change (IPCC) released its latest report on the impacts of climate change on humans and ecosystems (see go.nature.com/ad5v1b). These are real risks that need to be accounted for in planning for adaptation and mitigation. Pricing the risks with integrated models of physics and economics lets their costs be compared to those of limiting climate change or investing in greater resilience.

Last year, an interagency working group for the US government used three leading economic models to estimate that a tonne of carbon dioxide emitted now will cause future harms worth US$37 in today's dollars[1]. This 'social cost of carbon' represents the money saved from avoided damage, owing to policies that reduce emissions of carbon dioxide.

Governments, agencies and companies use such estimates to guide decisions about how much to invest in reducing emissions. In the United States, a previous estimate[2] made in 2010 informed the stricter fuel-economy requirements for new cars. The latest value is motivating President Barack Obama's plan to impose greenhouse-gas limits on coal-fired power plants by next year. Canada, Mexico, the United Kingdom, France, Germany and Norway have used similar numbers to guide regulatory decisions, as has the International Monetary Fund to analyse fossil-fuel subsidies.

Yet the social-cost benchmark is under fire. Industry groups, politicians — including leaders of the energy and commerce committee of the US House of Representatives — and some academics say that uncertainties render the estimate useless.

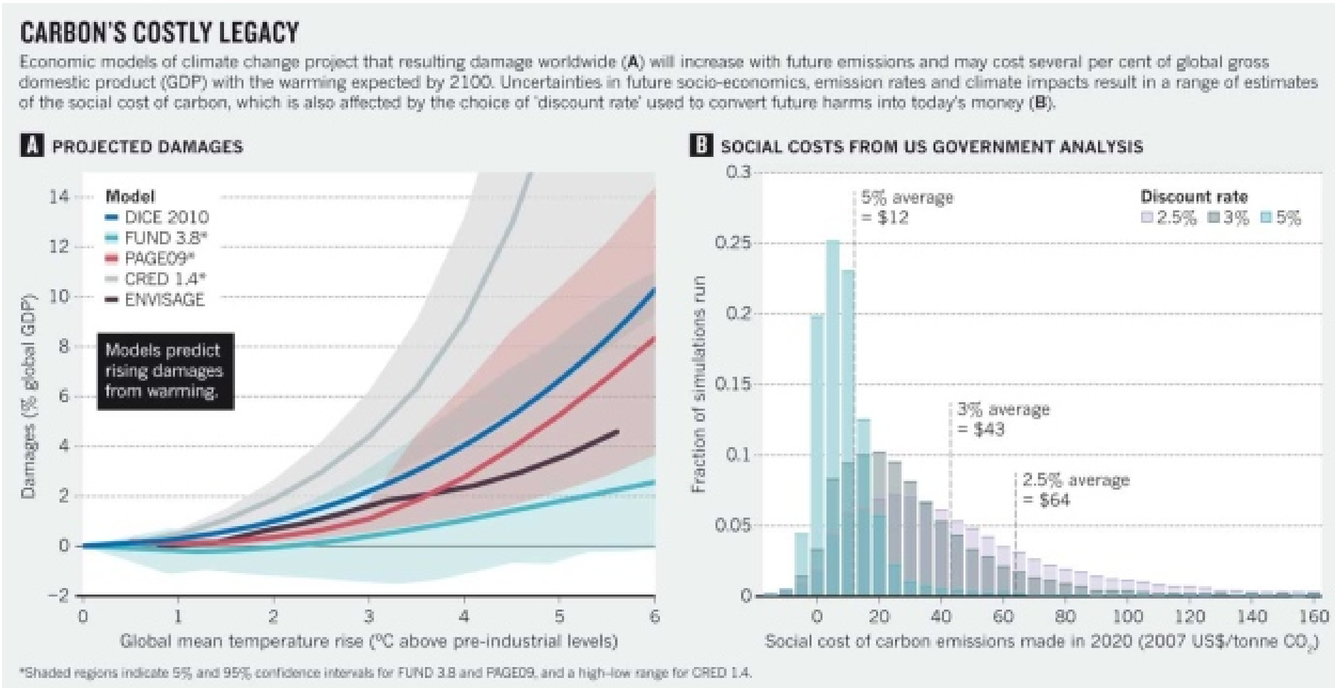
As legal, climate-science and economics experts, we believe that the current estimate for the social cost of carbon is useful for policy-making, notwithstanding the significant uncertainties. The leading economic models all point in the same direction: that climate change causes substantial economic harm, justifying immediate action to reduce emissions. In fact, because the models omit some major risks associated with climate change, such as social unrest and disruptions to economic growth, they are probably understating future harms. The alternative — assigning no value to reductions in carbon dioxide emissions — would lead to regulation of greenhouse gases that is even more lax.

Instead, climate-economic models need to be extended to include a wider range of social and economic impacts. Gaps need to be filled, such as the economic responses of developing countries and estimates of damages at extreme temperatures. Today, only a handful of researchers in the United States and Europe specialize in such modelling. A broader programme involving more people exploring more phenomena is needed to better estimate the social cost of carbon and to guide policy-makers. Otherwise policies will become untethered from economic realities.

***Nature* special:** Outlook for Earth

Social cost

The models in question aim to integrate estimates of the costs of greenhouse-gas emissions and of steps to reduce them. First, they translate scenarios of economic and population growth, and resulting emissions, into changes in atmospheric composition and global mean temperature. Then the models apply ‘damage functions’ that approximate the global relationships between temperature changes and the economic costs from impacts such as changes in sea level, cyclone frequency, agricultural productivity and ecosystem function. Finally, the models translate future damages into present monetary value.



SOURCE: A, REF.1 (DICE, FUND, PAGE)/Roson, R. & Mensbrugghe, D. V. D. Int. J. Sus. Econ. 4, 270–285 (2012) (ENVISAGE)/Ackerman, F., Stanton, E. A. & Bueno, R. Ecol. Econ. 85, 166–176 (2013) (CRED); B, REF.1

Sources of uncertainty are numerous[3]. They include: how the climate responds to carbon dioxide concentrations; positive and negative feedback loops in the climate system; emissions growth rates for various socio-economic scenarios; the completeness and accuracy of damage functions (especially with regard to catastrophic harms, migration and conflict, weather variability and feedbacks on economic growth); the ability of future generations to adapt to climate change; and the economic ‘discount rate’ used to translate future costs to current dollars.

The 2013 US analysis[1] used the then-most recent vintages of three long-standing models: FUND 3.8, DICE 2010, and PAGE09. Each model applies different climatic and economic functions to simplify the complex picture. Despite the range of approaches and uncertainties, each one predicted sizeable economic damage from greenhouse-gas emissions for warming beyond 2 °C above pre-industrial levels. Two models, ENVISAGE and CRED, published since the US analysis was structured in 2010, have broadly similar projections to these three (see ‘Carbon’s costly legacy’). The analysis suggested that — depending on assumptions about how future damages are valued in today’s money — the expected global cost of one tonne of carbon dioxide emitted in 2020 is between \$12 and \$64 (with \$43 as the central value).

Greater harm

A-26

The future costs of climate change could be even higher, for four reasons. First, the impacts of historic temperature changes suggest that societies and economies may be more vulnerable than current models predict and that weather variability is more important than average weather in determining impacts, particularly for crop growth and food security. For example, the yields of some crops may decline rapidly above certain temperatures[4].

Second, the models omit damages to labour productivity, to productivity growth, and to the value of the capital stock, including buildings and infrastructure. By lowering the annual growth rate, these damages could have deeper and longer-lasting effects on the global economy than the static losses of annual economic output currently represented in the three main models[5, 6]. A significant decline in human welfare is possible in the medium and long run owing to the compounding effects of lost growth. Also not taken into account are the risks of climate-induced wars, coups or societal collapses and the resulting economic crises[7].

Third, the models assume that the value that people attach to ecosystems will remain constant[8]. Yet as a commodity becomes more scarce, its value increases. In the desert, water is extremely valuable. During a flood, dry land is highly prized. Because the services provided by ecosystems are likely to decline as warming degrades them, the costs of future ecosystem damage from climate change will rise faster than the models predict.

ALESSANDRO GAROFALO/Reuters/Corbis

Storms caused chaos on roads in northwestern Italy in 2011.

Fourth, the US analysis assumes a constant discount rate to translate future harms into today's money. However, for impacts that are both highly uncertain and occurring in the distant future, economists have shown[9] that a discount rate that declines over time should be used, with discount rates for the far future significantly below those that were used in the 2013 analysis. This approach would yield a higher present value to the long-term impacts of climate change and thus a higher value for the social cost of carbon.

It is true that future technological developments might better equip society to cope with climate change. And of course overall bias cannot be determined simply by adding biases in each direction. But the bulk of the literature and arguments indicates that social-cost models are underestimating climate-change harms.

Better models

What now? Modellers, scientists and environmental economists must continue to step outside their silos and work together to identify research gaps and modelling limitations.

Climate hot spots in the developing world are one such gap, because economic responses in these regions cannot be extrapolated simply from estimates made for developed countries. The impacts of extreme temperatures are also uncertain. Current damage estimates are generally calibrated for warming of less than 3 °C (ref. 6). Yet without mitigation, the IPCC projects that we could see warming in excess of 4 °C by the end of the century. Such conditions would be beyond human experience. If warming continues unchecked into the twenty-second century, it could render parts of the planet effectively uninhabitable during the hottest days of the summer, with consequences that would be challenging to monetize[10].

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The models should be revised more frequently to accommodate scientific developments. Researchers commonly test model sensitivity to new parameters. But the structure and in some cases the calibration of the damage models is stuck in the 1990s, when the original versions were created, owing to a lack of funding.

IPCC reports help to set the research agenda on climate. The release of the Fifth Assessment Report reminds us of the progress so far. It is important to ensure that the sixth assessment takes a substantive step forward. By facilitating efforts to refine estimates of the social cost of carbon, the IPCC will be performing its most important function: informing the global political conversation about how best to address the looming threat of climate change.

Nature **508,** 173–175 (10 April 2014) doi:10.1038/508173a

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3 comments

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http://www.nature.com/nclimate/journal/v3/n9/full/nclimate1972.html?WT.ec_id=NCLIMATE-201309

Wilson Hendal • 2014-04-08 04:06 AM

Todd, if you have new information this is incredibly important. Please post references for the following information - we don't want people to think you have just made them up: 1. "The total global warming since 1904, yes 1904, is 2/10 of 1 degree F." 2. "There has been absolutely no global warming in over 17 years" Of course, if the earth was due to enter a cooling cycle and we prevented this by heating the earth, then we could still be heating the earth without the temperature actually increasing, right? 3. "There is not one global warming model that can account for how far off all the computer models have been" - (not sure this one makes sense? How can you model a model? Please clarify) 4. "When these alarmists can show us all proof of their assertions, they might regain some credibility" - please clarify what proof you would like (beyond the hundreds of papers already published). Regards, Wilson.

Todd Nelson • 2014-04-08 02:51 AM

This article is full of ifs, mays, and coulds. There are 2 indisputable truths this article conveniently leaves out. The total global warming since 1904, yes 1904, is 2/10 of 1 degree F. There has been absolutely no global warming in over 17 years. There is not one global warming alarmist computer model that can account for how far off all the computer models have been. When these alarmists can show us all proof of their assertions, they might regain some credibility. But, as this is all being written, there is no proof at all of any of their claims, so there is no credibility in what has been written in this article. Science either is or isn't, there is no belief foundation in any scientific fact, and there are no scientific facts in this article.

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Exhibit C

OMITTED DAMAGES:

What's Missing From the Social Cost of Carbon

March 13, 2014
Peter Howard

EDF ENVIRONMENTAL DEFENSE FUND Finding the ways that work

Institute *for* Policy Integrity *new york university school of law*

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The Cost of Carbon Project is a joint project of the Environmental Defense Fund, the Institute for Policy Integrity, and the Natural Resources Defense Council.

ABSTRACT

The 2013 Interagency Working Group on the Social Cost of Carbon (IWG) updated the U.S. social cost of carbon (SCC) for 2015 from a central value of $24 to $37 using three integrated assessment models (IAMs): DICE-2010, FUND 3.8, and PAGE09. The SCC is the additional economic damage caused by one ton of carbon dioxide. While some have questioned the increase in the SCC as too high, a thorough examination of the latest scientific and economic research shows that $37 should be viewed as a lower bound. This is because the studies available to estimate the SCC omit many climate impacts—effectively valuing them at zero. Where estimates are available for a given type of impact, they tend to include only a portion of potential harms. This paper represents the first attempt to systematically examine and document these omissions for the latest versions of the three IAMs used by the IWG, as well as earlier versions when they are used in calibrating the updated models.

The table on the following page summarizes hot spot damages including increases in forced migration, social and political conflict, and violence; weather variability and extreme weather events; and declining growth rates. A better accounting of catastrophic damages is also needed, as well as many other impacts.

While there is a downward bias to the U.S. SCC estimates due to these omissions, the Office of Management and Budget (OMB) and other executive branch agencies should move forward to finalize proposed rules with the 2013 IWG's current SCC estimates, as measuring at least some of the costs of carbon dioxide is better than assuming they are zero. At the same time, the OMB should more thoroughly document downward biases of the current U.S. SCC estimates, potentially using this report to list in detail all of the currently omitted damages.

Missing or Poorly Quantified Damages Needed to Improve SCC Models*

General Impact	Category	Pages
Health	Respiratory illness from increased ozone pollution, pollen, and wildfire smoke	30
	Lyme disease	30
	Death, injuries, and illnesses from omitted natural disasters and mass migration	30
	Water, food, sanitation, and shelter	30
Agriculture	Weeds, pests and pathogens	20
	Food price spikes	Note 83
	Heat and precipitation extremes	41
Oceans	Acidification, temperature, and extreme weather impacts on fisheries, species extinction and migration, and coral reefs	18-20, 41-42
	Storm surge interaction with sea level rise	37-38
Forests	Ecosystem changes such as pest infestations and pathogens, species invasion and migration, flooding and soil erosion	20
	Wildfire, including acreage burned, public health impacts from smoke pollution, property losses, and fire management costs (including injuries and deaths)	20, 30
Ecosystems	Biodiversity**, habitat**, and species extinction**	29
	Outdoor recreation** and tourism	23
	Ecosystem services**	27-28
	Rising value of ecosystems due to increased scarcity	31-32
	Accelerated decline due to mass migration	34

General Impact	Category	Pages
Productivity and economic growth	Impacts on labor productivity and supply from extreme heat and weather, and multiple public health impacts across different damage categories	24-25
	Impacts on infrastructure and capital productivity and supply from damages from extreme weather events and infrastructure and diversion of financial resources toward climate adaptation	25
	Impact on research and development from diversion of financial resources toward climate adaptation	25
Water	Availability and competing needs for energy production, sanitation, and other uses	21, 41
	Flooding	41
Transportation	Changes in land and ocean transportation	21-22
Energy	Energy supply disruptions	21
Catastrophic impacts and tipping points**	Rapid sea level rise**	8, 36
	Methane releases from permafrost**	8, 36
	Damages at very high temperatures***	Note 23
	Unknown catastrophic events	36-37
Inter- and intra-regional conflict	National security	39, 41
	Increased violent conflicts from refugee migration from extreme weather, and food, water and land scarcity	34-35

*This table catalogues climate impacts that have been largely unquantified in the economics literature and are therefore largely omitted from SCC models. Quantified impacts represented in the models include: changes in energy (via cooling and heating) demand; changes in agricultural and forestry output from changes in average temperature and precipitation levels, and CO_2 fertilization; property lost to sea level rise; coastal storms; heat-related illnesses; and some diseases (e.g. malaria and dengue fever).

** These impacts are represented in a limited way in one or more of the SCC models: 1) they may be Included in some models, and not others; 2) they may be included only partially (e.g., only one or several impacts of many in the category are estimated); 3) they may be estimated using only general terms not specific to any one damage—in these instances, estimated damages are usually very small relative to their potential magnitude, and relative to the impacts explicitly estimated in the models. See complete report for details.

*** While technically represented in SCC models through extrapolations from small temperature changes, there are no available climate damage estimates for large temperature changes, and these may be catastrophic.

OMITTED DAMAGES:

What's Missing From the Social Cost of Carbon+

Peter Howard*

In 2008, the United States Court of Appeals for the Ninth Circuit ruled that executive branch agencies must include the climate benefits of a significant regulatory action in federal benefit-cost analyses (BCA) to comply with Executive Order 12,866. In response, an Interagency Working Group on the Social Cost of Carbon was formed in 2010 to develop a consistent and defensible estimate of the social cost of carbon (SCC) using models drawn from the literature (Masur and Posner 2011). The SCC is the global cost to all future generations from one additional unit of carbon pollution in a given time period; forest fires, drought, and disease are just some of the costly consequences of climate change that are ideally included within it.[1] Thus, the SCC captures the benefit of reduced carbon pollution from a policy in terms of expenses avoided.

The SCC is estimated using Integrated Assessment Models (IAMs), which integrate a simplified climate model and a simplified economic model into a cohesive numerical model to capture the feedback effects between the two.[2] Using a methodology specified in the 2010 Technical Support Document (IWG, 2010), the 2010 Interagency Working Group developed a central estimate (corresponding to a constant discount rate of 3 percent) of $24 for a 2015 emission of carbon using three Integrated Assessment Models (IAMs): DICE-2007 (Nordhaus 2008), FUND 3.5 (Anthoff and Tol 2010), and PAGE2002 (Hope 2006). Using an identical methodology and updated versions of these three models—DICE-2010 (Nordhaus 2010), FUND 3.8 (Anthoff and Tol 2012),[3] and PAGE09 (Hope 2011)—the 2013 IWG re-estimated the central SCC estimate at $37 in 2015.[4] See Tables 1-3 for a full comparison of the 2010 and 2013 SCC estimates.

With its release by the 2013 Interagency Working Group on the Social Cost of Carbon (IWG), the U.S. government's updated social cost of carbon estimate catapulted into the national political debate. This surge in interest is mostly the result of the approximately 54 percent increase in the federal government's central 2015 SCC estimate from 2010 to 2013. Because the 2013 IWG used the same methodology to estimate the global SCC as the 2010 IWG (IWG 2013),[5] all changes in the SCC estimates are the result of updates to the three IAMs used for estimation. Regardless, considerable debate has ensued due to the significant implication this increase has on current and future U.S. policies.

While some conservative politicians and industry groups question the increase saying it is too high, this report shows more generally that, if anything, these SCC estimates are biased downward, probably significantly so. This downward bias is the result of modeling decisions by the 2010 IWG and modeling decisions by the authors of the current IAMS, including the use of outdated damage estimates and the omission of several climate

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change impacts. This report focuses primarily on omitted damages due to the likelihood that their inclusion would have a significant effect on the SCC.[6] These omissions include climate impacts on the following market sectors: agriculture, forestry, and fisheries (including pests, pathogens, and weeds, erosion, fires, and ocean acidification); ecosystem services (including biodiversity and habitat loss); health impacts (including Lyme disease and respiratory illness from increased ozone pollution, pollen, and wildfire smoke); inter-regional damages (including migration of human and economic capital); inter-sector damages (including the combined surge effects of stronger storms and rising sea levels), exacerbation of existing non-climate stresses (including the combined effect of the over pumping of groundwater and climate-driven reductions in regional water supplies); socially contingent damages (including increases in violence and other social conflict); decreasing growth rates (including decreases in labor productivity and increases in capital depreciation); weather variability (including increased drought and in-land flooding); and catastrophic impacts (including unknown unknowns on the scale of the rapid melting of Arctic permafrost or ice sheets).

Despite these downward biases to federal SCC estimates, this report argues that the Office of Management and Budget (OMB) and other executive branch agencies should move forward to finalize proposed rules with the 2013 IWG's current SCC estimates; they are underestimates, but we should, at a minimum, count the damages we can. At the same time, the OMB should emphasize more strongly the downward bias of the current SCC estimates and commit to addressing this bias in future updates of the estimates.

This report focuses on identifying the important categories of harm from climate change that are omitted from current IAMs. We first review the general categories of climate damages. Second, we describe how the latest versions of the three IAMs (DICE-2013, FUND 3.6, and PAGE09) are calibrated.[7] Third, we discuss a frequent cause of omitting damages: a lack of sound damage estimate(s) in the literature resulting from scientific and economic uncertainty in determining the magnitude of the effect. Fourth, using the previous two sections as a basis, we discuss the important categories of damages that are omitted. Fifth, we discuss the treatment of adaptation in these models, and whether omitted damages are likely to be incurred. Finally, we conclude with a discussion of the findings and what our results imply for the future estimation of climate damages.

DAMAGES

The rising temperatures and ecological shifts brought on by global climate change are expected to affect myriad aspects of natural ecosystems and human civilization. Though climate change may create benefits in some regions and sectors, the long-term effects of climate change are projected to be overwhelmingly negative. To help policymakers weigh the costs of climate mitigation and adaptation, these impacts are monetized by economists as damages. Damages can be broadly segmented into market damages, which manifest as a loss of gross domestic product (GDP) and non-market damages, which manifest in terms of lost welfare. Damages also include shocks to political stability, massive ecological regime changes (such as tipping points and mass species extinction), and impediments to sustained economic growth, none of which are easily predicted or quantified (U.S. Climate Change Science Program, 2008; Yohe and Tirpak 2008).

Market Damages

Market damages refer to changes in welfare due to changes in income or the availability, quality, or price of a market commodity or input. Most market damages result from shifts in productivity and a corresponding shift in output and GDP. Market damages can also be the result of the loss or depreciation of capital such as land or infrastructure (Goulder and Pizer 2006; Mendelsohn 2003).[8]

Sectors in which market damages from climate change are forecast include agriculture, due to increased temperatures, CO_2 fertilization, changing rainfall patterns, pests, and pathogens; energy demand, largely due to the increased cost of space cooling and the decreased cost of space heating associated with global temperature rise; energy supply, due to changing energy supply costs (such as increasing power plant cooling costs) and extreme weather energy supply interruptions; transportation and communication, due to delays and infrastructure losses from extreme weather events; forestry, due to shifting suitable habitat ranges, pests, pathogens, and fires; fisheries, due to higher water temperatures, invasive species, and ocean acidification; and water resources, due to increased evaporation rates and changing rainfall patterns. Market damages in the form of land, property, and infrastructure loss and degradation are also expected as a result of sea level rise and extreme weather events. While health damages have market (for example, labor availability and increased healthcare costs) and non-market (such as suffering and the value of human life) aspects, the market damages from health are relatively small compared the non-market damages because households place a high value on human life (Tol 2009; Jorgenson et al., 2004).[9]

In some of these market sectors, climate change is projected to create a net benefit in some countries for low-level temperature increases. For example, increased temperature will increase agricultural and forestry productivity in some regions and increased CO_2 concentrations can improve the nutritional value of soil (via the CO_2 fertilization effect). In some models, the benefits in some sectors are significant enough to result in initial net benefits to the globe from climate change. These sector benefits and the resulting global net benefits, however, are expected to be short-lived as temperatures continue to rise (Warren et al., 2006; Jorgenson et al., 2004). While Tol (2009) finds evidence of net global benefits from climate change up to a 2.2 degrees Celsius increase in temperature, this threshold differs between the three IAMs and even within variants of the same IAM.[10] Some IAMs, such as many of the more recent variants of DICE, find no such evidence of initial benefits.[11]

Non-market Damages

Non-market damages refer to damages affecting goods or services for which no established market exists, but which still provide value to humans. These non-market goods and services, also referred to as non-market commodities, can generally be thought of as environmental good and services (such as ecosystem services). Environmental goods can be divided into use values, including direct-use values (for example, the pharmaceutical value of biodiversity) and indirect use values (such as the values of ecosystem, recreational, and aesthetic services), and non-use value (including existence, bequest, option, and altruistic values). Another way to subdivide non-market damages is into tangible damages, which by definition can be valued, and intangible damages, which by definition are extremely difficult to value given current methods. While economists have established valuation techniques for tangible damages, the accuracy of these estimates vary by the type of good and service. For example, use values, particularly direct-use values, are more easily quantified than non-use values.[12]

Projected damages to non-market goods from climate change that are included in one or more IAM include the loss of species and habitat, increases in rates of human mortality and morbidity, and changes in amenity values (that is, the direct welfare change from a more or less hospitable climate) (Anthoff and Tol 2012; Warren et al., 2006; Smith et al., 2003). All tangible damages from climate change are not included in IAMs, such as the medical value of biodiversity. Intangible benefits, including larger societal implications of climate change, have yet to be meaningfully addressed or incorporated into IAMs (Yohe and Tirpak 2008).

Socially Contingent Damages

Socially contingent damages are damages that result from changes in social dynamics due to climate change. Warmer temperatures, sea level rise, and changing water availability can affect how societies function. For example, mass migration will become more likely as some regions become more inhospitable. Similarly, interpersonal violence and social and political conflict will rise with increased food, water, and resource scarcity. The values of social dynamics are, in most cases, intangible (that is, unmeasured) given current valuation methods; it is difficult to quantify the social effect, let alone value it. As a consequence, socially contingent damages from climate change are almost completely excluded from IAMs.

Catastrophic Impacts

One of the most concerning aspects of climate change is the potential for catastrophic damages. Catastrophic damages are characterized as low probability-high damage events. These damages come from

- tipping points (also known as discontinuities)—"an environmental threshold over which small changes in the environmental state can causes rapid, frequently irreversible changes in ecosystem characteristics" (EDF, NRDC, Policy Integrity, and UCS comments, 2013);
- fat tails—uncertainty in the underlying economic and environmental parameters in IAMs that result in underlying "fat-tailed" distributions, which are distributions (often right skewed) characterized by an extended and fat tail on the upper end of the distribution relative to the normal (bell curve) distribution; and
- black swan events—(that is, unknown unknowns) that refer to currently unknown tipping points or parameter distributions.

While tipping points, fat tails, and black swan events are distinct concepts, they are overlapping issues; this is discussed further below. Furthermore, while IAMs often categorize catastrophic damages as a distinct type of damage from the previous three, they should actually be thought of as damages to market goods, non-market goods and services, and society via cataclysmic climate events—often thought of in this case as rapid and/or extreme climate change.

Catastrophic impacts are often cited as a key reason for immediate action on climate change. Using PAGE09, Hope (2013) demonstrates that tipping point damages, the first of these three types of damages, alone can be as important as economic damages in determining the social cost of carbon.

TIPPING POINTS. As mentioned above, an ecological tipping point is broadly defined as a threshold beyond which a small change in conditions causes rapid, often irreversible changes in ecosystem characteristics. Tipping points are generally more common in intricate systems with many interacting parts, such that even small changes in the system can potentially have large impacts through a snowball effect.[13] A simple but illustrative example of an ecological tipping point is the effect of deforestation in tropical rainforests. The large trees in the rainforest depend upon nutrient-rich topsoil to thrive. That topsoil is held in place by the root network of the plants it supports and can take centuries to accumulate. The removal of trees accelerates the rate of

Crowning fire in spruce forest. Photo: Murphy Karen, U.S. Fish and Wildlife Service

topsoil erosion while topsoil erosion impedes tree survival rates. Deforestation, then, creates a chicken-and-egg conundrum as reforestation efforts are doomed by a lack of topsoil and topsoil cannot be sustained without an established root network (Brahic 2009).

Within the context of climate change, a tipping point generally refers to a temperature or CO_2 concentration threshold beyond which (even by small perturbations) the future state of Earth's climate system is significantly and irreversibly altered. In other words, a tipping point is an abrupt change in the climate system between stable climate states at the regional scale (at the subcontinental scale or higher) or global scale (Overpeck and Cole 2006). Beyond the temperature or CO_2 concentration threshold that causes this abrupt change, ecological changes would be irreversible on human time scales even if temperature could be returned to pre-threshold levels (Overpeck and Cole 2006; Lemoine and Traeger 2011).

A global tipping point would likely be driven by a series of region-specific or system-specific tipping points (that is, tipping elements), which, taken collectively, would dramatically reduce the Earth's natural capacity to withstand climate change. Lenton et al., (2008) identifies the following tipping elements:

- Arctic sea-ice (decreased areal extent),
- Greenland ice sheet (decreased ice volume),
- West Antarctic ice sheet (decreased ice volume),
- Atlantic thermohaline circulation (decreased overturning),
- El Niño-southern oscillation (increased amplitude),
- Indian summer monsoon (decreased rainfall),
- Sahara/Sahel and West African monsoon (increased vegetation fraction),
- Amazon rainforest (decreased tree fraction), and
- boreal forest (decreased tree fraction).[14]

The probability and damages of tipping point scenarios are poorly understood (Weitzman 2011). Due to the considerable uncertainty surrounding these events, some IAMs exclude them altogether. This will be discussed later.

Tipping point damages can be modeled either explicitly or implicitly. If tipping point damages are modeled explicitly, the damages from the crossing of tipping points are modeled using an additional damage function (for example, Hope 2002; Hope 2009; Nordhaus and Boyer 2000; Nordhaus 2008). If tipping point damages are implicitly modeled, tipping points are modeled in IAMs through the choice of climate parameters, specifically the probability distribution functions that represent them, as in Lemoine and Traeger (2011), Weitzman (2009), and Anthoff and Tol (2013a).[15] In this case, tipping point damages are implicitly captured through assumed increases in market and non-market damages resulting from higher temperature from crossing climate tipping point.

Fat Tails. Fat tails refer to the upper ends (that is, the right sides) of the probability density functions of a range of climate change-related variables. Tail fatness is an indicator of how quickly the probability of an event declines relative to the severity of that event, with fatter tails corresponding to lower rates of decline.[16]

Martin Weitzman has argued that existing climate models fail to adequately account for the extreme risks of climate change. In Weitzman's eyes, prevailing "structural uncertainties" (that is, unknown unknowns) abound in the economics of climate change, and existing benefit-cost analyses (BCAs) and IAMs have yet to deal adequately with these uncertainties. While IAM modelers often choose thin tailed distributions (for example, the uniform distribution) and medium-tailed distributions (for example, the normal distribution) to represent uncertain climate variables, Weitzman argues that fat-tailed distributions (for example, Student-t-distribution) are more appropriate due to these structural uncertainties in climate change (that is, unknown unknowns) and the "unlimited" potential for the scale of damages (Weitzman 2011).[17] Fat tails arise due to the finite amount of information on catastrophic impacts (due to their rarity in historical record keeping) forcing analysts to specify probability distribution functions of probability distribution functions. In other words, Weitzman believes that existing IAMs and BCAs under account for the potential of extreme, irreversible impacts of climate change by assuming thin-tailed and medium-tailed distribution functions,[18] which render the likelihood of extreme damages from climate change small enough to write off (Weitzman 2009; Nordhaus 2012).

Weitzman (2011) identifies multiple sources of structural uncertainty in existing climate modeling literature and models; he emphasizes that these sources are not exhaustive, and more likely exist. The five structural uncertainties that he identifies are: (1) the unprecedented rate and scope of increases in atmospheric greenhouse gas (GHG) concentrations, (2) the uncertainty surrounding the response of global temperatures to this dramatic increase in GHG emissions, (3) the potential for positive feedback mechanisms to accelerate the release of GHGs such as methane, (4) uncertainty of the effects (that is, damages) of extreme climate change,[19] and (5) the proper discounting of the distant future (Weitzman 2011). At each of these steps in the climate model, parameters are highly uncertain and potentially represented by fat tails. As a consequence of the "cascading" uncertainties at each step in the climate model and the potentiality of fat tails at each step, climate impacts are also likely fat tailed. As Weitzman (2011) emphasizes, this is the fat tail that truly matters to climate economics—not the fat tails of the climate sensitivity parameter and the other parameters—for the Dismal Theorem to arise.

As a result of the potential for climate impacts having a fat tail, Weitzman develops a theory now dubbed the Dismal Theorem. According to Weitzman (2009), if IAMs were to model fat-tailed distributions, the expected marginal utility of consumption would "explode." In other words, the "limiting [willingness to pay] to avoid fat-tailed disasters constitutes all of output (Weitzman, 2011)." As a consequence of this result, traditional BCA collapses as the SCC becomes infinite.

While Weitzman (2009) suggests such events can have such large costs as to overwhelm the discount rate, Nordhaus (2009) finds Weitzman's results are exceptions to the rule. In particular, Nordhaus (2009) find that the Dismal Theory holds, that is, the expected cost of climate change is infinite, only under limited conditions: the tails are "very" fat or society is "very" risk adverse. In other words, "[the probability of a catastrophic event] must not go to zero and [marginal utility of consumption] must be indefinitely large as consumption declines" towards zero (Nordhaus 2012); Nordhaus argues that the former condition may not hold (particularly if there is an upper bound on climate parameters), and the latter condition does not hold. Furthermore, using DICE-2007, Nordhaus (2009) demonstrates that catastrophic outcomes are potentially avoided, even if the climate sensitivity parameter is high and major tipping points exist, if policymakers can learn about the risks of climate change before irreversible, catastrophic damages occur and policymaking works correctly. However, Nordhaus' rebuff of the Dismal Theory (and its implication that BCA does not apply to climate change) should not be construed as a rejection of fat tails—these he believes are important for inclusion in IAMs (Nordhaus 2012).

In response, Weitzman (2011) argues that the infinite number should not become a distraction, but merely emphasize the larger willingness to pay to avoid these structural uncertainties discussed above. To produce a finite SCC for BCA to continue, Weitzman argues for the inclusion of the value of civilization. Like the value of a statistical life, the value of civilization captures the "rate of substitution between consumption and the mortality risk of a catastrophic extinction of civilization or the natural world as we know these concepts (Weitzman 2009)." Crudely calculated, the value of civilization equals the present value of global income in the year that civilization would end divided by the probability that civilization would end in that year (Weitzman 2009; Weitzman 2011).[20]

The empirical work on catastrophic damages, that is, the willingness to pay to avoid structural uncertainty, finds mixed results. On the one hand, Newbold and Daigneault (2009) find large catastrophe risk premiums. In this case, the use of the value of civilization may be essential. On the other hand, Pindyck (2009) finds only a modest risk premium. Similarly, Nordhaus (2009) only finds large catastrophic damages when climate policy fails in the presence of high climate sensitivity and major tipping points. In these cases, the inclusion of a value of civilization may be unnecessary because benefit-cost analysis does not collapse.

Note that there is some overlap between tipping point events and fat tails. If tipping point damages are modeled explicitly, the probability of incurring tipping point damages can be modeled using a fat-tailed distribution if the probability distribution function of the event occurring is unknown. Similarly, the corresponding magnitude of the damages can be modeled using fat-tailed distributions if this probability distribution function (PDF) is also uncertain. If tipping point damages are modeled implicitly, that is, climate parameters are used to model tipping points explicitly, fat-tailed distributions can be used for the corresponding climate parameters' probability distribution functions. However, tipping points do not require fat-tail distributions if they are known unknowns. In other words, the use of fat tails to model the probability of tipping points or their damages is not necessary to the extent that their probability distribution functions are known, and they can be captured by thin- or medium-tailed distributions. Undoubtedly, some tipping points are unknown unknowns and require the use of fat tails in that probability and damages of tipping point scenarios are poorly understood (Weitzman 2011).

BLACK SWAN EVENTS. Black swan events refer to unknown catastrophic impacts, via unknown tipping point events or parameters within unknown probability distribution functions. Currently, black swan events still go unaddressed by IAMs. Along with the view that omitted climate damages likely outweigh omitted climate benefits (Mastrandrea 2009), there exists a general opinion that bad surprises are likely to outweigh good surprises in the case of climate change (Tol 2009b; Mastrandrea 2009).[21]

Just as tipping points and fat tails are related concepts, so are fat tails and black swan events. Fat tails can be thought of as a general way to capture unknown unknowns in the SCC. However, the choice of fat-tailed distributions, that is, the rate that the tail declines, is unknown. In other words, specifying a fat-tailed distribution is guessing at unknown unknowns. Furthermore, in terms of real practical applications, IAMs that include fat tails may still omit other unknown unknowns. In this sense, the inclusion of fat-tailed distributions into IAM models may not fully capture unknown unknowns.

CALIBRATION

Through the choice of damage sectors and the choice of calibration estimates, IAM developers determine what damages from climate change are included and excluded in the social cost of carbon.[22] Using damage estimates (measured as a percentage change in GDP) for a specified temperature increase (measured as the degree Celsius increase in regional or global average temperate from the pre-industrial temperature) drawn from the literature,[23] IAM developers calibrate damage functions in three ways: sector-region analysis, survey, or meta-analysis.

First, a sector-regional analysis is when studies are found that provide sector-specific damage estimates by region; extrapolation from observed regional damages to missing regions is often necessary. If an aggregate damage function is utilized, damages are summed across sectors and regions. Earlier versions of DICE (DICE-1999 and DICE-2007) fall within this category, as does FUND.[24] Second, a survey of the literature is when a consensus work, like the IPCC studies, is utilized, or when the author uses his discretion to decide on the level of damages. In either case, though no statistical analysis is performed, the damage estimates are based upon a survey of particular studies. PAGE relies on this methodology combined with uncertainty analysis.[25] Third, a meta-analysis is when a damage curve is fit to various damage estimates that vary in damage magnitude and future temperature level. The most recent version of DICE relies on this method. The latter two methods are problematic in that they make it difficult to determine the actual source behind the damage function, and thus, to determine what particular climate damages are included and excluded from the model.

In the following section, we discuss how each IAM is calibrated by its developer using the default version of each of these models.[26] This is done to reflect the version of the model that each modeler provides to the public and documents most thoroughly. Furthermore, the IWG uses the default versions of these IAMs. In the case of DICE-2013, which has not been utilized by the IWG, the default version is utilized for purposes of consistency.

Calibration of the DICE damage function

Since 2000, William Nordhaus has released four versions of the DICE model: DICE-99, DICE-2007, DICE-2010, and DICE-2013. Of these four models, DICE-2010 is not considered a major update of the DICE model but rather an aggregation of the RICE-2010 model, a regionalized version of DICE. Across all versions of DICE, William Nordhaus calibrates an aggregated global damage function that is quadratic in temperature.[27] The sources used to calibrate the DICE-RICE damage functions have changed over the various versions of the model. For the quadratic damage functions of the initial models, that is, DICE-99, DICE-2007, and DICE-2010, Nordhaus used damage estimates by sector drawn from specific sources and studies. For the more recent version of the model, that is, DICE-2013, Nordhaus utilizes a meta-analysis approach.

EARLY VERSIONS OF DICE. The DICE-99 damage function was calibrated against region-sector damage estimates for a 2.5 degree and 6 degree Celsius increase in global mean surface temperature above the pre-industrial level.[28] The sectors in the DICE-1999 model are: agriculture; other vulnerable markets—forestry, fisheries, water transportation, hotels and other lodging places, outdoor recreation, and energy; coastal—sea level rise and storms; health—malaria, dengue fever, other tropical diseases, and pollution; non-market amenities—the allocation of time to leisure activities; settlements and ecosystems; and catastrophic impacts. Thus, the DICE-1999 model includes market, non-market, and catastrophic damages. See Table 4 for sources of damage estimates and Table 5 for DICE-1999 region-sector specific damage estimates.[29] See forthcoming Appendix A for a full discussion of the calibration of DICE-1999.

Instead of DICE-1999, the 2010 Interagency Working Group utilized DICE-2007 in the estimation of the U.S. Social Cost of Carbon, as documented in the 2010 Technical Support Document. There are no major changes from DICE-1999 to DICE-2007. In particular, as with DICE-1999, Nordhaus uses sector-based damage estimates to calibrate the aggregate DICE-2007 damage function. There is no change in the types of damages.[30] See forthcoming Appendix B.

The 2013 Interagency Working Group utilized DICE-2010 to estimate the U.S. Social Cost of Carbon, as documented in the 2013 Technical Support Document. The actual calibration method is almost identical to DICE-2007. The main difference is that for the 2010 version of the model, Nordhaus explicitly specifies the aggregate damage function as a quadratic function of both sea-level rise and temperature, instead of only temperature (Nordhaus, 2010; Nordhaus and Sztorc, 2013). See forthcoming Appendix C.

Given the similarities between DICE-1999, DICE-2007, and DICE-2010, this paper focuses on the omitted damages from DICE-1999. Of these three versions of DICE, DICE-1999 is chosen because it is used by Hope as one of the calibration sources of the PAGE09 damage function.

RECENT VERSION OF DICE. Nordhaus states that DICE-2013 is the first major update of the DICE model since the 2007 version. There are three major updates from 2007 to 2013 in the DICE aggregate damage function. First, Nordhaus updates the sources of his damage estimates used for calibration. Instead of using Nordhaus and Boyer (2000) as the basis of this calibration, he uses the damage estimates in Table 1 of Tol (2009), as seen in Table 7 below and Figure 2 in Nordhaus and Sztorc (2013). Second, he increases these damage estimates by 25 percent to account for omitted non-monetized benefits, such as "several important factors (biodiversity, ocean acidification, and political reactions), extreme events (sea-level rise, changes in ocean circulation, and accelerated climate change), impacts that are inherently difficult to model (catastrophic events and very long-term warming), and uncertainty (of virtually all components from economic growth to damages)." Last, Nordhaus no longer utilizes a sector-region analysis to calibrate DICE's aggregate damage function, but instead switches to the meta-analysis technique; see forthcoming Appendix D.

Determining what damages are included and excluded from the DICE-2013 damage function is difficult. This is because Nordhaus switches from a sector-region analysis to calibrate DICE's aggregate damage function to the meta-analysis technique, which relies on 13 studies cited in Tol (2009); see Table 7. For several reasons, this makes determining the damages included in the DICE-2013 model nearly impossible. First, many of the studies cited in Tol (2009) rely on a multitude of studies to produce their estimates, resulting in the need to go through a large number of papers in detail to decipher what damages are included and excluded from DICE. Second, when these studies do not rely on a multitude of cited papers, they utilize author discretion or statistical techniques to determine damage estimates. Both of these methods make it difficult to determine which sectors are included in the damage estimates, and the latter estimates, which include cross-national regressions, can often suffer from statistical inference problems. Last, it is difficult to determine what damages are included in the damage function because the 13 studies differ in what damages they include and exclude in their analyses. Specifically, what does it mean to have one of 13 studies include catastrophic damages or three out of 13 studies explicitly model the effect of climate change on vector-borne diseases? It seems reasonable to argue that the inclusion of these damages by a minority of studies implies their general exclusion from the DICE-2013 damage function. However, two studies exclude non-market damages and another two studies exclude market damages. Are non-market damages and market damages completely accounted for in DICE-2013? The answer to this question is debatable.

The DICE-2013 damage function was not used by either the 2010 or 2013 Interagency Working Group because the model was not yet peer-reviewed. It is our view that the IWG should be wary of using DICE-2013 in the future, given the inherent difficulty in understanding its foundations. Furthermore, if a meta-analysis is used, it should be conducted at either the sector or region-sector levels where more data are available. This is discussed further in the conclusion.

Calibration of the FUND 3.6 damage functions

FUND 3.6 is the only model of the three to model damages as functions of physical processes. Specifically, in FUND, Tol calibrates sector-specific damages functions to a 1 degree Celsius increase in temperature, and assumes dynamic equations to extrapolate damage estimates to higher temperature levels and different future states (rate of climate change, CO_2 levels, and socio-economic scenarios). These equations depend on various assumptions about physical and economic processes, and also rely on additional parameter calibration. Unlike DICE and PAGE, some sector damages, that is, agriculture and ecosystem services, are functions of the rate of temperature change, in addition to the level of temperature change, sea-level rise, and amount of CO_2 in the atmosphere.

FUND includes market and non-market damages, but fails to explicitly model catastrophic damages. The model's damage sectors include: agriculture, energy consumption, forestry, (fresh) water resources, sea level rise, human health, ecosystem degradation, and extreme weather (Anthoff and Tol, 2012). While FUND does not explicitly model catastrophic damages, FUND captures catastrophic damages via uncertain parameters.[31] Of the three IAMs utilized by the IWG, FUND 3.6 is the only one to model a socially contingent response to climate change: migration from sea level rise.

For FUND 3.6, Anthoff and Tol (2012) calibrate multiple damage functions per sector. Tol and Anthoff (2013) calibrate three agricultural damage functions using agricultural damage estimates derived using a general equilibrium approach; the three damage functions model the effect of rate of climate change (the cost of farmer mal-adaptation), level of climate change (effect of temperature level on crop production), and carbon dioxide fertilization on agricultural production (potential increases in agricultural production due to a rise in the atmospheric concentration of CO_2), respectively. In energy, Anthoff and Tol include the cost to the energy sector due to increased demand for space cooling and decreased demand for space heating from a rise in temperature. In forestry, Anthoff and Tol (2012) include the cost of climate change impacts on industrial wood manufactured products from changes in mean temperature and atmospheric concentrations of carbon dioxide relative to pre-industrial levels. In water resources, Anthoff and Tol (2012) include the effect of climate change on fresh water resource. For sea level rise, Tol accounts for losses of dry land and wetland, the coastal protection and migration costs. In health, Tol accounts for the mortality and morbidity costs of diarrhea, vector-borne diseases (malaria, schistosomiasis, and dengue fever), and heat and cold related illnesses (cardiovascular and respiratory disorders) due to a rise in temperature. With respect to ecosystems, Anthoff and Tol (2012) estimate a value for species loss. Finally, with respect to storms, Tol estimates the economic costs of the destruction and the value of life lost from tropical storms (hurricanes, typhoons) and extratropical storms (cyclones).

Due to the extensive use of data sources necessary to calibrate the physical processes, this section does not contain an extensive discussion of data; see forthcoming Appendix E.

Calibration in the PAGE-2009 damage functions[32]

PAGE09 models damage functions for four generalized impact sectors: market, sea-level rise, non-market, and non-linear (or tipping point) damages. Hope (2011a; 2011b; 2013) specifies a triangular distribution for each of the parameters in the damage function.

The non-catastrophic damage functions in PAGE09 (market, non-market, and sea-level rise) are calibrated using various versions of DICE and FUND. Thus, PAGE09 omits similar damages as do these two models. In PAGE09, Hope calibrates the distribution of economic (that is, market), non-economic (that is, non-market), and sea-level rise damages as a percentage of GDP for a 3 degree temperature increase (corresponding to a 0.5 meter sea-level rise) using a range of damage estimates from Warren et al (2006) and the IPCC 4th Assessment Report (IPCC, 2007). Warren et al (2006) discusses DICE-1999, FUND2.9, PAGE02, and MERGE; PAGE2002 is calibrated based on DICE-1999 and FUND 2.0.[33] Fig 20.3a from AR4 WGII on page 822 (Figure 1 below), which is used to inform the range (the minimum and maximum combined effect) of market and non-market damages (a range between 0.3 percent to 1.8 percent GDP decline for a 2.5 degree Celsius increase), cites Nordhaus and Boyer (2000) – DICE-1999, Tol (2002b) – FUND 2.0, and Mendelsohn et al (2000); this figure is identical to Figure 19.4 in IPCC (2001a, Chapter 19) upon which the PAGE2002 damage estimates were partially based. In other words, the market, non-market, and sea-level damage functions in the PAGE09 model are "highly" dependent on DICE and FUND, though Hope uses his discretion to specify a range of estimates to allow for the possibility that these models have underestimated impacts.

Flooding in downtown Binghamton, New York due to the remnants of Tropical Storm Lee. Photo: National Weather Service, Binghamton

Hope (2011) also reduces the magnitude of these damages by including initial climate benefits, which can result in some regions experiencing positive net benefits from climate change at low temperature increases, and by placing a limit on climate damages so that they can be no greater than 100 percent of GDP at high temperature increases. In addition to damages, Hope (2011b) includes an additional terms in each of the three non-catastrophic impact sectors based on the findings of Tol (2002) to capture initial climate benefits for lower temperature increases; these initial benefits are set equal to zero for sea-level rise in the default version of the PAGE09 model.[34] These expressions are defined such that these benefits dissipate as temperature increase until they become zero (that is, do not yield any actual benefits) at some temperature threshold, and then they become damages (in addition to the previously discussed calibrated damages) for further temperature increases. Assuming no adaptation, the temperature thresholds for both market and non-market damages are 3 degrees Celsius.[35] Hope (2011) also limits damages to 100 percent of GDP in any given time period. Instead of maintaining polynomial damage functions across all temperature levels, damage functions shift from polynomial functions to logistic functions at certain damage levels to constrain damage to 100 percent of GDP. Following Weitzman (2009), the saturation point (that is, the point where damages as a percentage of consumption starts to become limited) is characterized by a triangular distribution with range 20 percent to 50 percent, a mean of 33.33 percent, and a mode of 30 percent (Hope, 2011a; 2011b). Given the modeling assumption of PAGE09, the initial benefit terms do not yield any actual benefits (that is, are equal to zero) and the damage functions are still polynomial functions for a 3 degree Celsius increase and a 0.5 meter sea-level rise. In other words, non-catastrophic damages equal their calibration value of 2.03 percent of GDP at the calibration temperatures increase of 3 degrees Celsius when there is no adaptation (Hope 2011).

In PAGE09, Hope explicitly models climate tipping points as a singular, discrete event that has a probability of occurring in each time period. This probability increases in temperature. If this event occurs, a decline of 5 percent to 25 percent of GDP occurs; See Table 9 below.[36]

PAGE09 calculates climate damages for the European Union, and then scales these damages to other regions. PAGE09 uses the relative length of coastline to inform the corresponding ranges of scaling factors; Anthoff et al., (2006) is the data source for the weighting factors. While these scaling factors do no differentiate between developed and developing countries, Hope includes equity weights in PAGE09 that account for differences in GDP per capita between European Union and other regions (Hope 2011b). Finally, Hope specifies regional damage functions in PAGE09, which are functions of regional temperature, not global mean surface temperature. Thus, PAGE09 captures some regional differences in climate damages using several mechanisms. See forthcoming Appendix F for further discussion.

Damages generally included in IAMs

From this discussion about how the three latest IAMs are calibrated, we can make some general statements about what types of damages are accounted for by IAMs. Currently, they cover a number of direct effects of climate change, that is, a rise in global average surface temperature, on economic (that is, market) activity, and to a lesser extent the direct effects of climate change on the environment and human settlements. The three Integrated Assessment Models (IAMs) capture the direct effects of higher temperature levels and higher CO_2 levels (via soil fertility) on agriculture and forestry yields (but excluding climate change effects on pests, pathogens, and fires), and the effects of trade through general equilibrium effects. The models only capture the effects of higher temperature on fisheries to a very limited extent, and exclude the effects of habitat loss (particularly mangroves and coral reefs), ocean acidification, and invasive species all together. The models also capture some effects of climate change on energy demand and fresh water resources, though these are still limited in important ways (see discussions on fisheries, energy supply, ecosystem services, and destabilizers of existing non-climate stressors below). While IAMs capture the effects of heat and cold related illnesses (cardiovascular and respiratory disorders) to different extents, all three capture some effects of climate on vector-borne diseases, including malaria and dengue fever. For example, the direct cost of vector-borne diseases on human life is included, but not the effects of such diseases on labor supply or productivity (as discussed below). To different extents, all three models capture the effects of increased storm strength on coastal property values and sea level rise on preventative expenditures, lost property, and lost ecosystems. To the extent possible with current models, all IAMs consider some effect of climate change on ecosystems and biodiversity—though improved estimates are needed with respect to both of these damage estimates. Finally, there are a variety of damages that are captured by only one or two of the IAMs, but not all three: effects of climate change on morbidity; mortality from storms, pollution, and diarrhea; recreational activities; climate amenities (that is, the willingness to pay to live in a location with more sunny days); and catastrophic damages.

As is discussed more thoroughly in the conclusion of this report, many of the smaller climate damages are not considered by the authors of IAMs because they are considered cancelled out by omitted climate benefits. The views of Tol (2009) and Yohe and Tirpak (2007) are that a better job has to be done with respect to including only major damage categories: catastrophic damages, socially contingent damages, and weather variability. See the conclusion of this paper for more of a discussion.

CAUSES OF THE OMISSION OF DAMAGES

In general, the more difficult a climate impact is to estimate in the natural sciences (which measure the physical impact) and/or value in economics, the more likely that climate impact is to be excluded from IAMs (Yohe and Tirpak, 2008); see Figure 2. With respect to the natural sciences, damages corresponding to more certain (that is, known) climate trends (for example, average temperature increases and sea level rise) are included in IAMs; bounded trends, that is, climate change for which a range and/or distribution is specified, such as extreme weather events and weather variability (for example, droughts, floods, storms, and so on), are less likely to be included; and abrupt changes, in general, are the least likely to be included because they are the effects characterized by the greatest uncertainty. With respect to economics, damages that are easier to value are more likely to be included, such that many more market damages are included than non-market damages. Environmental goods and services are more likely to be omitted from IAMs by analysts than market damages because the former does not have observable market prices and instead must be valued by the analysts. While the value of some environmental goods and services can be indirectly observed in market data (for example, housing sales) using revealed preference techniques, other environmental goods and services (for example, biodiversity) can only be valued using stated preference techniques;[37] this latter group of environmental goods and services are more likely to be omitted. Socially contingent damages (for example, famine, political unrest, migration, and so on), which are often the result of multiple stressors, are usually omitted because they are difficult to quantify, predict, and value (Yohe and Tirpak, 2008). Figure 2 below, taken from Yohe and Tirpak (2008), organizes all types of climate damages into nine categories of damages corresponding to three levels of scientific uncertainty (that is, three rows) and three levels of economics uncertainty (that is, three columns) discussed above.

The nine categories of climate of climate benefits and damages in Figure 2 (and discussed in the previous paragraph) can be further organized into three groups of damages based on their levels of representation in IAMs:

- Group 1: Included damages—market damages from certain climate trends. Area I in Figure 2.
- Group 2: Partially included damages—bounded and tipping-point market damages and certain and bounded non-market damages. Areas II, III, IV, and V in Figure 2.
- Group 3: Excluded damages—socially-contingent damages and non-market tipping point damages. Areas VI, VII, VIII, and IX in Figure 2.

Group 1 damages, that is, certain market damages, are included, but can still be improved by accounting for geographic variability. Other market damages, for all real purposes, are excluded: fisheries, energy supply, transportation, communication, and recreation and tourism.

Group 2, which includes bounded and tipping-point market damages and certain and bounded non-market damages, has been less successfully included into IAMs. The three IAMs have included certain and bounded non-market damages, but in a less than comprehensive manner due to data and method limitations. In other words, while many of these damages have been included in IAMS (for example, heat stress, loss of wetlands, biodiversity, and loss of life), the included estimates require significant improvement.[38] Similarly, while some IAMs (earlier versions of DICE and PAGE), have explicitly accounted for catastrophic market damages, Yohe and Tirpak (2008) argue that these estimates have been less than comprehensive, and most likely omit non-market and socially contingent consequences of these changes.[39] Furthermore, while IAMs have included market sectors that are affected by climate variability (agriculture, fresh water resources, forestry), little has been done to account for the damages of increased climate variability in these sectors. It is critical to account for increased climate variability because average changes mask extreme events, such as droughts, heavy rains, heat waves, and cold spells.

Group 3, that is, socially contingent damages and non-market tipping point damages, has only recently been investigated (or has not been investigated at all) by impact papers. As a consequence, they are completely omitted from IAMs (Yohe and Tirpak, 2008).

With each generation of IAM, a discussion ensues over whether climate damages are accurately captured. While several studies have identified missing damages in earlier versions of these three IAMs (Warren et al., 2006; Dietz et al., 2007; Yohe and Tirpak, 2008; Tol, 2009), this report is the first to thoroughly identify and discuss the various damages omitted from the most recent versions of these three IAMs (specially the default versions): DICE-2013, FUND 3.6 (which is identical to FUND 3.7 and FUND 3.8 in terms of damage captured), and PAGE09. By analyzing the calibration methods and data sources of the latest version of the three IAMs, as discussed in the previous section, this report is able to provide a comprehensive discussion of which important categories of harm are included and excluded from these IAMs. Please see Appendices A through F for a more thorough discussion of the calibration of each IAM, and which damages are included and excluded from the default version of each of these models.

OMITTED DAMAGES

Based on the analysis of the three IAMs in the previous two sections, this section will discuss the damages currently omitted from IAMs: market damages—fisheries, pests (IWG, 2010), pathogens (IWG 2010), erosion (Vose et al., 2012), weeds (Rosenzweig et al., 2001), air pollution (Warren et al., 2006; Cline, 1992), fire (Cline, 1992), energy supply (Tol, 2009; IPCC, 2007b), transportation (IPCC, 2007b; Koetse and Rietveld, 2009), communication, ecological dynamics (Gitay et al., 2001; Norby et al., 2005), and decreasing growth rate (Fankhauser and Tol, 2005; Tol, 2009; Dell, Jones, and Olken, 2013; Moyer et al., 2013); non-market damages—recreational value (Tol, 2009), ecosystem services, biodiversity and habitat (IWG 2010; Tol, 2009; Nordhaus and Sztorc, 2013; Freeman and Guzman, 2009), omitted health costs (Tol, 2002a; Warren et al., 2006), and relative prices (IWG, 2010; Sterner and Persson, 2008; Hoel and Sterner, 2007); socially contingent damages— migration, social and political conflict, and violence (Stern, 2007–Chapter 6; Yohe and Tirpak, 2008; Tol, 2009; Dell, Jones, and Olken, 2013); catastrophic impacts (IWG 2010; Yohe and Tirpak, 2008; Tol, 2009); inter-regional damages (IWG 2010); and across sector damages—inter-sector damages (IWG, 2010; Warren et al., 2006), exacerbation of existing non-climate stresses (Free man and Guzman, 2009), ocean acidification (Brander et al., 2009; Cooley and Doney, 2009; Guinotte and Fabry, 2009), and weather variability (Yohe and Tirpak, 2008; IWG, 2010).[40]

Omitted damages can involve omitted damage sectors, such as fisheries, or omitted effects of climate change within and across sectors, such as ocean acidification. This poses a taxonomy problem in that it is hard to classify damages within the simple market, non-market, socially contingent, and catastrophic damage categories that we have laid out earlier. For clarification purposes, we highlight when this is a particular problem with respect to omitted effects of climate change: ocean acidification; wildfires; and pests, pathogens, and weeds.[41] In addition, we add two additional types of omitted damages to the taxonomy: inter-sector damages and cross-sector damages. The former captures the damages that arise due to the interaction of climate change effects between two or more damage sectors, and the latter captures omitted damages that affect multiple sectors. See Table 10 for the taxonomy of omitted damages used in this paper, and Table 11 for an alternative taxonomy based on omitted damage sectors and omitted climate effects.

Market damages

There exist several market damages that remain unaccounted for in the market damage literature. As mentioned earlier, Yohe and Hope (2013) argue that few updates to market damages will have a significant effect. However, there are several potential additions that should be considered for having potentially large effects: fisheries (and relatedly, including effects of ocean acidification more broadly), market sector disturbances (pests, pathogens, air pollution, erosion, and fires), energy supply, transportation, and economic growth.

FISHERIES. Fisheries are, for the most part, excluded from IAMs. DICE-1999, which is utilized as a damage source in DICE-2010 and PAGE09 (both are used by the 2013 IWG), includes fisheries in a generalized "other market" sector, along with forestry, energy systems, water systems, construction, and outdoor recreation. Citing Cline (1992), Nordhaus (1991), and Mendelsohn and Neumann (1999) damages estimates to these sectors for the United States, Nordhaus and Boyer (2000) argue that damages not related to energy are equal to zero. Implicitly, this assumes that climate damages to fisheries are equal to zero even though the sources he cites do not explicitly discuss damages to fisheries, particularly Cline (1992) and Nordhaus (1991). As a consequence, Nordhaus and Boyer (2000) essentially fail to account for fisheries. In FUND 3.6, freshwater and saltwater fisheries are excluded. Consequently, PAGE09, which heavily relies on early versions of DICE and FUND to calibrate its market damage function, excludes fisheries as well. Finally, DICE-2013, at most, partially captures fisheries. Many of the enumerative studies upon which DICE-2013 relies in the calibration of its damage function, exclude fisheries altogether.[42] Similarly, in the statistical studies, the effect on fisheries, particularly offshore salt-water fisheries, may be excluded; see forthcoming Appendix D.[43]

Fisheries support a significant portion of the world's population. Many individuals rely on fishing and aquaculture for employment. Also, many individuals rely on seafood as their primary source of protein. Climate damages to fishery resources will cause particular harm to those regions most reliant on fisheries (WFC, 2007). According to Allison et al., (2009), the most vulnerable fisheries are located in developing nations, which are the most dependent on fisheries in terms of livelihood and nutrition.

Climate change will affect fisheries in several ways. First, rising sea surface temperatures will damage coral reefs, an important habitat for many fisheries, and result in more frequent algae blooms, which negatively affect fish stocks via decreased oxygen availability. Rising temperatures will also positively affect the growing season, winter mortality rates, and growth rates. Second, rising land temperatures will increase the temperatures of fresh water systems, resulting in declined fish stocks through reduced water quality, invasive species and pathogens, and decreased food abundance; again, warmer temperatures in cold waters may have some benefits in terms of increased growth rates. Third, rising sea levels will negatively affect coastal habitats, including mangroves and salt water marshes, and freshwater water habitats via saltwater intrusion; rising sea levels may also benefit shrimp and crab aquaculture. Fourth, increased weather variability and extreme events, including floods and droughts, and decreased water availability in some regions is likely to negatively affect fish stocks, particular fresh water and aquaculture; changing precipitation patterns may affect marine populations via water salinity (WFC 2007). Fifth, changes in ocean chemistry, including ocean acidification, which is discussed more below, and decreased oxygen content from increased algae blooms, which is discussed above, will negatively affect fish stocks, particularly mollusks. Sixth, melting sea ice may increase access to Arctic fisheries. Last, climate change will likely compound the negative effect that human activity, including over fishing, has on future fish stocks.[44] These damages and benefits will vary regionally, particularly as fish shift locations. They are also highly uncertain due to uncertainty over climate change and its effects (particularly on the scale that is relevant to marine life and fisheries – continental shelves), complex aquatic food web and ecosystem dynamics, the ability of species to adapt, and the range of human and environmental impacts fisheries (WFC, 2007; Hollowed et al., 2013; Sumaila et al., 2011).

Adaptation by species and humans may be able to reduce these negative effects. Fish species will be able to adapt to some of these change by moving toward the Poles and into deeper water (Sumaila et al., 2011). However, these changes may still result in habitat loss for some freshwater and saltwater fish, even with this ability to adapt, such that some species will experience declines and extinction (Hollowed et al., 2013). Furthermore, these shifts imply regional effects, such that some regions benefit and others are harmed (Hollowed et al., 2013), and quality effects, as fisherman are forced to switch to new species. Finally, humans may be able to adapt to mitigate losses and meet increased demand by expanding aquaculture to replace decreased wild catch and increasing trade (Brander 2010). However, human adaptation at the local level will come at an increased capital cost, and a loss of capital as some fisherman scrap their vessels (Sumaila et al., 2011).

In addition to climate change affecting fish stocks, climate change will also affect human capital and infrastructure necessary for production. Increased storm strength and frequency will negatively affect infrastructure, particularly aquaculture, located near coastal areas. Coupled with rising sea levels that will negatively affect coastal ecosystems that act as a buffer from coastal storms, storm effects could be significant (WFC, 2007). The ability of regions to adapt to these events will vary regionally.

There is a lack of estimates for the impacts of climate change on fisheries (Sumaila et al., 2011). This is partially due to the difficulty of estimating the net impacts on production across multiple species and uncertain future environments, which results in highly uncertain estimates. While it is clear that damages will vary regionally—hurting tropical regions and possibly benefiting artic regions—these regional results are uncertain given the large scale effects of climate change on oceans; this includes ocean acidification and higher ocean temperatures—both of which effect phytoplankton (Toseland et al., 2013).[45] Because developing nations are focused predominately in tropical and subtropical subclimates, fishing industries in poor nations are likely to be disproportionately affected. These nations are often already at an open-access equilibria due to overfishing and lack of management, and, as a consequence, are unlikely to experience a significant change in profits due to climate change. However, in developing nations, large portions of the population rely on subsistence fishing for calories and protein. Thus, the effects of climate change on consumer welfare via fisheries are likely to be substantial in developing nations.

NATURAL DISTURBANCES: PESTS, PATHOGENS, AND WEEDS, EROSION, AIR POLLUTION, AND FIRES. Pest (weeds and insects) and pathogens (Rosenzweig et al., 2001), erosion (Vose et al., 2012), air pollution (for example, the effects of climate change on increased ozone pollution, which affects crops and public health),[46,47] and fire are natural disturbances that affect agriculture and forestry. While these disturbances are currently being excluded from the agricultural and forestry sectors (Ackerman and Stanton, 2011, Cline 1992), these disturbances are likely to be substantially affected by climate change (IPCC, 2007b, Chapter 5). Climate may expand the geographical extent of pests, pathogens, and weeds (particularly for livestock and forests) and increase the likelihood and severity of pest and pathogen outbreaks due to earlier springs and more extreme events. Forestry may be negatively affected by increased erosion from higher precipitation and other extreme weather events (Vose et al., 2012). Increased ozone exposure will also decrease timber production and crop yields, while increasing crop susceptibility to pest outbreaks. Increased fire risks may decrease forestry production and costs (IPCC, 2007b), and have significant impacts on human health and infrastructure (Fowler, 2003). While each of these natural disturbances may have only modest effects, their interactions (along with drought) and their combined effects are likely to be substantial.

These natural disturbances also affect agricultural and forestry via the fertilization effect, which is the increase in plant growth, and thus production, from an increase of carbon dioxide in the atmosphere. Current estimates of the CO_2 fertilization effect are from laboratory experiments where plants are not subject to competition from pests, pathogens, and weeds that may also benefit from CO_2 fertilization.[48] More recent estimates, known as Free-Air CO_2 Enrichment (FACE) experiments, are field experiments where plants are subject to these pressures; the resulting benefits from increased CO_2 are lower under FACE experiments (Hanemann, 2008, IPCC, 2007a). Furthermore, air pollution (ozone), which is completely unaccounted for, may further limit the CO_2 fertilization effect (IPCC, 2007b Chapter 5).

Increased pests, pathogens, and weeds, erosion, air pollution, and fires will also affect ecosystems, wildlife, and human settlements. These costs are also currently excluded from the default versions of these IAMs.

ECOLOGICAL DYNAMICS. Ecological dynamics are omitted from the analysis despite their significance in timber production. In addition to disease and insects (Gitay et al., 2001; Norby et al., 2005) and wildfires, studies of climate change impacts on ecological dynamics of forests cited by Gitay et al., (2001) include those concerning, seasonality, timing of freeze-thaw patterns, length of growing season, nutrient feedbacks, disturbance, diurnal temperature patterns, local climatic extremes, late and early frost, changes in precipitation, and extreme weather events. Climate change will further affect forestry to the extent that these dynamics contribute to forest ecology and will be impacted by climate change.

ENERGY SUPPLY. Tol (2009) argues that energy costs may decrease due to climate change relative to a future world without climate change. This is due to decreased costs of supplying renewable energy from wind and wave sources, and the increased availability of oil due to higher temperatures in the Arctic. However, warmer water temperatures will increase the cooling costs of thermal power plants (conventional and nuclear), and decreased water availability in some regions may increase the cost of hydro-electric energy (IPCC, 2007b Chapter 1 and Chapter 7). The increased frequency and intensity of extreme weather events (heat waves, droughts, and storms) have the potential to further disrupt energy supplies, particularly coastal energy and energy transmission infrastructures, while the melting of permafrost is also threatening energy infrastructure in Arctic regions (IPCC, 2007 Chapter 7). It is difficult to determine whether the net effects of climate change on the cost of supply energy will be positive or negative.

TRANSPORTATION. Transportation is critical for the movement of populations and goods, including energy resources. However, the effects of climate change on the transportation sector in terms of lost infrastructure, costs, delays, and safety (including fatalities) are rarely emphasized according to Koetse and Rietveld (2009). This may partially be due to the sparse literature in this area and the general ambiguous effects of climate change on transportation due to countervailing effects (Koetse and Rietveld, 2009).

On the one hand, higher temperatures imply fewer transportation delays from snow and ice (Tol 2009, IPCC 2007). While traffic congestion and accidents result from adverse weather conditions (including rain, snow, and poor visibility), less snow overall will result in less traffic congestion and fewer accidents. Furthermore, many areas will experience decreased costs of dealing with these cold weather events, including less salting of roads and plowing equipment. While higher temperatures will also come with some costs, including buckled rails and roads, these costs can likely be overcome gradually with updating of the road and railway systems during their regular maintenance schedule. Higher temperatures also decrease ice cover in rivers, lakes, and oceans, which decreases shipping costs during the winter. In particular, higher Arctic temperatures may make shipping through the Northwest Passage possible at some times during the year; this has the potential to lower overall shipping costs (Koetse and Rietveld, 2009; IPCC, 2007).[49]

The BLM and the U.S. Forest Service work together to manage wildfires. Photo: Bureau of Land Management

On the other hand, greater weather variability and a higher frequency of extreme weather events (droughts, heavy precipitation events, floods, high winds, and storms) will potentially hurt traffic and disrupt transportation. While higher temperatures and less snow decrease some effects of climate change on traffic congestion, delays, and accidents, the overall effects are unclear because increased precipitation variability due to climate change will likely have a countervailing effect, as precipitation following a dry spell significantly increases the number of accidents (Koetse and Rietveld, 2009). Similarly, while decreased ice cover due to higher temperatures reduces shipping costs, extreme weather events significantly disrupt transportation and destroy transportation infrastructure. Flooding is particularly problematic for the transportation systems of coastal communities (and potentially the most costly of the transportation effects), while droughts will be more of a concern for inland waterway transportation.[50] In addition to the inconvenience to travelers, these events could disrupt trade due to the temporarily shutting down of trade routes, road and port closings, and train and airport delays and cancellations. While ports are more affected (in terms of area and numbers effected) by flooding and storm surges than roads, railways, and airports, even small effects to these latter three infrastructures may have significant costs due to network effects.[51] Due to the increase in exposure to extreme weather events, particularly along the coasts, without adaption, the costs from transportation delays and infrastructure losses will undoubtedly be substantial. Furthermore, changing weather patterns may change trade patterns, which may require infrastructure investment, and require that Arctic regions update their transportation infrastructure in response to melting permafrost (Koetse and Rietveld, 2009; IPCC, 2007).

Traffic safety in terms of the frequency of accidents and changes in mortality and injury rates due to accidents is also another important component of transportation costs. While adverse weather increases the likelihood of aircraft accidents, the bulk of deaths related to travel are road traffic related. However, calculating the change in related deaths due to climate change turns out to be complicated because of the complex number of effects: (1) higher temperatures increase the number of accidents due to heat-stress, (2) increased precipitation increases the frequency of accidents, (3) adverse weather decreases the severity of damages due to reduced traffic speed, (4) snowfall causes more accidents than rainfall, and (5) precipitation after a dry spell has a greater effect on accidents and fatal accidents than precipitation alone. Therefore, the effects of climate change on traffic mortalities and injuries are ambiguous, as is the case for traffic safety in general, congestion, and shipping costs. Effects will likely vary regionally (Koetse and Rietveld, 2009).

Adaptation is also likely to reduce some of the costs associated with extreme weather events. In particular, damages due to sea level rise and floods may be preventable through adaptation, including the building of sea walls. As a consequence, many of the current cost estimates available in the literature, which mainly focus on the eastern United States, may be upper bounds.

Current IAMs do not explicitly model climate damages to the transportation sector. DICE-1999 explicitly assumes transportation is negligibly effected by climate change (with the exception of water transportation), though it is possible in early versions of DICE that transportation costs may be captured indirectly through damages to human settlements and sea level rise. Similar to DICE, FUND does not explicitly address transportation costs, though climate damages due to storms and sea level rise may already include some of these costs. Because the market and sea level rise damages in PAGE09 are greatly informed by DICE and FUND, it is unclear the extent to which PAGE09 includes transportation costs. Similar issues arise for DICE-2013.

COMMUNICATION. Communication infrastructure will experience similar disruptions as the energy and transportation infrastructures due to extreme weather. While a possible adaptation is to bury these infrastructures underground, this strategy is costly (IPCC, 2007). Like energy and transportation, these costs are excluded from IAMs. However, Nordhaus and Boyer (2000) categorize damages to the communication sector as insignificant.

RECREATION. The recreation sector will also be affected by climate change, and is omitted from IAMs according to Tol (2009). While there are clearly redistribution effects across regions, its ultimate effect is uncertain according to Tol (2009). Similarly, Bigano et al (2007) find that climate change has unclear, but generally negligible, effects on global tourist expenditures.[52] Alternatively, using a general equilibrium model, Berrittella et al., (2006) find that "climate change will ultimately lead to a non-negligible global loss" in 2050. This estimate includes only the direct impacts of climate change on recreation, and it omits the indirect impacts such as the loss of some beaches and islands due to sea level rise and the loss of particular ecosystems (such as coral reefs) and species (such as polar bears). The inclusion of these indirect impacts will likely further increase the recreational cost of climate change.

CHANGES IN OUTPUT GROWTH. There is evidence that higher temperatures effect labor productivity (Kjellstrom et al., 2009), the growth rate of economic output (Dell, Jones, and Olken, 2009; Dell, Jones, and Olken, 2012; Hsiang, 2010), and the growth rate of exports (Jones and Olken, 2010), and some of these negative effects on growth continue into the medium-run and long-run (Dell, Jones, and Olken, 2009; Dell, Jones, and Olken, 2012). However, as discussed earlier, the popular IAMs are built on enumerative studies that estimate climate damages to a particular economic (or non-economic) sector of a geographical region in a specific time period. These studies, for the most part, omit dynamic considerations with respect to damages. As a consequence, the current IAMs based upon these estimates fail to model the potential effects of climate change on economic growth—a dynamic phenomenon—and instead focus on the effect of climate change on the level of output (Fankhauser and Tol, 2005, Tol, 2009; Moyer et al., 2013).[53]

In their default versions, the popular IAMs (DICE, FUND, and PAGE) all assume the relentless march of output growth. In FUND and PAGE, regional GDP per capita growth rates (and total factor productivity growth) are exogenous inputs into the models that are determined by the economic and population scenarios chosen by the modeler. As a consequence, climate change affects consumption only. In DICE, economic growth (increased GDP due to all factors including changes in inputs—labor and capital—and technological progress) is endogenous and total factor productivity growth (increased GDP due solely to technological progress) is exogenous. As a consequence, climate change potentially affects the growth path by decreasing the marginal production of capital (and as a consequence the optimal savings rate) and decreasing output (and as a consequence decreasing the total amount of investment and capital accumulation) for a given savings rate (Fankhauser and Tol, 2005).[54] However, in DICE, climate change still only has an indirect effect on growth because there are no direct effects of climate change on the inputs of production or total factor productivity. Just as climate change cannot significantly affect the economic trajectory of the global economy in DICE as currently specified, Moyer et al., (2013) shows that climate damage eight to 17-fold higher does not contract economic output by 2300 in DICE. Furthermore, in the U.S. government analysis, the IWG modify DICE to have an exogenous savings rate, such that, like FUND and PAGE, climate change affects only consumption.[55]

The consequence of this unthreatened growth path is that it is not optimal to divert resources for mitigation purposes in the short-run, but rather to continue higher levels of current consumption (and, according to DICE, current investments in capital) (Moyer et al., 2013). In this scenario, the future is always richer than the present due to a growth path of per capita consumption that is rarely overwhelmed by climate change. As a consequence, the discount rate (through the Ramsey equation) almost never declines rapidly, though this prospect is unlikely according to Fankhauser and Tol (2005).[57,58]

While most IAMs provide estimates of declines in output in the present period and do not analyze the implications of climate change for stable, long-term economic growth, climate change may also affect economic growth of economies (Tol, 2009). In general, the risk of climate change creating long-term implications for economic growth are particularly relevant for less developed countries characterized by low reserves of financial capital (Dell, Jones and Olken, 2008; Aziadaris and Stachurski, 2005). In other words, recent research asks whether the exogenous growth assumption is valid, particularly for developing nations. Dell, Jones, and Olken (2012) find a 1.3 percent decline in the economic growth rate of poor countries for a 1 degree Celsius increase in annual average temperature.[59] Hsiang (2010) finds an overall decline of 2.4 percent for a 1 degree Celsius increase in Caribbean and Central American countries resulting from declines in the agricultural and non-agricultural sectors. Even small changes in the growth rate, such as 0.6 percent to 2.9 percent declines in the annual growth rate in poor countries would dominate all other economic damage estimates over the three-century timeline of IAMs (as specified in the IWG analysis). In further support of these findings, Jones and Olken (2009) find that a 1 degree Celsius increase in the temperature of a developing nation reduces exports by 2 percent to 5.7 percent.

There are several mechanisms through which climate change can directly affect economic growth. First, poor regions may suffer from further depleted funds due to climate change and be unable to adapt to rising temperatures and other climatic changes. This could result in a poverty trap (Tol 2009). Second, climate change could affect growth rates via a rise in social conflict (Tol 2009). While social conflict may affect economic growth, particularly political violence (Butkiewicz and Yanikkaya 2005), it is unclear by which mechanism this effect may occur.[60]

Third, there is evidence that climate change will directly affect labor productivity through work capacity limits (that is, a physical and/or mental limit on the amount of time or effort that individual can expend in a given day),[61] irritation, and disease (Lecocq and Shalizi, 2007; Tol, 2009).[62] Dell, Jones, and Olken (2012) summarize much of this literature, including lab experiments and natural experiments, to find that "labor productivity losses ... center around 2 percent per additional 1 degree when baseline temperatures exceed 25 degrees." These studies generally focus on indoor employment where adaptation is possible, but productivity losses are more substantial for outdoor labor, such as agriculture, and labor intensive industries in non-climate-controlled environments where adaptation to higher temperature and/or avoidance of rain is difficult (Hsiang 2010; Dell, Jones, and Olken 2012). Furthermore, decreased output from climate change could also decrease labor productivity via investments in labor productivity and/or human capital (Fankhauser and Tol, 2005).

In recent work that assumes no adaptation (including increased use of air conditioning), Kjellstrom et al., (2009) estimates labor productivity losses from climate change (resulting from work capacity limits and not an increase in the number of sick days) of up to 11.4 percent to 26.9 percent in some developing regions of the world by 2080. These losses are somewhat reduced when accounting for shifts in regional labor forces between the agriculture sector to industry and service sectors. Using regionalized estimates from Kjellstrom et al., (2009), the authors of ENVISAGE, an alternative IAM, find that declines in labor productivity are of paramount importance in terms of economic damages (accounting for at least three-quarters of all damages). Labor productivity accounts for about 84 percent of total global damage in 2050 and 76 percent in 2100, which is equivalent to a 1.5 percent decline in GDP in 2050 and a 3.5 percent decline in GDP in the year 2100 (Roson and van der Mensbrugghe, 2010).

Fourth, labor supply may potentially fall as labor productivity declines. Most IAMS assume an exogenous labor supply equal to population, such that the labor supply grows according to an exogenous path. However, in labor intensive industries, Zivin and Neidell (2010) find a decrease in the labor supply by as much as one hour at temperatures above 85 degrees Fahrenheit.[63] While there is evidence of partial acclimation and the strong potential for adaptation, accounting for adaptation fully may be difficult because it includes: temporal choices (shifting activities to different times of the day and/or different days of the week), activity choice (for example, shifting activities indoors), location choice (for example, moving), and climate neutralizing technologies (for example, using an air conditioner). Furthermore, the labor supply may further decline if a rise in morbidity from climate change forces individuals out of the labor force, or a rise in mortality from climate change decreases the potential labor force (Fankhauser and Tol, 2005).

Fifth, higher temperatures, increased intensity of storms, rising sea-levels, and tipping point events will increase the capital depreciation rate through losses of the capital stock and decreases in the longevity of capital (Hall and Behl, 2006; Fankhauser and Tol, 2005). Losses in capital stock are likely to result from sudden changes, such as from storms and tipping points, rather than slow changes that would allow for adaptation via the movement of capital (Hall and Behl, 2006). For example, Freeman (2000) cites potential capital stock losses of 1 percent, 5 percent, 12 percent, and 31 percent for a one in 10-, 50-, 100-, and 500-year storm, respectively, for Honduras. Another example is Hurricane Andrew and Hurricane Iniki in 1992, which combined to reduce the U.S. capital stock by $55 billion (Cashell and Labonte, 2005). While the overall economic effect of natural disasters is debated (due to positive effects of reconstruction and remittances), it is clear that storms negatively affect growth through declines in the capital stock and that larger storms (which are more common under climate change) have overall negative effects (Fomby, Ikeda, and Loayza, 2011; Hochrainer, 2009).[64]

Sixth, climate change could also affect economic growth via the capital stock through investment decisions. On the one hand, climate change could influence the relative prices of investment and consumer goods. Climate change is expected to affect a variety of market sectors that produce consumer goods and is generally expected to raise prices and decrease output in these sectors. Higher prices for consumer goods and lower levels of per capita output would lead to lower levels of consumption, while increased future prices could influence investment levels upward (Jorgenson et al., 2004). On the other hand, climate change could lower the amount of output available for investment, which would decrease the amount of capital via capital accumulation. Furthermore, decreases in the labor force and population from climate could decrease the amount of savings available for investment (Fankhauser and Tol, 2005).

Seventh, forward-thinking agents may also change their investment decisions due to the expected effects of climate change. However, it is unclear in which direction. On the one hand, forward-thinking agents may invest more now due to expected declines in future incomes. On the other hand, they may invest less due to lower expected returns on investments (Fankhauser and Tol, 2005; Moyer et al., 2013).

Eighth, increases in temperature may decrease capital productivity if we believe that the electricity grid becomes more unreliable with climate change. Ninth, according to Fankhauser and Tol (2005), Scheraga et al., (1993) argue that climate change could have structural effects on the economy by changing the relative size of sectors. This could have an effect on the composition of GDP. Tenth, the combination of declining tax revenue, due to declines in output, and increased investment in adaptation could decrease non-adaptation investments that grow the economy. In other words, climate change adaptation, particularly in terms of restoring or producing lost ecosystem services, drains capital and labor from research and development (Fankhauser and Tol, 2005; Moyer et al., 2013).

Last, an argument can be made for adding land to the production function. While this is not an input into production in the neoclassical growth model, it is one of the three factors of production in most political-economic work that predates the marginal analysis revolution. This would add additional channels through which climate change could affect economic growth: declining land due to sea level rise and the loss of ecosystem services. This would allow for the loss of ecosystems to have more than a temporary effect on the economy.

Only DICE can be easily modified to capture these changes in growth. In FUND and PAGE (and DICE in the IWG analysis), it is difficult to model changes in the GDP growth rates due to climate change because economic growth rates are determined by an exogenous socio-economic scenario, as discussed above. In these models, the inclusion of the effects of climate change would require a change in the socio-economic scenario; this would make modeling the marginal effects of an additional unit of CO_2 more difficult. However, it is possible.

Modeling the effects of climate change on economic growth in an endogenous growth model, like DICE, is much easier although it requires the specification of a particular mechanism through which climate change may affect growth. As discussed above, DICE, as specified by Nordhaus and not IWG, is the only one of the three IAMs to use an endogenous growth model to estimate climate damages. DICE, as originally intended by Nordhaus, examines climate change using a variation of the Cass-Koopmans model with a single good that can be used for either consumption or saving/investment.[65] However, while DICE does allow for endogenous economic growth, all shocks are to consumption via a general shock to GDP; there are no shocks to labor, capital, or total factor productivity. Thus, modeling the effects of climate change on economic growth via the mechanisms discussed above will require modifications of DICE's structure. As currently specified, the endogenous economic growth structure of the DICE model, which allows for capital investment through an increased savings rate and investment in carbon abatement, allows for some mitigation of climate damages via: (1) increased capital investment that can offset climate damages to output, and (2) substitution of consumption for a reduction in carbon emissions (Nordhaus, 2011; Nordhaus and Sztorc, 2013).[66]

Moyer et al., (2013) modifies DICE-2007 in two different ways to capture the effect of climate change on total factor productivity corresponding to the Cobb-Douglas production function that represents global economic output. First, Moyer et al., (2013) modify DICE such that a portion of climate damages affects the level of total factor productivity. As a consequence, climate damages affect output and economic growth. The authors find that even a small diversion of damages to total factor productivity can produce negative economic growth rates, such that even one-quarter of damages affecting total factor productivity can result a devastatingly high social cost of carbon dioxide of $1,600. Second, they modify DICE such that climate damages reduce the growth rate of total factor productivity. As specified, total factor productivity cannot shrink as to produce economic contractions, and instead is limited to stalling economic growth. While this specification of the damage function does not result in economic collapse from climate change, like the previous specification, it implies an unequivocal increase in the SCC. From these results, Moyer et al., (2013) conclude that modeling the effects of climate change on economic growth can be as important as the discount rate in determining the magnitude of the SCC.

Two alternative IAMs, ENVISAGE and ICES, model the effects of climate change on economic growth (via shocks to labor, capital, and total factor productivity) in a general equilibrium model, GTAP. The authors of ENVISAGE model several damage sectors: agricultural, sea level rise, water, tourism, energy demand, human health and heat-related labor productivity.[67] Unlike DICE, FUND, and PAGE where climate damages affect consumption directly, climate change affects economic output through effects on labor, capital, and land productivity and stock, multi-factor productivity (that is, total factor productivity), and energy and tourist demand (Van der Mensburgghe, 2008). Depending on the damage sector, these shocks to productivity, input availability, and consumer demand can be heterogeneous and homogenous across economic sectors, that is, economic activities (Van der Mensburgghe and Roson, 2010). Using ENVISAGE, Roson and van der Mensbrugghe (2010) estimate damages of 1.8 percent and 4.6 percent of global GDP for increases of 2.3 degrees Celsius and 4.9 degrees Celsius,

Gonaïves, Haiti, after the hurricanes. Photo: Roosewelt Pinheiro/ABr

respectively, above 2000 temperatures; as noted earlier, labor productivity accounts for about 84 percent of total global damage in 2050 and 76 percent in 2100 (Roson and van der Mensbrugghe, 2010). The authors of ICES model several damage sectors: agricultural, sea level rise, forestry, floods, tourism, energy demand, and human health.[68] In ICES, damages affect economic activity through supply side shocks to capital and land stocks and capital, labor, and land productivity (Bosello, Eboli, and Pierfederici, 2012). Like ENVISAGE, the authors of ICES also model demand shocks to tourism and energy demand in addition to supply shocks. Bosello et al., (2012) estimate a 0.5 percent decline on global GDP for a 1.9 degrees Celsius increase in global temperatures relative to pre-industrial temperatures.

Non-market damages

Yohe and Tirpak (2008) and Tol (2009) note that many non-market damages are still missing from current estimates and need further study. Among these are the non-market impacts of ocean acidification (as mentioned earlier), the loss of ecosystem services, the loss of biodiversity, and the omission of some health costs (Tol, 2009). While not an omitted damage per se, the default versions of the IAMs also fail to capture the increase in the value of non-market commodities relative to market goods due to their increase in scarcity. This failure results in a systematic underestimation of non-market damages, particularly biodiversity and ecosystem services, as the value of losses increase.[69]

ECOSYSTEM SERVICES. Natural ecosystems provide a multitude of services that benefit humanity, which are collectively known as ecosystem services. Many of these services are essential for human existence. The United Nations Millennium Ecosystem Assessment groups ecosystem services into four types: (1) provision (food—crops, livestock, fisheries, aquaculture, wild plant and animal products; fiber—timber, cotton, hemp, silk, wood fuel; genetic resources; biochemical, natural medicines, and pharmaceuticals; ornamental resources; fresh water), (2) regulating (air quality regulation; climate regulation—global, regional, and local; water regulation; erosion regulation; water purification and waste treatment; disease regulation; pest regulation; pollination; natural hazard regulation), (3) cultural (cultural diversity; spiritual and religious values; knowledge systems; educational values; inspiration; aesthetic value), and (4) supporting services (soil formation, photosynthesis, primary production, nutrient cycling, and water cycling). The ecosystems that provide these services are known as natural capital; their value equals the present value of all future streams of ecosystem services.

By the end of the century, climate change will be the most important driver of natural capital loss, ecosystem change, and ecosystem service loss. While some regions may experience some initial benefits from climate change in terms of increased ecosystem service provision, overall, the globe will experience negative effects and eventually all regions will experience losses (Millennium Ecosystem Assessment; IPCC, 2007). While not all services are affected by climate change, many of them are. Of these services, only a few are currently included in the IAMs.

Some ecosystem services are already accounted for in the social cost of carbon via other damage sectors. Some of these ecosystem services are explicitly captured by all three IAMs. For example, food and fiber services (particularly crops, livestock, and timber) are explicitly captured via the agricultural, forestry, and "other market" sectors.[70] Some ecosystem services are only captured by some IAMs. For example, only PAGE09 and early versions of DICE explicitly include climate regulation services (particularly globally) in their estimates of the social cost of carbon via their tipping point and catastrophic damage functions, respectively; see the catastrophic damage section below for further discussion.[71] Finally, some ecosystem services are clearly excluded from the default versions of current IAMs, such as pest regulation and pollination as discussed earlier.[72] Some of these omitted services can be thought of as examples of inter-sector services from the non-market sector to the market sector, and will be discussed indirectly in the subsection on the omission of inter-sector damages.

It can be difficult to determine whether ecosystem services are already captured via existing damage functions for two reasons. First, whether an ecosystem service is captured in the damage function(s) is dependent on whether the source of the damage estimate accounted for this service. For example, it could be potentially argued that water purification and water cycling services of ecosystems are already captured in FUND and early versions of DICE (and thus PAGE09, which includes estimates from both other IAMs) via the water sector and the "other market" sectors, respectively. However, this is only true if the water purification and cycling services of ecosystems are directly measured by the underlying studies used to calibrate these models, and this is not the case. In the case of water purification services, forested catchments supply 75 percent of the globes fresh water supplies (Shvidenko et al., 2005; IPCC, 2007 – Chapter 4), and these services could potentially be accounted for in the underlying forestry damages. While the forestry sectors in both models account for the effect of climate change on the value of timber sales, the water sector (within the "other market" sector in DICE-1999) fail to explicitly account for the water purification services of ecosystems. Thus, none of the three IAMs are likely to capture the effect of climate change on the water supply via its effect on forest ecosystems.[73]

Second, some of these omitted services, including water purification and cycling services, may be captured in general attempts by IAMs to capture the value of natural capital. In FUND 3.5 to 3.8, ecosystem damages from climate change are based on a "warm-glow" effect whereby the population's valuations of damages are independent of any real change in ecosystems (Anthoff and Tol, 2012). The warm glow effect is measured by how much people say they are willing to pay for services resulting from habitat preservation services (for example, to preserve wildlife), and Tol (2002) explains that the effect "suggest that people's willingness to pay reflects their desire to contribute to a vaguely described 'good cause,' rather than to a well-defined environmental good or service." However, Anthoff and Tol (2012) calibrate the ecosystem damage function to estimates from Pearce and Moran (1994), who report a mean willingness to pay of $50 per person in OECD nations for habitat. While Pearce and Moran use the $50 value to specifically value loss of habitat services (for example, to preserve species), FUND generalizes this figure to be a warm-glow valuation of people's willingness to contribute to the environment as a societal good. However, this extrapolation is not valid: Tol excludes many of the non-habitat services of ecosystems from FUND because these estimates are based on provision of habitat services by ecosystems and not the other tangible and intangible ecosystem outputs.[74] Therefore, FUND likely omits the value of many ecosystem services.

Alternatively, Nordhaus and Boyer (2000) use their own discretion to determine regional economic damages from climate change to ecosystems in DICE-1999 (also one of the sources used to calibrate the default version ofPAGE09); the authors develop their own rough estimates of the loss of natural capital because of the highly speculative nature of estimates. The authors assume that the capital value of the portion of human settlements and ecosystems sensitive to climate change is between 5 percent and 25 percent of regional GDP depending on their size, mobility, and robustness and sensitivity. It is further assumed that a region's annual willingness to pay to prevent climate damages to human settlements and ecosystems equals 1 percent of their capital value, "which is one-fifth of the annualized value at a discount rate on goods of 5 percent per year (Nordhaus and Boyer 2000)." Therefore, the default version of PAGE09 partially captures some of these "omitted" ecosystem services. However, it is impossible to tell to what extent because (1) the PAGE09 default damage functions are also greatly informed by damage estimated from FUND, in addition to DICE-1999, which potentially only captures the value of habitat services (as discussed in previous paragraph), and (2) it is impossible to tell what damages to ecosystem services are omitted from the DICE-1999 climate damage estimates because of the speculative nature of this valuation.

In DICE-2013, the value of natural capital is likely excluded (or at best partially captured) due to a failure of many of the underlying studies to consider them, particularly the studies that only capture market damages.

BIODIVERSITY. The habitat services of ecosystems may or may not include the value of biodiversity in some IAMs. By the end of the century, climate change will be the single most import driver in biodiversity loss (Millennium Ecosystem Assessment). According to the IPCC (2007), "approximately 20-30% of plant and animal species assessed so far are likely to be at increased risk of extinction if increases in global average temperature exceed 1.5-2.5°C." Given the significant species loss that could occur by the end of the century and the likelihood of continued biodiversity loss with even higher temperatures thereafter, accurate estimates of the value of biodiversity loss are essential.

Tol (2009) considers biodiversity loss to be among the largest of the omitted impacts of climate change. Economists not only struggle to place a value on biodiversity, but they also lack the understanding of how climate change will affect intricate systems and processes like nutrient cycles. Furthermore, rather than occurring more gradually as does sea level rise, biodiversity loss is likely to be characterized by a series of system failures and ecological shocks, making it even more difficult to model (Tol 2009). Thus, current default versions of the IAMs may be omitting the value of biodiversity loss. This statement may seem inconsistent with Tol's FUND model given the inclusion of biodiversity loss in FUND 3.6, as a function of species loss (that is, the value of biodiversity increases with the loss of species) and temperature change. However, Tol (2009) is essentially arguing that future work is necessary to improve the accuracy of the estimate of the value of biodiversity, and he will continue to use the warm glow effect (as discussed in the previous section) in FUND until a better estimate becomes available.[75,76]

Like ecosystem services in general, it is unclear how extensively the default versions of the other two IAMs, DICE-2013 and PAGE09, account for biodiversity. These are for the same reasons as discussed in the previous subsection.

OMITTED HEALTH COSTS. According to Tol (2002a), morbidity and mortality can be directly influenced by climate in six ways: (1) high and low temperature (that is, heat and cold stress), (2) vector-borne infectious disease (3) non-vector-borne infectious disease (including, zoonotic and waterborne diseases (NIH 2010) (4) air quality, (5) floods and storms, and (6) inter-sector effects of agriculture and water quality. A seventh path of influence, which is missed by Tol (2002a), is humanity's socially contingent response to climate change, including forced migration, political and civil unrest, and increased violence.

None of the three IAMs discussed by the IWG includes all categories of damages. DICE-1999, which is utilized as a damage source in the default version of PAGE09, focuses on air pollution and the expansion of the geographical distribution of tropical diseases, including vector-borne diseases (malaria, dengue fever, trypanosomiasis, Chagas disease, schistosomiasis, leishmaniasis, lymphatic filariasis, and onchocerciasis) due to higher temperatures (Nordhaus and Boyer, 2000). Second, FUND 3.6, earlier versions of which were also utilized as a damage source in the default version of PAGE09, captures mortality and morbidity from four sources: diarrhea, vector-borne diseases, cardiovascular and respiratory disorders, and storms (Anthoff and Tol, 2012). Within the causes of health damages considered in FUND, however, modeling assumptions omit relevant damages. For example, heat-related cardiovascular mortality and morbidity is limited to urban areas, but we see no reason to ignore these effects within rural populations (Ackerman, 2010). Additionally, "the total change in mortality is restricted to a maximum of 5% of baseline mortality (per cause)" (Anthoff and Tol, 2012); under high levels of warming (for example, 6 degrees Celsius), this may be an unjustifiable restriction that will bias social cost of carbon estimates downward. Last, it is unclear what health damages are included in DICE-2013 because of its meta-analysis structure, and because several studies utilized in the analysis rely on statistical methods that are less explicit in what types of health costs are captured.

Early versions of DICE, upon which the default version of PAGE09 is partially based, and recent versions of FUND are not consistent in what types of health damages are included. On the one hand, DICE-1999 excludes many negative health effects of climate change captured by FUND: diarrhea (fourth and eleventh leading cause of death worldwide in 1990 and 2020, respectively, according to Murray and Lopez [1997]), cardiovascular disorders, respiratory disorders, tropical storms (hurricanes and typhoons), and extra-tropical storms (cyclones). Additionally, DICE fails to account for the cost of morbidity. On the other hand, FUND fails to account for declining air quality due to pollution that results from climate change, some of which DICE-1999 captures.

There are many health effects that DICE or FUND, and thus likely PAGE, omit. This includes: mortality and morbidity from the combined effects of storms and rising sea levels (that is, coastal flooding), flooding more generally (inland flooding from flash floods and the overflow of rivers), mortality, morbidity and air pollution effects from forest fires, non-vector-borne infectious diseases, some vector borne infectious diseases (like Lyme disease), and decreased air quality due to pollination; decreased labor productivity due disease and increased heat (see the subsection above of the effects of climate change on the economic growth rate for further discussion); and indirect health damages from climate change via agriculture and water resources (Ackerman and Munitz, 2012; Hanemann, 2008; IPCC, 2007; Tol, 2002; WMO, 2006). Finally, violence (the 16th and 14th leading cause of death worldwide in 1990 and 2020, respectively, according to Murray and Lopez, 1997) and war injuries (the 20th and 15th leading cause of death worldwide in 1990 and 2020, respectively, according to Murray and Lopez, 1997) may increase if social conflicts arise due to climate change.

There are also general equilibrium effects of health damages that are omitted by the IAMs. Tol (2009) referring to the results of his own paper, Bosello, Rosen, and Tol (2006), states that "the direct costs are biased towards zero for health, that is, direct benefits and costs are smaller in absolute value than benefits and costs estimated by a general equilibrium model. This is because countries that would see their labor productivity fall (rise) because of climate change would also lose (gain) competitiveness, so that trade effects amplify the initial impact." Therefore, the exclusion of these general equilibrium impacts may further bias the health damages included in IAMs further downwards.

RELATIVE PRICES. Climate change is predicted to affect market and non-market goods produced outdoors (such as agricultural, fisheries, forestry, and environmental goods and services) more than market goods produced indoors; market goods insensitive to climate change account for the majority of GDP (Nordhaus and Boyer, 2000). As a consequence, outdoor produced goods will become relatively scarcer than indoor produced goods over time. Based on the law of scarcity, the value of outdoor produced goods and services will increase relative to indoor produced market goods. However, current damage estimates to climate sensitive goods and services reflect the current ratio of their economic value to climate insensitive goods, which is based on the current ratio of their quantities. By extrapolating these estimates to future time periods without making any explicit adjustment for relative prices, that is, without accounting for relative change in value of outdoor produced goods and services to indoor produced goods over time, the developers of IAMs implicitly assume constant relative prices, and bias the SCC downward.

A methodically sounds way to address this issue is to explicitly model relative prices. However, most IAMs (including DICE, FUND, and PAGE) include only an aggregate consumption good, as measured by per capita consumption, in the social welfare function.[77] On the consumer side of the economy, this assumption implies all goods and services, including market goods and non-market goods, are perfectly substitutable (even in the long-run), and that they have constant relative prices (Gerlagh and van der Zwaan, 2002; Sterner and Persson, 2008). Constant relative prices imply the ratio of the prices of any two goods must remain constant, regardless of the amounts available of either good.[78] As a consequence, the current IAMs fail to capture the increase in value of outdoor produced goods and services relative to other traditional consumption goods produced indoor (Gerlagh and van der Zwaan, 2002; Sterner and Persson, 2008).[79] Therefore, the simplifying assumption of modeling only one generalized consumption good biases the social cost of carbon estimates downward because future damage estimates to climate sensitive goods and services fail to account for the increase in relative value of these goods and services, as discussed in the previous paragraph.

Recent work has looked at the effect of disaggregating per capita consumption into market goods and non-market goods. Developing a simple social welfare function with two sectors (market and non-market) that grow at different rates, Hoel and Sterner (2007) find that increasing consumption of market goods and constant or decreasing consumption of environmental services will increase the relative value of environmental services due to their increasing relative price when the elasticity of substitution is less than one, that is, it is difficult to substitute market goods for non-market goods.[80,81] Hoel and Sterner (2007) demonstrate, as Gerlagh and van der Zwaan (2002) did before them, that the value of market goods will collapse to zero in the long run if these paths continue. After deriving an updated equation for the discount rate (similar to the Ramsey equation) resulting from the new specification, Hoel and Sterner (2007) also find that the combined effect of a newly derived discount rate and the change in relative prices can result in damage estimates that exceed those calculated under traditional discounting.[82] The work in Hoel and Sterner (2007) applies to any two sectors of the economy, not just market and non-market goods.[83]

To capture these effects on the optimal emissions path, Sterner and Persson (2008) modify DICE to restrict substitutability between non-market and market goods. Like Hoel and Sterner (2007) and Neumayer (1999) before them, Sterner and Persson (2008) find that allowing a change in relative prices can increase the costs of climate change relative to a model assuming constant relative prices. More specifically, the authors find that damages double from 1.05 percent of GDP for a 2.5 degree Celsius increase to 2.1 percent of GDP; this implies that the SCC would also increase with a switch away from constant to relative prices. Using their base parameters, Sterner and Persson (2008) also find that allowing for a change in relative prices achieves a lower optimal emissions path than the Stern Review (Sterner and Persson, 2008; Heal, 2009).[84] In this sense, relative prices can be as important as the discount rate in determining the optimal climate change prevention policy. However, their results are highly dependent on the assumed elasticity of substitution. The lower the actual elasticity of substitution is, that is, the more difficult it is to substitute market goods for lost non-market goods to make society as equally well off under climate change, the more likely the current integrated assessment models are to underestimate the environmental cost of climate change by assuming perfect substitutability.

As is common in these models, we are left with uncertain parameters determining the optimal level of conservation. In this particular case, this is the elasticity of substitution. This recasts the argument about whether or not to act now from a disagreement about the discount rate into a debate of whether poor (strong) sustainability or perfect (weak) sustainability, that is, an elasticity of substitution less than or greater than 1 in the context of the CES utility function, holds in the long run (Gerlagh and van der Zwaan, 2001). Unlike the pure rate of time preference and the elasticity of the marginal utility of consumption, the elasticity of substitution is not an ethical parameter. However, there is still considerable uncertainty about this parameter due to a lack of empirical data (Neumayer, 1999). Sterner and Persson (2008) argue that a lower elasticity of substitution is more likely because some environmental goods are unique and irreplaceable (for example, drinking water), and these goods are likely to dominate the calculation of the elasticity of substitution as environmental goods become more scarce. In a similar argument, Heal (2009) states that market goods and environmental services are complements because some of the services in the former group are irreplaceable and essential to life (Heal, 2009; Dasgupta and Heal, 1979). Heal (2009) points out that this has two implications: some level of environmental services is essential and that the elasticity of substitution is not a constant.[85] Gerlagh and van der Zwaan (2002) demonstrate that even if the substitutability varies with the amount of environmental services, there often exists a level of environmental services below which poor substitutability occurs in the long run. While these arguments support an elasticity of substitution below which it is difficult to substitute consumption goods for environmental goods (elasticity of substitution of less than one), future debate is likely to ensue as current statements are more a matter of belief due to a lack of empirical evidence (Neumayer, 1999).

Greenland ice loss exceeds that of Ice gain. Photo:Christine Zenino, Chicago, US

All three IAMs include only an aggregate consumption good in the social welfare function, and so assume constant relative prices and perfect substitutability. While FUND 3.6 does account for the increase in the relative value of habitat services due to the loss of species, this is done in a limited way. Therefore, all three IAMs systematically underestimate climate damages to non-market commodities, possibly by a large margin.

Socially contingent damages

Many social scientists and economists have argued that the ill-effects of damages to commoditized goods from climate change will extend beyond the calculated loss of value to affect societal dynamics (U.S. Climate Change Science Program, 2008). For example, agricultural damages account for the value of diminished productivity and lost crops, but not for the social repercussions of food insecurity and famine. In many regions, shifting weather patterns, rising sea levels, and increased natural disasters will threaten infrastructure, habitable lands, crop yields, and water resources. Under the resulting intensified resource competition, individuals will have to choose among adapting to resource scarcity, relocating to a region with more abundant resources, or using force to secure a share of the available resources. Each coping pathway has implications for political and social stability (Buhaug, Gleditsch & Theisen, 2009).

The IPCC, which once included social consequences (such as migration) as direct consequences of climate change, has since revised its stance, focusing instead on "human vulnerability," a measure expressing the relative risk of welfare impacts of climate change for individuals and communities (Raleigh & Jordan, 2010; IPCC, 2001). Vulnerability is determined both by physical factors (for example, drought likelihood) and social factors (for example, social status). Highly vulnerable societies are less likely to succeed in their adaptation efforts, and consequently, more likely to resort to conflict and migration. Adaptation strategies used in poorer regions such as removing children from school to provide additional income or subsisting on fewer resources, diminish the welfare of those employing them, and thereby increase the incentives for migration or armed conflict over time. Homer-Dixon (1999) argues that the developing world is more vulnerable to resource scarcity because the "innovation gap"—the difference in capacity between those who are able to innovate solutions to resource scarcity and those who are not—is largely dictated by the financial, physical, and human capital stores and the capacity to mobilize them. As a consequence, developing countries are much more likely to be susceptible to social and political instability from climate change (Homer-Dixon, 1999).

The study of climate change's social impacts is still emerging despite a lack of ability to predict their severity or likelihood. The risks of these broader, complex social responses to climate change are poorly understood and difficult to anticipate, and historical studies are of little use given the unprecedented nature of climate change. In particular, because climate change is a contributing factor and not the direct cause of migration and conflict, isolating the role and corresponding social damages of climate change is especially difficult (Homer-Dixon, 1999; Buhaug, Gleditsch & Theisen, 2008). In addition, the identification strategies of many papers are confounded by various statistical difficulties (Dell, Jones, and Olken, 2013).

Partially as a result of this difficult identification problem, the most recent versions of the three IAMs used by IWG do not address socially contingent damages, such as migration, social and political conflict, and violence. The one exception is FUND, which partially accounts for this social cost indirectly by modeling migration from permanent flooding. However, as discussed under inter-regional damages, FUND ignores most of the costs of migration, including the social conflict caused by an influx of migrants.

MIGRATION. Increases in labor migration and distress migration are likely results of increasing temperatures, reduced rainfall, shorter growing seasons, and sea level rise. Labor migration, generally driven by the "pull" force of economic opportunity, is common in many societies and can play an important role in the adaptation of communities by diversifying income sources and providing supplemental income through remittances. Distress migration, driven by the "push" force of local calamity, tends to be a coping mechanism of last resort. Labor migration is particularly sensitive to climate change-related factors, especially those that are gradual or chronic, which increase the need for income diversification and the allure of economic opportunities elsewhere. Distress migration only increases under sudden shifts, such as natural disasters (for example, severe storms) or irreversible changes (for example, permanent flooding from sea level rise). Distress migration is also more sensitive to social factors than labor migration. The ease of evacuation and availability of relief affect the rates of distress migrations, while community support, economic opportunities, and governmental policies influence resettlement rates. The severity and permanence of damage also play important roles in determining rates of migration and relocation (Raleigh & Jordan, 2010).[86]

It should be noted that mass migration, as predicted by many analysts, may also have significant effects on non-market goods and services. Specifically, mass migration into lesser affected areas may result in damages to environmental goods and services to the incoming nations (Oppenheimer, 2013). This type of damage would qualify as an inter-sector effect, which is discussed in a following section.

CONFLICT. In large scale crises, such as climate change, conflict tends only to occur in societies with histories of armed violence and deep political and social fragmentation. The developing world, which is slated to bear the brunt of climate change due to a lack of adaptive capacity, is considered especially vulnerable to climate-change-related social crises because their economic and political institutions tend to be less stable than those of the developed world (Millner & Dietz, 2011; Buhaug, Gleditsch & Theisen, 2008). Lower availability of financial resources and insurance also tend to increase the rate and permanence of climate change damages in developing countries, making conflict more likely, and intensifying existing conflicts (Millner & Dietz, 2011).

Buhaug, Gleditsch and Theisen (2008) advance four narratives on how climate change can drive conflict by contributing to political instability, economic instability, migration, or inappropriate governmental response. Climate change can exacerbate political instability when weak political institutions fail either to adequately address climate-related catastrophes (droughts, famines, and so on) or to deliver other public goods (such as healthcare, education, and infrastructure) because remediating such catastrophes diverts significant resources. Climate change can contribute to economic instability when decreased availability of a renewable resource drives down household incomes, which can compound existing intergroup inequalities and reduce the governmental funds available to adapt to climate change. [87] Migration driven by natural disasters or sea level rise could cause influxes of climate refugees, increasing environmental, economic, social and political stresses in receiving areas, particularly when the incoming refugees are of a different nationality or ethnic group. Finally, unpopular responses to climate change, such as draconian emission reduction mandates, could result in social uprisings in response. Dell, Jones, and Olken, (2013) also highlights the possibility that weather can directly lead to conflict through "changing the environment" or increasing human aggression.

There is literature studying the effect of weather and social and political conflict that is summarized quite thoroughly in Dell, Jones, and Olken (2013). In particular, there are a variety of cross-country and subnational studies which indicated that higher temperatures and lower-than-average precipitation (including droughts) cause civil conflicts and political instability (for example, coups), particularly via the lower household income mechanism. While there are various studies showing the effect of weather on social and political conflict, there is some ambiguity in the effect because of (1) the low explanatory power of weather of conflict (that is, the noise), (2) a variety of statistical problems, including endogenous controls and spatial correlation, (3) the difficulty of measuring weather, particularly precipitation due to the negative effect of too much (for example, floods) and too little (for example, droughts), and (4) the difficulty of determining if weather changes the timing of conflict or actually causes conflict.

Two important recent papers identifying the connection between climate change and social and political conflict are: Hsiang, Meng, and Crane (2011) and Hsiang, Burke, and Miguel (2013). Hsiang, Meng, and Crane (2011) use more than 50 years of data to show that the probability of conflict doubled in the tropics during El Niño years as compared with La Niña years. Based on their analysis, El Niño contributed to 21 percent of the civil conflicts in the tropics taking place between 1950 and 2004, providing some evidence that warmer temperatures do result in more social conflict. This paper is important in that it provides evidence that weather caused more conflict, and displaced only a portion of conflicts over time.[88]

In another study, Hsiang, Burke, and Miguel (2013) conduct a meta-analysis across 60 multi-disciplinary papers.[89] The authors find that the median effect of a 1-standard-deviation change in climate variables over time causes a 13.6 percent change in the risk of intergroup conflict and a 3.9 percent change in interpersonal violence.[90,91] Similarly, precision-weighted average effects, in which studies were down-weighted based on their precision, are 11.1 percent and 2.3 percent, respectively. Even though the magnitude of this effect is heterogeneous (that is, varies over time and space), given that scientists predict a 2- to 4-standard-deviation change in temperature by 2050, possible increases in conflict as the result of climate change are likely to be significant this century in many areas across the globe. In general, the authors find that all types of conflict increase with temperature and precipitation, regardless of the temporal scale, but intergroup violence is less common in rich countries than poor countries.[92] Furthermore, the evidence indicates that adaptation possibilities are limited in that slow-moving climate change still adversely affects conflict, and these effects will continue into the next century. While the authors note that several avenues are possible to connect climate change to social conflict, more research is necessary to select between competing theories on these linkages.[93] Additionally, it is still unclear whether these mechanisms increase the probability of a conflict occurring or the probability of an existing conflict becoming violent.

VIOLENCE AND CRIME. Dell, Jones, and Olken (2013) review the literature studying the effect of weather on violence. In the criminology literature, there is a well-known relationship between higher temperatures and crime, particularly as it relates to aggression. Specifically, many authors find that higher temperatures increase criminal activity, especially as it relates to violent crime. There is an ongoing debate within the literature on whether the cause is neurologically based or a socially contingent response. With respect to precipitation, there is more of a mixed result with some evidence that a lack of precipitation may increase crime and violence through a channel of lower income.

Catastrophic climate change

There is agreement within the literature on the importance of catastrophic damages. However, there is significant debate within the literature about the extent of their importance; see earlier discussion. Regardless of the side one takes, it is clear that these catastrophic damages should be included in IAMs, and the current failure to do so in some IAMs biases their SCC estimates downward. Given Hope's (2013) finding that tipping-point damages can be as important as the sum of economic damages included in IAMs in determining the social cost of carbon, these biases may be significant.

TIPPING POINTS. The IAMs differ in their treatment of climate tipping points. Earlier versions of DICE, that is, DICE-1999, DICE-2007, and DICE-2010, include certainty equivalent damages of catastrophic events as estimated in a survey of experts in Nordhaus (1994a).[94] For the most recent version of the model, that is, DICE-2013, Nordhaus moved to a meta-analysis based on estimates in Table 1 of Tol (2009). Most of these sources do not include tipping point damages, and it is unclear to the extent that they are included in these newer versions of DICE.[95] While DICE-2013 does include the possibility to explicitly model catastrophic damages, it is excluded from the default version of the model (correspondence with Nordhaus).[96]

PAGE explicitly models tipping points in the default version of his model. From PAGE2002 to PAGE09, Hope moved from modeling discontinuous impacts using certainty equivalence to modeling them as a singular, discrete event that has a probability of occurring in each time period when the realized temperature is above a specified temperature threshold (with a central value of 3 degrees Celsius in the default version of the model), and this probability is increasing in temperature. Of the recent versions of the three models, only PAGE09 fully explicitly models tipping point damages; still a risk premium for aversion to such an event is generally not included in the default versions of IAMs (Kouskey et al., 2011).

While PAGE09 and early versions of DICE explicitly model tipping point damages, an alternative, as represented by Lemoine and Traeger (2011), is to implicitly capture tipping point damages by explicitly modeling tipping points. As stated by the authors, they "directly model the effect of a tipping point on climate dynamics rather than approximating its effects by shifting the damage function." Specifically, Lemoine and Traeger (2011) model two broad types of climate tipping points within DICE: (1) increased climate sensitivity (that is, the increase in global surface temperature from a doubling of the CO_2 concentration in the atmosphere) due to increased strength in climate feedback effects beyond current predications, and (2) increased greenhouse gas atmospheric longevity beyond current climate models.[97] It should be noted that this is distinct from modeling fat tails because these modeling changes do not require the use of fat-tailed distributions.

In a similar way, FUND implicitly models tipping points by explicitly modeling the uncertainty of almost 900 parameters in the FUND model.[98] According to Anthoff and Tol (2013a), this captures catastrophic damages more generally by capturing the possibility of catastrophic outcomes, that is, welfare effects. It is unclear to the extent that this method captures tipping points as evidenced by the decision by Hope to jointly model parameter uncertainty and a catastrophic damage function in PAGE09. In other words, FUND may not sufficiently capture catastrophic damages via climate tipping points by simply modeling the uncertainty underlying all parameters in the model.

FAT TAILS. The popular IAMs differ in their ability to capture the catastrophic damages that result from fat tails. However, for the most part, those IAMs fail to model fat tails as suggested by Weitzman. This is because "numerical model(s) cannot fully incorporate a fat-tailed distribution (Hwang, Reynès, and Tol, (2011)."

On the one hand, both FUND and PAGE explicitly model the uncertainty of model parameters by specifying parameter distributions and run Monte Carlos simulations.[99] However, neither model explicitly chooses fat-tailed distributions in its default version. Hope chooses triangular distributions, which explicitly specify minimum and maximums for the probability distribution function, for many of the uncertain parameters in the default version of PAGE; the exception is the climate sensitivity parameter which follows the IPCC (2007) report. In FUND, Tol tends to choose triangular and gamma distributions; the gamma distribution is thin tailed (Weitzman, 2009).[100] However, while Anthoff and Tol (2013a) do not explicitly utilize fat-tail distributions to represent the probability distributions of their 900 uncertain parameters, the distribution of net present welfare from a Monte Carlos simulation of 10,000 runs of FUND 3.6 is fat tailed.[101] While fat tails arise in the distribution of welfare in the FUND model, explicitly modeling parameter distributions as fat tailed may further increase the SCC.

On the other hand, the default versions of the DICE models fail to model any parameter uncertainty. As a consequence, the default versions of all DICE models fail to capture catastrophic damages via the fat tails of uncertain parameters. This is particularly significant when parameters have a right-skewed distribution, such as the climate sensitivity parameter and the possible discontinuity outcomes. Therefore, DICE-2013 mostly excludes catastrophic damages via tipping points and fat tails when parameter uncertainty is ignored.

There have been several attempts to include fat-tailed distributions in the popular IAMs. First, Hwang, Reynès, and Tol (2011) found an increase in the optimal carbon tax when accounting for fat tails in DICE; the optimal carbon tax increases in the uncertainty of the climate sensitivity parameter. Similarly, Ackerman, Stanton, and Bueno (2010) find that fat tails over the climate sensitivity parameter increases the economic costs of climate change, and hence the SCC, in DICE, but the magnitude of this increase is highly dependent on the exponent of the DICE damage function. Second, Pycroft et al., (2011) replaces above the 50th percentile of the original triangular distributions for the climate sensitivity parameter and the damage function (sea level rise, market, and non-market) exponents in the PAGE09 model with thin-tailed (specifically, the normal distribution), medium-tailed (specifically, the log-normal), and fat-tailed (specifically, the Pareto) distributions;[102] they switch off the catastrophic damage function when they modify the distributions of the damage function exponents, decreasing the PAGE09 SCC estimate from $102 in the default version of PAGE to $76, because tipping points and fat tails are related concepts, as discussed earlier in this paper. The authors find that the PAGE09 SCC estimate without a catastrophic damage function increases by 44 percent to 115 percent when medium and fat tails are integrated into PAGE09; this corresponds to an increase from $76 to $135 (thin), $147 (medium), and $218 (fat).[103] Larger percentage increases are observed for the 95th and 99th percentile SCC estimate. In other words, the use of fat-tailed distributions is possible and will significantly increase the social cost of carbon. At the same time, because its value is not infinite, as it is using Weitzman's Dismal Theory analysis, the SCC is still useful for benefit-cost analysis.

By explicitly modeling the probability distribution function of the climate sensitivity parameter using the Roe-Baker distribution, the 2013 IWG analysis may partially capture the effects of fat-tailed distributions; the Roe-Baker distribution used in this analysis is fat-tailed (Pindyck, 2013).

BLACK SWAN EVENTS. All three IAMs may exclude black swan events. While it is unclear how these events could be integrated into these models, it is clear that their exclusion biases SCC estimates downward because scientists believe that bad surprises are more likely than good surprises when it comes to climate change. As discussed earlier, these events may be captured by integrating fat-tail distributions for uncertain parameters into IAMs, but the "correct" fat-tailed distribution is still unknown.

Inter-sector damages

According to both Kopp and Mignone (2012) and the IWG (2010; 2013) IAMs fail to capture inter-sector damages, that is, damages from the interaction of damage sectors. There are a variety of potential inter-sector effects of climate change, and their omission generally tends toward a downward bias. Inter-sector damages include: agriculture and water quality on human health (Tol, 2009; IPCC, 2007); the effects of water supply and quality on agriculture; the combined effects of increased storm strength and rising sea levels (Yohe and Hope, 2013); the effects of ocean acidification on human settlements; and the effects of ecosystem services on the market sector. As mentioned earlier, many of these inter-sector damages include damages that arise from the interaction of climate change effects between sectors in the market-, non-market-, socially-contingent-, and catastrophic-damage categories.

For the most part, the major integrated assessment models (FUND, PAGE, and DICE) calibrate their damage functions, and as a consequence estimate the social cost of carbon, using sector specific studies, or, at least, rely on studies that utilize sector specific damage estimates, that is, enumerative studies.[104] Implicitly, the authors of the IAMs assume that each sector is an island, independent of all other sectors. Therefore, inter-sector damages are captured by IAMs only if the underlying studies account for these inter-sector damages. For example, agricultural studies that account for the effect of climate change on precipitation and the water supply for irrigation will include the effects of the water supply sector on the agricultural sector. However, most damage studies are incomplete as they omit these inter-sector damages (Yohe and Hope, 2013).[105]

The developers of PAGE and FUND argue that these models capture inter-sector effects. On the one hand, Hope (2006) argues that only inter-sector damages between market and non-market sectors, such as ecosystem services, are excluded. Specifically, he argues that all other inter-sector damages are captured because "PAGE2002 models two damage sectors: economic and non-economic. ... Using highly aggregated damage estimates from the literature allows PAGE2002 to capture interaction effects implicitly." This is something of a tautology – that is, I utilize generalized aggregate damage functions, and because they are general, I capture interactions. As stated above, inter-sector damages can only be captured if the underlying damage estimates account for them, and they do not in the case of the default version of PAGE09. On the other hand, Tol (2009) goes even further by arguing that IAMs, such as FUND, may be double counting inter-sector damages. For example, the effect of water supply on the agricultural sector may be captured by both the water and agricultural sector damages.[106] Again, this can only be the case if the underlying studies explicitly account for these damages, and this is not the case in FUND due to its reliance on enumerative studies that do not account for inter-sector damages.[107]

The latest versions of the three IAMs utilized by IWG omit inter-sector damages. FUND3.6 and DICE-1999 utilize sector-specific damage estimates (from enumerative studies), and by the arguments above omit most, if not all, of the inter-sector damages excluded from the underlying studies. Because PAGE09 is greatly informed by FUND and DICE-1999, it too omits these inter-sector damages even though it relies on aggregate market- and non-market-damage functions. Finally, DICE-2013 also omits most inter-sector damages. Of the 13 studies underlying the DICE-2013 meta-analysis, eight (Nordhaus, 1994a; Fankhauser, 1995; Tol, 1995; Nordhaus and Yang, 1996; Plambeck and Hope, 1996; Nordhaus and Boyer, 2000; Tol, 2002; Hope, 2006) of them rely on sector-specific calibration techniques (that is, rely on enumerative studies), and omit any inter-sector damages excluded from the underlying studies. Four of the remaining five studies (Mendelsohn, Schlesinger, and Williams, 2000; Maddison, 2003; Rehdanz and Maddison, 2005; and Nordhaus, 2006) utilize statistical technique to estimate the damages from climate change. While statistical methods can capture inter-sector effects, all four of these studies omit the damages from the interaction of market and non-market sectors; Maddison (2003) and Rehdanz and Maddison (2005) only include non-market damages, and Mendelsohn, Schlesinger, and Williams (2000) and Nordhaus (2006) include only market damages. Thus, like the other IAMs, DICE-2013 fails to account for many inter-sector damages.

Wind erosion is evident on this rangeland during severe drought in Arriba County, New Mexico.
Photo by Jeff Vanuga, USDA Natural Resources Conservation Service.

Cross-Sector Damages

As discussed earlier, many of the omitted effects of climate change comprise both market- and non-market-damage sectors. This section discusses omitted climate impacts that affect multiple categories of damages (as opposed to inter-sector damages, where multiple impacts interact to contribute to damages in a specific sector): market, non-market, socially contingent, and catastrophic damages. This includes inter-regional damages, destabilizers of existing non-climate stressors, weather variability and climate extremes, and ocean acidification.

INTER-REGIONAL DAMAGES. Inter-regional damages are spillovers from one region to another. For the most part, the major integrated assessment models (FUND, PAGE, and RICE) estimate the social cost of carbon assuming each region of the world is independent of all other regions. There are a variety of potential inter-regional effects of climate change, and their individual omissions may result in an upward or downward bias. While the individual biases are in both directions, Freeman and Guzman (2009) argue that the overall effect very likely leads to an underestimation of the SCC for the United States.

Freeman and Guzman (2009) lay out several international spillover scenarios with respect to the United States. First, there are potential supply shocks to the U.S. economy in terms of decreased availability of imported inputs, intermediary goods, and consumption goods. This includes energy and agricultural goods. Second, there could be demand shocks as affected countries decrease their demand for U.S. imports. Third, there may be financial market effects as international willingness to loan to the United States dries up and the value of U.S. firms decline as foreign markets shrink. Fourth, mass migration from heavily affected areas, such as Latin America, will potentially strain the U.S. economy, and likely lead to increased expenditures on migration prevention. Fifth, increases in infectious diseases are likely due to the combined effects of ecological collapse, the breakdown of public infrastructure in poor nations, and declines in the resources available for prevention; increasing mass migration will intensify the spread of diseases across borders. Last, climate change is likely to exacerbate security threats to the United States, partially through its potential destabilizing effect on politics. As a consequence, climate change is a "threat multiplier" in terms of security. In summary, there are a variety of pathways for the effects of climate change in one region to cause damages in another: trade, capital markets, migration, disease, and social conflict.

There are also several potential positive spillover scenarios currently excluded from the SCC. First, trade has the potential to reduce the SCC by reducing the welfare losses to consumers in particularly hard hit regions (Darwin, 1995).[109] While consumers in exporting nations and producers in importing nations are harmed by trade, this loss is more than offset by gains to consumers in importing nations and producers in exporting nations according to economic theory. For example, low elevation nations will experience a decline in domestic agricultural production, but importing food from higher elevation nations will mitigate some of the consumer welfare loss from domestic production declines (Darwin, 1995). Through this lens, trade can be thought be as a form of human adaptation to climate change whereby humans move tradable market goods between the least- and most-affected regions to satisfy the needs of those with the highest demand.[110] However, trade can also result in general equilibrium costs, which are also currently omitted (Tol, 2009).[111] Second, technology spillovers between nations may reduce the regional costs of mitigation and/or adaptation. Investment by developed nations into mitigation and adaptation technologies may reduce the costs of mitigation and adaptation in developing nations (Löschel, 2002; Buonanno et al., 2003; Rao, 2006).[112]

The inclusion of inter-regional interactions requires integrating the various regional economic models into an international model. This is technically complex and requires many additional assumptions (Freeman and Guzman, 2009). Care must also be taken to avoid double counting of damages. Rather than simply adding inter-regional damages estimates, modelers have to return to the country-specific damage estimates to examine how they were constructed.

In general, all three IAMs exclude inter-regional damages. There are a few exceptions. First, all three IAMs (DICE-2013, FUND 3.6, and PAGE09) capture general equilibrium effects of trade in the agricultural sector. Second, because GDP measurements include net exports, damage estimates at least partially capture trade indirectly through GDP. Last, FUND models migration as it relates to sea level rise.

FUND 3.6 migration cost estimates are relatively ad hoc and omit several types of damages. First, the method of determining the destination of migrants is ad hoc, and this affects the costs of migration because they are dependent on the destination region.[113] Second, the cost of migration to the sending region is three times its regional per capita income per migrant; Tol (2002) describes three as an "arbitrary" parameter. This approach will underestimate costs of migration if per capita income in coastal regions is greater than the regional average, which would be the case if cities with concentrations of economic activity are affected most by sea level rise. Third, in the region that is receiving migrants, costs per migrant equal 40 percent of per capita income of the receiving country (Cline, 1992 from Fankhauser (1995) from Anthoff and Tol, 2012b); Cline (1992; 120) approximates the costs of migration to the United States based on state and local government infrastructure spending (education, roads, police, sanitation) and taxes paid by immigrants. However, this figure from Cline (1992) was simply an illustration of the cost of migration to the United States and was hardly a "guesstimate," as stated by Fankhauser. Furthermore, these migration-cost estimates exclude the costs of social conflict from migration pressures (for example, the effect of Syrian migrants on Bulgaria), the potential stress on the receiving country's social, environmental, and physical infrastructure under cases of mass migration, the psychological cost to migrants of losing their homeland, and the potential physical health costs to refugees (Fankhauser, 1995). Last, FUND sets intra-regional migration costs equal to zero though there is still likely to be stress on the receiving nations (for example, the effect of Syrian migrants on Lebanon and Jordan from the recent Syrian Civil War).[116]

DESTABILIZERS OF EXISTING NON-CLIMATE STRESSORS. Climate change is often referred to as a threat multiplier. For example, Freeman and Guzman (2009) state that "the consistent message of [national security] studies is that climate change is a 'threat multiplier' (Freeman and Guzman, 2009)." While Freeman and Guzman (2009) are mainly referring to national security issues worsening due to climate change further weakening already volatile regions and political unstable nations, their arguments can be generalized to other future challenges that the world faces with or without climate change: social and political instability (Freeman and Guzman, 2009); disease, including the flu (Freeman and Guzman, 2009);[117] ecosystem and biodiversity loss (United Nations' Millennium Ecosystem Assessment);[118] decreased water availability.[119] In other words, just as the multiple effects of climate change will interact within different economic sectors, as discussed in the previous section under inter-sector damages, non-climate related economic, societal, and environmental pressures will result in multiple damages across sectors due to their interaction with the effects of climate change.

Like inter-sector damages, the interaction of non-climatic factors and the effects of climate change must be captured in the underlying studies utilized to calibrate the IAM damage functions. In most cases, the studies underlying the calibration of the IAMs' default damage functions do not account for these interactions. Thus, the default versions of the early versions of DICE, DICE-2013, FUND3.6, and PAGE09 by and large omit these damages.

WEATHER VARIABILITY AND CLIMATE EXTREMES. Climate change does not only affect the long-run averages of temperature, precipitation, and sea-level, but also the variability of weather around these changing means. In other words, many more extreme weather events should be expected, including the likelihood of increased: frequency of heat waves, areas experiencing droughts (and some areas experiencing decreased rainfall during monsoons and others experiencing increased aridity), frequency and areas experiencing heavy precipitation events (for example, floods), intensity of tropical cyclones, and extreme high sea level (IPCC, 2007a); see Table 14.

Current IAMs partially capture some of these extremes: tropical storms (hurricanes and typhoons), extra-tropical storms (cyclones), and heat waves. FUND 3.6 explicitly models the economic destruction in terms of lost property and human life (mortality and morbidity) of the increased strength of tropical storms, and the cost to human health (mortality and morbidity) of heat waves, but only to the extent that damages are limited to heat stress. Early versions of DICE, that is, DICE-1999 and DICE-2007, only make an ad hoc account of the loss property, such as human settlements, due to storms in the coastal sector. While both models account for sea-level rise, they fail to account for the interaction between storms and sea level rise, which results in extreme high sea level rise (Yohe and Hope, 2013). As a consequence, the default version of PAGE09 (the damage function of which is greatly informed by FUND and DICE-1999) partially accounts for the cost of the increased intensity of storms and frequency of heat waves. Because most of the underlying studies in DICE-2013 exclude climate extremes, DICE-2013 appears to exclude the economic costs of weather variability (flooding, droughts, and heat waves).

However, these IAMs may implicitly capture some of these extreme events to the extent that these variables are correlated with temperature. Nordhaus (1994a) argues that "in thinking about the impact of climate change we must recognize that the variable focused on in most analyses—globally averaged surface temperature—has little salience for impacts. Rather, variables that accompany or are the result of temperature change—precipitation, water levels, extremes of droughts or freezes, and thresholds like the freezing point or the level of dikes and levees—will drive the socioeconomic impacts. Mean temperature is chosen because it is a useful index of climate change that is highly correlated with or determines the most important variables." Given that these events are not perfectly correlated with temperature, these events are partially omitted from the analysis. As

Tol (1995) states: "only if the relevant climate parameter relates linearly to the global mean temperature, and the relationship is perfectly known, is the temperature an adequate proxy." Therefore, these events are already included in the IAMs to the extent that global average surface temperature is correlated with these extreme events. To the extent that they are not, they are excluded.

OCEAN ACIDIFICATION. None of the most widely adopted IAMs for estimating the SCC (DICE, FUND, and PAGE) address the multiple damages due to ocean acidification. As defined by Shinryokan (2011): "Ocean acidification refers to a reduction in the pH of the ocean over an extended period, typically decades or longer, which is caused primarily by uptake of carbon dioxide from the atmosphere." In terms of market damages, ocean acidification impacts fisheries via its effects on marine ecosystems and organisms, particularly shellfish and crustaceans. In addition to fisheries, ocean acidification will impact ecosystems, biodiversity, and tourism via its effect on coral and also human settlements. While the economic effects of acidification are likely substantial, few economic values of the damages are available because scientists only recently recognized the threat of ocean acidification to marine life (Guinotte and Fabry, 2009) and fisheries, for the most part, are excluded from IAMs; see previous sub-section.

Though fisheries are expected to suffer significant economic damage as a result of ocean acidification, there are few studies of the economic costs of these impacts. Since 2009, economists have completed several impact studies that attempt to more accurately quantify the economic costs of climate change to fisheries. Two such studies, Cooley and Doney (2009) and Narita et al., (2012), estimate these monetary effects with a focus on mollusk production; recent scientific literature finds that acidified ecosystems significantly reduce mollusk populations. Cooley and Doney (2009) conduct a case study of the effect of ocean acidification on U.S. fisheries revenues, with a focus on mollusks. If there were a reduction of 10 percent to 25 percent in the U.S. mollusk harvest from the 2007 level, $75 million to $187 million of direct revenue would be lost each subsequent year;[120] these values correspond to a net present value loss (that is, the sum of annual losses over all futures years in terms of its current dollar value) of $1.7 billion to $10 billion through 2060. Similarly, using a partial-equilibrium model to assess the welfare loss to society from a decline in shellfish supply, Narita et al., (2012) find that the costs of ocean acidification could exceed $100 billion. Because mollusks represent a small fraction of total fisheries, the cumulative economic impact of ocean acidification on fisheries will likely be significantly larger.

In addition to fisheries, ocean acidification will impact tourism associated with the ocean, particularly coral reefs. Coral reefs are expected to be among the worst-affected ecosystems. A study by Brander et al., (2009) considers the economic damages associated with coral reefs and estimates valuation per area. They expect losses in this sector to be at least $50 billion annually by 2050. It should be noted that the overall effects of climate change on tourism are also excluded, but the magnitude and direction of these effects is uncertain (Tol, 2009; Bigano et al., 2007) and potentially negative (Berrittella et al., 2006).

Adaptation

Some policymakers and analysts may argue that the IAMs need not worry about these omitted damages due to society's ability to adapt. In other words, adaptation implies that these costs will not be incurred. While adaptation must be accounted for when including the above damage estimates, an altogether elimination of these omitted damages (that is, such that they can be ignored) is unlikely. This is particularly the case for non-market, socially contingent, and catastrophic damages, in general, where adaptation is likely be less effective. This is also increasingly the case for market damages as temperatures increase (Hope, 2011). Furthermore, adaptation will be particularly difficult for faster-than-expected temperature increases (Anthoff and Tol, 2012; Hope, 2011). The ability to prevent substantial damages through adaptation is limited as evidenced in current IAM damage estimates.

The current IAMs account for adaptation in different ways. In the early versions of DICE and DICE-2013, adaptation is implicit in the damage estimates.[121] As a consequence, the assumptions about adaptation costs are captured in the underlying damage estimates used to calibrate their damage functions (Warren et al., 2006). While Nordhaus implicitly accounts for adaptation to agriculture, other market, health, coastal, and settlement and ecosystem sectors in the early versions of DICE (DICE-1999, DICE-2007, and DICE-2010)—sometimes in an ad hoc way—he essentially assumes high levels of human adaptation at virtually no cost (IWG, 2010). According to IWG (2010) and Warren et al., (2006), this is particularly evident for the other market sectors. It is less clear the extent to which the DICE-2013 damage function captures these adaptation costs due to the use of a meta-analysis. In all versions of DICE, adaptation is not effective enough to eliminate damages.

In FUND, Tol models adaptation explicitly and implicitly. For adaptation to agriculture, ecosystem, and sea level rise damages, Tol models adaptation explicitly. In the first two of these sectors, Tol captures adaptation by modeling damage costs as a function of the rate of climate change (Anthoff and Tol, 2012); see forthcoming Appendix E. In the case of sea level rise, Tol models the cost of building seawalls. Like in DICE, the assumptions about adaptation costs in the other FUND sectors are captured in the underlying damage estimates used to calibrate these damage functions. Additionally, Tol accounts for adaptation implicitly in the energy and human health sectors by allowing regional sector costs to be a function of regional wealth, such that wealthier societies are better able to adapt (IWG, 2010). According to Warren et al., (2006), FUND assumes perfectly efficient adaptation without accounting for adjustment costs, except in the agriculture and ecosystem sectors. Therefore, Tol may underestimate adaptation costs in some sectors of FUND. While climate change results in net global benefits at low temperature changes, higher temperature increases result in costs that adaptation cannot overcome as evidenced by the negative impacts of climate change on consumption by the late 21st century as predicted by FUND 3.6 (Tol, 2013).

Unlike Nordhaus and Tol, Hope (2011) explicitly models climate adaptation in PAGE09. Hope explicitly models adaptation and the cost of adaptation. For each non-catastrophic damage sector (sea level rise, market, and non-market), he specifies a temperature level up to which adaptation is 100 percent effective, a temperature level up to which adaptation is partially effective, and a level of effectiveness (the percentage of damages not incurred) for temperature increases between these two levels. For catastrophic damages, there is no adaptation. Like DICE and FUND, adaptation is not effective enough to significantly eliminate damages.

Given that included damages are significant despite current adaptation assumptions, adaptation as an argument for ignoring currently omitted damages is not justifiable. Furthermore, the three IAMs used by the IWG are often accused of being overly optimistic in their adaptation assumptions, particularly for the versions used by the 2010 IWG (Dietz et al., 2007; Ackerman, 2010; Warren et al., 2006; Hanemann, 2008; Ackerman et al., 2009; Masur and Posner, 2011). In particular, none of the three IAMs explicitly model mal-adaptation. Therefore, omitted damages are likely to still be significant, and current SCC estimates from DICE-2013, FUND 3.6, and PAGE09 are likely biased downward due to a tendency to be overly optimistic about adaptation (Masur and Posner, 2011).[122]

CONCLUSION – MOVING FORWARD

The IWG SCC estimates are likely biased downward due to the modeling decisions of EPA scientists and IAM developers, including the use of outdated damage estimates and the omission of a significant number of damage categories. While some of the damage estimates utilized by IAMs are outdated (Ackerman, 2010; Stern Review – Chapter 6; Stern, 2007; Dietz et al., 2007; Warren et al., 2006; Warren et al., 2010; Tol, 2009), updating these estimates is likely to have a minimal effect on the SCC (Yohe and Hope, 2013). Instead, this paper focuses on cataloging the more significant damages omitted from the recent versions of the three IAMs used by the Interagency Working Group (DICE-2010, FUND 3.8, and PAGE09), and the latest version of DICE (DICE-2013).[123] These omissions occur due to the omission of sectors (for example, socially contingent damages), the omission of relationships between regions and sectors (for example, inter-sector and inter-region damages), and the omission of types of climate damages from the underlying studies used for calibration (for example, fires).

The main question is whether the inclusion of these omitted damages matter. Tol (2009) argues that, for the most part, many omitted damages are small (saltwater intrusion in groundwater, increased cost of cooling power plants, adapting urban water management systems, storm frequency, intensity, and range, ocean acidification, and value of firewood),[124] and are balanced out by omitted climate benefits (decreased costs of some traditional and alternative energies—oil, wind, and wave, lower transport costs, lower expenditures on food and clothing due to lower demand from higher temperatures, and fewer transportation and other disruptions from cold-related weather).[125] For others, like tourism, the effects are unknown according to Tol (2009). Instead, Tol (2009) argues that research should primarily focus on estimating and including unknowns that potentially could have large effects, such as biodiversity loss, catastrophic damages, socially contingent damages, and damages at high temperature levels.[126] In other words, Tol (2009) argues that research should focus on tipping point damages and socially contingent damages; see row 3 and column 3 in Figure 2. Yohe and Tirpak (2007) for the most part agree with this assessment, but also include bounded risks (row 2 in Figure 2), which includes the effects of weather variability (droughts, floods, heat waves, and storms); the effects of weather variability are still greatly omitted from many of the included market and non-market damages. Furthermore, black swan events, that is, unexpected effects, related to climate change should further increase the SCC because researchers expect more negative than positive effects (Tol, 2009b). The inclusion of all omitted damages, including these more significant omitted damages, is likely to result in an increase in the SCC (Mastrandrea, 2009; Tol, 2009a). Given the difficulty of deciding *a priori* what damages are likely to be significant, this report advocates that IAMs should work to include all available damage estimates, particularly those discussed in this paper. However, priority for developing new damage estimates should be given to hot spots—regions and damages that are likely to be significant—for which estimates are not currently available.

There is a general consensus that future IAM research must focus on hot spots. The "hot spot" regions are those that are geographically predisposed to climate change (for example, low lying nations and island nations), and those nations with insufficient ability to adapt (for example, developing nations). The "hot spot" sectors are those discussed above: catastrophic damages, weather variability, and socially-contingent damages. While studying these sectors is difficult, analysts need to look at multiple metrics and regions. The current practice is to omit these difficult to estimate damages or to extrapolate damages estimates from developed to developing nations due to limited data availability. To overcome these shortcomings, future work will require the development of reliable datasets in developing nations and advancements in the science of climate variability and tipping points that specify credible scenarios at a regional level (Yohe and Tirpak, 2007). Furthermore, to develop consistent estimates of damages, the current pipeline of damage estimation, whereby scientists estimate potential damages and economists draw on these estimates in their studies independent of input from scientists, must be replaced with collaborative research between the disciplines.[127] This type of research ensures that economists understand the science behind the climate impacts that they are citing, but also ensures that the scientific estimates are developed with the final impact measurement, that is, the dollar impact, in mind.

Alternatively, further attempts to utilize meta-analysis at the aggregate scale (across regions and sectors) as is done in DICE-2013 are ill-advised.[128] There are several reasons to advise against this type of damage-function estimation. First, using meta-analysis makes determining which damages are included and excluded difficult. It requires an analyst to thoroughly study each of the underlying studies to determine which climate impacts on a sector are included and excluded. Furthermore, it is difficult to interpret whether an impact is included if only several studies include the impact. Second, there are too few data points at this scale to properly account for statistical issues: time trends, omitted damage sectors or impacts within sectors, and correlated standard errors between studies that include estimates from the same authors and similar estimation methods. Last, as discussed by Tol (2009), the data points from various studies are not really a time-series, and should not be treated as such. An alternative is to conduct meta-analyses at the sector level where a sufficient number of studies are available. For example, there are a multitude of agricultural studies, and a meta-analysis to estimate a regional-agricultural or global-agricultural damage function would be possible. Another alternative, laid out by Kopp, Hsiang, and Oppenheimer (2013) is to develop an infrastructure that uses statistical (for example, Bayesian) methods to update damage functions as new estimates become available.

Though not discussed in this paper, there are several additional compounding aspects of IAMs that are likely to further bias current SCC estimates downward. In particular, they fail to account for (1) uncertainty in extrapolating damages to higher temperatures given that IAMS assume only moderate temperature increases,[129] (2) a declining discount rate due to uncertainty over future economic growth (Arrow et al., 2013),[130] (3) aggregated and overly simplified spatial and temporal resolution (IWG 2010; Hanemann, 2008; Stern, 2007), and (4) the option value that arises from the irreversibility of CO_2 emissions. These shortcomings, by and large, point to a further bias downward of the social cost of carbon.

While there is a downward bias to the federal SCC estimates, this report advocates that the Office of Management and Budget (OMB) and other executive branch agencies should move forward to finalize proposed rules with the 2013 IWG's current SCC estimates, as measuring at least some of the costs is better than assuming there are none. In doing so, the OMB should emphasize more strongly the downward bias of the current U.S. SCC estimates and commit to addressing them in future updates of these estimates. Potentially, OMB can utilize the research provided in this report to list in detail all of the omitted damages in the current U.S. SCC estimates.

Table 1. 2010 and 2013 SCC Estimates at 3% Discount Rate by Model

IAM	2010 Global SCC at 3% Discount Rate (IWG 2010)	2020 Global SCC at 3% Discount Rate (IWG 2013)	% Change
DICE	$28	$38	34%
FUND	$6	$19	222%
PAGE	$30	$73	143%

Source: IWG (2013 Revision)

Table 2. 2010 SCC Estimates, 2010–2050 (in 2007 dollars per metric ton)

Discount Rate Year	5% Avg	3% Avg	2.5% Avg	3% 95th
2010	4.7	21.4	35.1	64.9
2015	5.7	23.8	38.4	72.8
2020	6.8	26.3	41.7	80.7
2025	8.2	29.6	45.9	90.4
2030	9.7	32.8	50.0	100.0
2035	11.2	36.0	54.2	109.7
2040	12.7	39.2	58.4	119.3
2045	14.2	42.1	61.7	127.8
2050	15.7	44.9	65.0	136.2

Source: IWG (2010)

Table 3. 2013 SCC Estimates, 2010–2050 (in 2007 dollars per metric ton)

Discount Rate Year	5% Avg	3% Avg	2.5% Avg	3% 95th
2010	11	32	51	89
2015	11	37	57	109
2020	12	43	64	128
2025	14	47	69	143
2030	16	52	75	159
2035	19	56	80	175
2040	21	61	86	191
2045	24	66	92	206
2050	26	71	97	220

Source: IWG (2010)

Table 4. Damage Studies and Income Elasticities Used to Estimate DICE-1999 Damage Function

Sector	Source of Damage Estimate (2.5 degrees Celsius)	Notes	Income Elasticity
Agriculture	Darwin et al (1995) and Dinar et al (1998)	Sub-regional impact estimates: Darwin et al (1995) and Dinar et al (1998); mainly uses Appendix Table B6 from Darwin et al (1995) assuming second most unfavorable GCM and land use is unrestricted.	0.1
Other Market Sectors	Author discretion	Unknown sources for sub-regional damage estimates. No damages to temperate climates based on Cline (1992), Nordhaus (1991), and Mendelsohn and Neumann (1999). Damages in non-temperature climates (cold, tropical, and semi-tropical) based on energy sector alone.	0.2
Coastal Vulnerability	Author discretion	Not directly based on one specific study, but highly influenced by Yohe and Schlesinger (1998); study omits storms, undeveloped land, and settlement so accounted for by author discretion.	0.2
Health	Murray and Lopez (1996)	Assign regional impacts based on the region from Murray and Lopez (1996) with which it most overlaps.	0
Non-market Impacts	Nordhaus (1998)	Use the Nordhaus (1998) estimate from climate-related time use in the U.S.; focusing mainly on increased outdoor recreation.	0
Human Settlement and ecosystems	Author discretion	Cite their own unpublished estimates of the capital value of climate sensitive human settlements and natural ecosystems in each sub-region, and estimate that each sub-region has an annual WTP of 1% of the capital value of the vulnerable system for a 2.5 degrees increase.	0.1
Catastrophic Climate Change*	Nordhaus (1994)	Assume 30% loss of global GDP for such an event and a rate of relative risk aversion of 4 for catastrophic risk. They use expert opinions of probabilities of a cataclysmic change drawn from Nordhaus (1994); the authors double the probabilities in the study for increasing concerns about these events for both 2.5 (measured at 3 degrees in study) and 6 degrees.	0.1

*Calibration sources are provided for 2.5 degrees of warming, but not 6 degrees of warming. The one exception is catastrophic events.

Source: Nordhaus and Boyer (2000) and Warren et al (2006)

Table 5. Sector-Region Specific Damage Estimates for DICE-1999

	Non-catastrophic impacts						Catastrophic impact		TOTAL	
Subregion	Agriculture	Other vulnerable market	Coastal	Health	Non-market time use*	Settlements and ecosystems*	2.5 degrees Celsius	6 degrees Celsius	2.5 degrees Celsius	6 degrees Celsius
Africa	0.05%	0.09%	0.02%	3.00%	0.25%	0.10%	0.39%	2.68%	3.91%	-
China	-0.37%	0.13%	0.07%	0.09%	-0.26%	0.05%	0.52%	3.51%	0.22%	-
Eastern Europe	0.46%	0.00%	0.01%	0.02%	-0.36%	0.10%	0.47%	3.23%	0.71%	-
High Income OPEC	0.00%	0.91%	0.06%	0.23%	0.24%	0.05%	0.46%	3.14%	1.95%	-
India	1.08%	0.40%	0.09%	0.69%	0.30%	0.10%	2.27%	15.41%	4.93%	-
Japan	-0.46%	0.00%	0.56%	0.02%	-0.31%	0.25%	0.45%	3.04%	0.50%	-
Low Income	0.04%	0.46%	0.09%	0.66%	0.20%	0.10%	1.09%	7.44%	2.64%	-
Lower-middle Income	0.04%	0.29%	0.09%	0.32%	-0.04%	0.10%	1.01%	6.86%	1.81%	-
Middle Income	1.13%	0.41%	0.04%	0.32%	-0.04%	0.10%	0.47%	3.21%	2.44%	-
OECD Europe	0.49%	0.00%	0.60%	0.02%	-0.43%	0.25%	1.91%	13.00%	2.83%	-
Other High Income	-0.95%	-0.31%	0.16%	0.02%	-0.35%	0.10%	0.94%	6.39%	-0.39%	-
Russia	-0.69%	-0.37%	0.09%	0.02%	-0.75%	0.05%	0.99%	6.74%	-0.65%	-
United States	0.06%	0.00%	0.11%	0.02%	-0.28%	0.10%	0.44%	2.97%	0.45%	-
Global: 2100 GDP weights (i.e., 2.5 degrees Celsius)										
Output-weighted	0.13%	0.05%	0.32%	0.10%	-0.29%	0.17%	1.02%	6.94%	1.50%	8.23%

Source: Nordhaus and Boyer (2000) and Warren et al (2006)

Table 6. Sector-Region Specific Damage Estimates for DICE-2007

	Non-catastrophic impacts						Catastrophic impact		TOTAL	
	Agriculture	Other vulnerable market	Coastal	Health	Non-market time use*	Settlements and ecosystems*	2.5 degrees Celsius	6 degrees Celsius	2.5 degrees Celsius	6 degrees Celsius
United States	0.03%	0.00%	0.10%	0.02%	-0.28%	0.10%	0.94%	4.00%	0.91%	5.34%
European Union	0.03%	0.00%	0.46%	0.02%	-0.43%	0.25%	1.09%	4.80%	1.42%	9.06%
Add'l High Income	-0.05%	-0.32%	0.09%	0.02%	-0.35%	0.10%	1.11%	4.80%	0.61%	8.99%
Russia	-0.82%	-0.80%	0.05%	0.02%	-0.75%	0.05%	1.12%	4.80%	-1.13%	8.43%
Eurasia	0.03%	0.00%	0.01%	0.02%	-0.36%	0.10%	0.94%	4.00%	0.73%	4.76%
Japan	0.02%	0.00%	0.27%	0.02%	-0.31%	0.25%	1.07%	4.80%	1.31%	8.84%
China	0.02%	0.32%	0.08%	0.09%	-0.26%	0.05%	1.04%	4.00%	1.34%	7.92%
India	0.32%	0.29%	0.09%	0.40%	0.30%	0.10%	1.57%	6.00%	3.08%	12.94%
Middle East	0.35%	0.20%	0.04%	0.23%	0.24%	0.05%	0.96%	4.00%	2.08%	8.41%
Africa	0.67%	0.32%	0.02%	1.00%	0.25%	0.10%	1.78%	7.00%	4.13%	16.55%
Latin America	0.42%	0.28%	0.10%	0.32%	-0.04%	0.10%	1.30%	5.20%	2.48%	10.36%
Other Asia	0.52%	0.21%	0.09%	0.32%	-0.04%	0.10%	1.23%	5.00%	2.43%	10.00%
Global: 2105 weights (i.e. 2.5 degrees Celsius)										
Output weighted	-	-	-	-	-	-	1.16%	4.72%	1.77%	8.23%

Source: Nordhaus (2007)

Table 7. Damage Studies Used to Estimate the DICE-2013 Damage Function

Study	Temperature	Damage Estimate
Tol (2002)	1	-2.875
Rehdanz and Maddison (2005)	1	0.5
Hope (2006)	2.5	-1.125
Mendelsohn, Schlesinger, and Williams (2000)	2.5	0
Maddison (2003)	2.5	0.125
Nordhaus (2006)	2.5	1.125
Fankhauser (1995)	2.5	1.75
Nordhaus and Boyer (2000)	2.5	1.875
Nordhaus and Yang (1996)	2.5	2.125
Tol (1995)	2.5	2.375
Plambeck and Hope (1996)	2.5	3.125
Nordhaus (1994a)	3	1.625
Nordhaus (1994b)	3	6

Source: Tol (2009)

Table 8. PAGE 2002 Damage Function Parameters and Data Sources

Damage parameter	Mean	Min	Mode	Max	Source
Market Damages					
Econ impact in EU (%GDP for 2.5°C)	0.5	-0.1	0.6	1	IPCC (2001a, pp. 940, 943.)
Drop in econ impact OECD (%)	90				As in PAGE95a
Drop in econ impact RoW (%)	50				As in PAGE95a
Tolerable temp OECD economic (°C)	2				As in PAGE95a
Non-Market Damages					
Non-economic impact in EU (%GDP for 2.5°C)	0.73	0	0.7	1.5	IPCC (2001a, pp. 940, 943.)
Drop in non-econ impact (%)	25				As in PAGE95a
Market and Non-market					
Impact function exponent	1.76	1	1.3	3	As in PAGE95
Eastern Europe & FSU weights factor	-0.35	-1	-0.25	0.2	IPCC (2001a, p. 940.)
USA weights factor	0.25	0	0.25	0.5	IPCC (2001a, p. 940.)
China weights factor	0.2	0	0.1	0.5	IPCC (2001a, p. 940.)
India weights factor	2.5	1.5	2	4	IPCC (2001a, p. 940.)
Africa weights factor	1.83	1	1.5	3	IPCC (2001a, p. 940.)
Latin America weights factor	1.83	1	1.5	3	IPCC (2001a, p. 940.)
Other OECD weights factor	0.25	0	0.25	0.5	IPCC (2001a, p. 940.)
Tipping Point Damages					
Tolerable before discontinuity (°C)	5	2	5	8	IPCC (2001a, p. 952.)
Chance of discontinuity (% per °C)	10.33	1	10	20	
Loss if discontinuity occurs, EU (%GDP)	11.66	5	10	20	IPCC (2001a, p. 947.)

Source: Hope (2006)

Table 9. PAGE 2009 Damage Function Parameters and Data Sources

Damage parameter	Mean	Min	Mode	Max	Source
Sea Level Rise					
Initial Benefit (%GDP/°C)	0	0	0	0	-
Calibration sea level rise (m)	0.5	0.45	0.5	0.55	Anthoff et al., 2006
Sea level impact (% GDP)	1	0.5	1	1.5	Warren et al., 2006*
Sea level exponent	0.73	0.5	0.7	1	Anthoff et al., 2006
Market Damages					
Economic Initial benefits (%GDP/°C)	0.13	0	0.1	0.3	Tol, 2002
Econ impact in EU (%GDP for Cal. Temp.)	0.5	0.2	0.5	0.8	Warren et al., 2006*; IPCC AR4
Economic exponent	2.17	1.5	2	3	Ackerman et al, 2009
Non-Market Damages					
Non-economic Initial benefits (%GDP/°C)	0.08	0	0.05	0.2	Tol, 2002
Impact in EU (%GDP for Cal. Temp.)	0.53	0.1	0.5	1	Warren et al., 2006*; IPCC AR4
Non-economic exponent	2.17	1.5	2	3	Ackerman et al, 2009
Market and Non-market					
Calibration temperature (°C)	3	2.5	3	3.5	Warren et al., 2006*
Sea Level Rise, Market, and Non-market					
Impacts saturate beyond (% consumption)	33.33	20	30	50	Weitzman, 2009
US weights factor	0.8	0.6	0.8	1	Anthoff et al, 2006; Stern 2007, p143.**
OT weights factor	0.8	0.4	0.8	1.2	
EE weights factor	0.4	0.2	0.4	0.6	
CA weights factor	0.8	0.4	0.8	1.2	
IA weights factor	0.8	0.4	0.8	1.2	
AF weights factor	0.6	0.4	0.6	0.8	
LA weights factor	0.6	0.4	0.6	0.8	

Damage parameter	Mean	Min	Mode	Max	Source
Tipping Point Damages					
Tolerable before discontinuity (°C)	3	2	3	4	Lenton et al, 2008, table 1; Stern, 2007, box 1.4
Chance of discontinuity (% per °C)	20	10	20	30	Ackerman et al, 2009; Lenton et al, 2008, table 1; Stern, 2007, box 1.4
Loss if discontinuity occurs, EU (%GDP)	15	5	15	25	Anthoff et al, 2006 is the lower number; middle range is Nicholls et al, 2008, and the upper figure is Nordhaus, 1994.
Half-life of discontinuity	90	20	50	200	Hansen (2007) for short values; medium and long-run effects from Nicholls et al. (2008) and Lenton et al. (2008)

* Hope (2011) states that "They produce a mean impact before adaptation of just under 2% of GDP for a temperature rise of 3 °C (Warren et al, 2006), including the associated sea level rise of just under half a meter (Anthoff et al, 2006)."

Table 10. Taxonomy of Omitted Damages – Used in This Paper

Damage Category	Missing Damage Sector
Market Damages	Fisheries
	Pests, pathogens, and weeds
	Erosion
	Fire
	Energy Supply
	Transportation
	Communication
	Ecological dynamics
	Decreasing growth rate
Non-Market Damages	Recreational goods and services
	Ecosystem services*
	Biodiversity and habitat*
	Health care costs*
	Relative prices
Socially-Contingent Damages	Migration
	Social and political conflict
	Violence and crime
Catastrophic Damages	Tipping point*
	Fat tails
	Black swan events
Inter-Sector Damages	Inter-sector damages
Cross-Sector Damages	Inter-regional damages
	Destabilizers of existing non-climate stressors
	Weather variability and climate extremes
	Ocean acidification.

*Partially and/or insufficiently captured in current versions of DICE, FUND, and PAGE

Table 11. Alternative taxonomy of Omitted Damages

Damage Category	Damage sub-category	Missing Damage Sector
Missing Sector	Missing market and non-market sectors	Fisheries
		Energy Supply
		Transportation
		Communication
		Recreational goods and services
	Missing interactions	Inter-sector damages
		Inter-regional damages
	Poorly/incompletely estimated sectors	Biodiversity and habitat*
		Ecosystem services*
		Health care costs*
Missing Climate Effects	Broad system changes	Tipping point*
		Fat tails
		Black swan events
		Weather variability and climate extremes
		Ocean acidification
	Specific impacts from broad system changes	Ecological dynamics
		Pests, pathogens, and weeds
		Erosion
		Fire
	Missing dynamic climate effects	Decreasing growth rate
		Relative prices
		Socially contingent damage

*Partially and/or insufficiently captured in current versions of DICE, FUND, and PAGE

Table 12. Percentage Difference in Damages (with respect to European Damages) by Region and IAM (%)

	PAGE02	Mendelson et al (2000)	Nordhaus and Boyer (2000)	Tol (1999)	Tol's SE	Tol's Lower 95%	Tol's Upper 95%
US	25	-	17.86	91.89	-	-171.24	71.79
Europe	100	-	100	100	-	100	100
Japan/ Other OECD	25	-	17.86	27.03	-	188.89	39.39
Eastern Europe	-35	-	25 and -25	54.05	-	890.20	117.92
Middle East	-	-	-	29.73	-	524.84	67.55
Latin America	183	-	71.43	-2.70	-	208.50	13.43
South East Asia/India	250	-	175	-45.95	-	630.07	5.69
China	20	-	7.14	56.76	-	1258.17	148.53
Africa	183	-	139.29	-110.81	-	1374.51	2.65

Source: IPCC (2001)

Table 13. Damages by Region (as a % of GDP) and IAM

	PAGE02	Mendelson et al (2000)	Nordhaus and Boyer (2000)	Tol (1999)	Tol's Lower 95%	Tol's Upper 95%
US	-0.32	0.3	-0.5	3.4	1.048	5.752
Europe	-1.28	-	-2.8	3.7	-0.612	8.012
Japan/ Other OECD	-0.32	-0.1	-0.5	1	-1.156	3.156
Eastern Europe and Russia (FSU)	0.448	11.1	-0.7 and 0.7	2	-5.448	9.448
Middle East	0	-	0.7	1.1	-3.212	5.412
Latin America/Brazil	-2.3424	-1.4	-2	-0.1	-1.276	1.076
South East Asia/India	-3.2	-2	-4.9	-1.7	-3.856	0.456
China	-0.256	1.8	-0.2	2.1	-7.7	11.9
Africa	-2.3424	-	-3.9	-4.1	-8.412	0.212

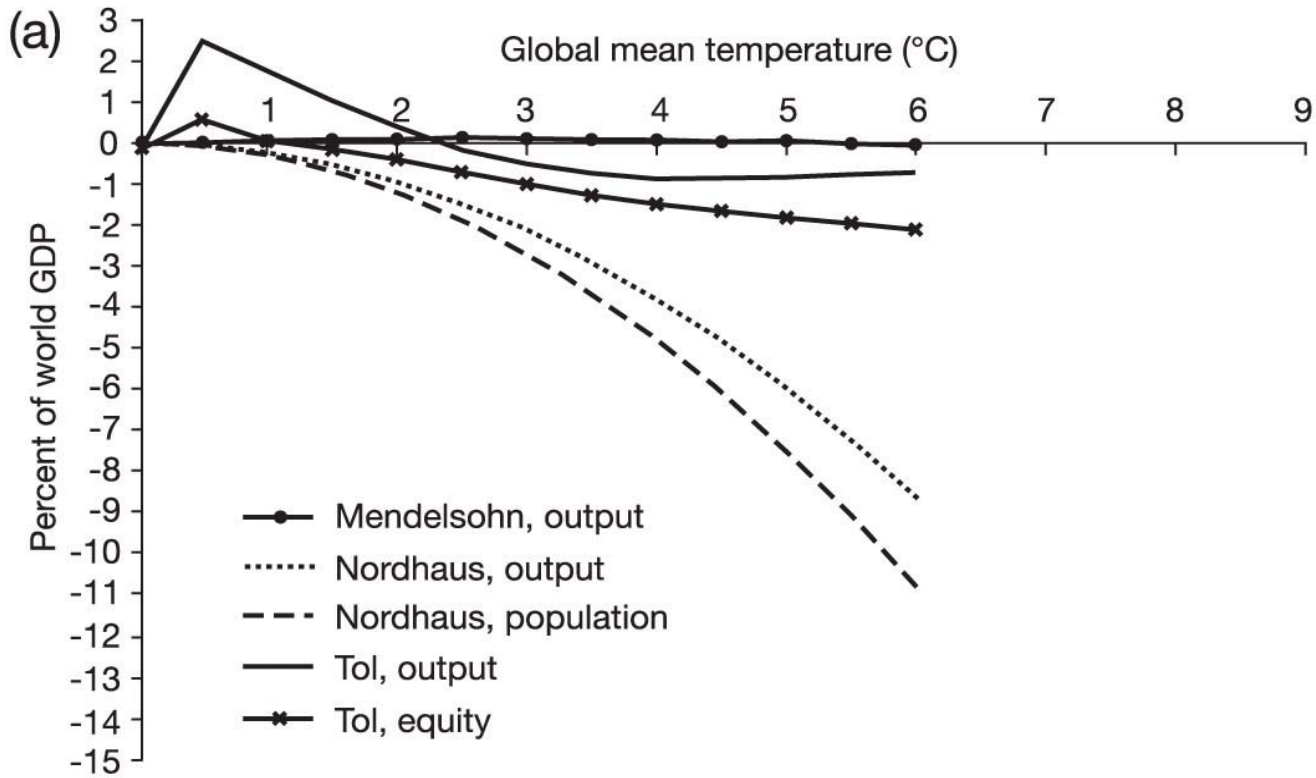
Source: IPCC (2001)

Table 14. Extreme Events

Phenomenon and direction of trend	Likelihood that trend occurred in late 20th century (typically post 1960)	Likelihood of a human contribution to observed trend	Likelihood of future trends based on projections for 21st century using SRES scenarios
Warmer and fewer cold days and nights over most land areas	Very likely	Likely	Virtually certain
Warmer and more frequent hot days and nights over most land areas	Very likely	Likely (nights)	Virtually certain
Warm spells/heat waves. Frequency increases over most land areas	Likely	More likely than not	Very likely
Heavy precipitation events. Frequency (or proportion of total rainfall from heavy falls) increases over most areas	Likely	More likely than not	Very likely
Area affected by droughts increases	Likely in many regions since 1970s	More likely than not	Likely
Intense tropical cyclone activity increases	Likely in some regions since 1970	More likely than not	Likely
Increased incidence of extreme high sea level (excludes tsunamis)	Likely	More likely than not	Likely

Source: IPCC (2007a) – Summary for Policymakers, Table SPM.2 on page 8

Figure 1. Damage Estimates as a % of Global GDP vs. Global Mean Temperature



Source: Figure 20.3a in IPCC (2007) and Figure 19.4 in IPCC (2001b)

Figure 2. Map of types of damages in IAMS by level of scientific and economic uncertainty

UNCERTAINTY IN VALUATION →

UNCERTAINTY IN PREDICTING CLIMATE CHANGE ↓

	MARKET	NON MARKET	(SOCIAL CONTINGENT)
PROJECTION (e.g. sea level rise)	I Coastal projection Loss of dryland Energy (heating/cooling)	IV Heat stress Loss of wetland	VII Regional costs Investment
BOUNDED RISKS (e.g. droughts, floods, storms)	II Agriculture Water Variability (drought, flood, storms)	V Ecosystem change Biodiversity Loss of life Secondary social effects	VIII Comparative advantage & market structures
SYSTEM CHANGE & SURPRISES (e.g. major events)	III Above, plus Significant loss of land and resources Noon-marginal effects	VI Higher order Social effects Regional collapse	IX Regional collapse

Source: Yohe and Tirpak (2007)

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NOTES

[1] In other words, the SCC is the marginal cost of carbon as measured by the present value of all future damages.

[2] This integration is necessary to capture the various steps of the climate process that translate an additional unit of carbon into a social welfare loss: economic and population growth emissions atmosphere concentrations temperature changes economic damages welfare loss.

[3] FUND 3.5 and FUND 3.8 were released in 2009 and 2012, respectively. At the time that this report was written, documentation for FUND was only available up until version 3.6. Since then, Tol released the documentation for version 3.7. Only small changes were made between versions 3.7 and 3.8 based upon peer reviewed science updates.

[4] The IWG provides four SCC estimates. Averaging SCC estimates across all IAMs and socio-economic scenarios (giving each equal weight), the updated estimates for the 2015 social cost of carbon are $11, $37, and $57 for discount rates of 5 percent, 3 percent, and 2.5 percent, respectively, and $109 for the 95th percentile SCC at a 3 percent discount rate averaged across all IAMs and scenarios.

[5] This includes maintaining assumptions about the climate sensitivity parameter, socio-economic and emissions scenarios, and discount rates used in 2010 estimates.

[6] While continued effort is necessary to update damage estimates currently included in IAMs, which often date back to the 1990s (Ackerman 2010; Dietz et al., 2007; Warren et al., 2006; Tol 2009), Yohe & Hope (2013) demonstrates, within the context of the PAGE model, that updates to market damage estimates (equivalent to a 10 percent increase or decrease) will only slightly affect the SCC. Instead, Yohe & Hope (2013) highlight non-economic (also known as non-market) damages, some of which are omitted from IAMs, as areas for more effective improvement (Yohe & Tirpak 2008). In other words, significant downward bias is more likely to result from omitted damages than from outdated damages.

[7] The three models we discuss in this report are not those used by the 2013 IWG. Similar to the 2013 IWG, we discuss PAGE09. Unlike the 2013 IWG, we also discuss DICE-2013 and FUND 3.6. The 2013 IWG utilized DICE-2010 in their calculations instead of DICE-2013. However, because DICE-1999 is utilized in the calibration of PAGE09 and the damage function in DICE-2010 is very similar to the damage function in DICE-1999, we implicitly discuss the omitted damages in DICE-2010. The 2013 IWG utilized FUND 3.8 in their calculations instead of FUND 3.6. However, at the time this report was researched, documentation for FUND was only available up until FUND 3.6. Tol only made minor changes between versions 3.6 and 3.8. For the purposes of this report, no additional damages were included by the author.

[8] Market damage estimates are generally based on either an enumerative approach or a statistical approach. The enumerative approach takes estimates of the physical impacts of climate change by sector (e.g., impact on crop yield or land lost through sea level rise) and then applies economic indicators (e.g., market crop prices or coastal land values) to estimate damages. Specifically, analysts combine physical impact studies from the sciences with prices from economic studies to determine damage estimates, and then, because many of these damage studies are region and sector (e.g., agriculture, forestry, etc.) specific in nature, utilize benefit transfer and aggregation methods to produce a global damage estimate. The statistical approach estimates welfare changes by observing variations in prices and expenditures across space under varying climate conditions. Specifically, analysts estimate climate damages using econometric techniques based on current observations of the climate and economic variables (income, budget shares, and happiness measurements). Enumerative studies have been criticized for ignoring overlaps and interactions between sectors. Statistical surveys draw criticism for overlooking important, non-climate regional differentiators such as structural institutions and for excluding damages that vary temporally but not spatially (i.e., sea level rise and catastrophic impacts). In other words, both estimation methods rely heavily on extrapolation (Goulder & Pizer, 2006; Tol, 2009; Brouwer & Spaninks, 1999).

[9] For example, in the United States, climate-related increases in morbidity and mortality comprise 6 percent to 9 percent of the decrease in GDP but 13 percent to 16 percent of the decrease in household welfare (Jorgenson et al., 2004).

[10] While the transition point from climate benefits to climate damages in Tol (2009) is incorrect in magnitude due to a sign error in the citation of the damage estimate from PAGE02 (Hope 2006) and several other citation errors, the general result of positive net benefits from climate change will likely still hold for low temperature increases after their correction. However, the transition point is likely to occur at a lower temperature threshold.

[11] While Nordhaus assumes no initial benefits from climate change in DICE-2007 and DICE-2013, he allows for initial benefits in DICE-1999 and DICE-2010; Nordhaus estimates net global benefits from climate change up until a 1.29°C increase in global surface temperature in DICE-1999, and no initial benefits in DICE-2010. Hope explicitly models initial benefits in PAGE09, but does not in PAGE02; only Eastern Europe and the former Soviet Union experience climate benefits in PAGE02, which is captured implicitly through a negative damage weighting factor. In PAGE09, Hope includes an additional term in the market and non-market damage functions to account for climate benefits for low temperature increases above pre-industrial levels. This allows for the possibility of positive benefits from climate change, though the exact threshold depends on the parameters drawn; see discussion below. In FUND 2.0, Tol (2002a) finds a net global benefit from climate change equivalent to 2.3 percent of GDP for a one degree Celsius increase; the resulting threshold is less clear.

[12] Because prices are not directly associated with non-market goods as they are with market commodities, a range of alternative valuation methodologies estimating preferences can be used. The value methodologies are traditionally grouped into revealed and stated preference techniques. Revealed preference techniques use market goods to estimate the value of environmental or safety amenities embedded in their prices (e.g., property value variations as a function of parks or pollution levels associated with different homes). In other words, these revealed preference methodologies assume that the price of market goods (e.g., property values) reflect the value of the ecological services or that, ceteris paribus, people will pay more to travel to places with greater ecological value. The usefulness of revealed preference methods in assessing non-market damages is limited because most non-market impacts do not induce price or quantity changes; this is particularly true for the valuation of species, habitat, and ecosystem services. Stated preference methods use interviews or surveys asking participants to identify either the price they would pay for a given ecological commodity, or the amount of a non-market commodity they would demand at a given monetary amount. While stated preference methods can be utilized to assess the willingness to pay (WTP) for non-market goods (Tol 2009; Smith et al., 2003), they have other limitations. In particular, answers depend on question wording, ordering effects, and practical or cognitive limitations in putting dollar values on intangible goods. They may also suffer from information limitations, depending on the good being valued.

With respect to environmental non-market goods, Boyd & Krupnick (2009) and others have compared ecological and economic production systems, arguing that valuation of ecosystem services implies a valuation of their respective outputs. These "outputs" (e.g., reduced flood risk, flourishing fish populations) can be reliably understood and valued by the public in ways that specific ecosystem services (e.g., nutrient cycling) cannot. Because an individual values the endpoint and not the process itself, when asked to value a specific ecosystem service, an individual will base his WTP for the service on his WTP for the "output" of that service. Stated preference valuation that focuses on the value of specific services (instead of outputs) often prove inaccurate because those surveyed assume ecological production factors that may not be consistent with each other or with reality (Boyd & Krupnick 2009).

[13] In other words, tipping points are generally more common in systems with intricate, codependent processes that when altered by exogenous conditions result in the failure of beneficial negative feedback loops or the propagation of detrimental positive feedback loops.

[14] Using a similar set of tipping elements, Nordhaus (2013) identifies four global tipping points: (1) collapse of large ice sheets, (2) large-scale change in ocean circulation, (3) feedback processes that trigger more warming, and (4) enhanced warming over the long-run.

[15] Anthoff and Tol (2013a) claim that FUND implicitly captures catastrophic damages. Specifically, catastrophic impacts arise by modeling the uncertainty of 900 parameters in the FUND model.

[16] More formally, Weitzman (2009) defines a probability distribution function as having fat tails "when its moment generating function (MGF) is infinite—that is, the tail probability approaches 0 more slowly than exponentially." Conversely, he defines a thin-tailed distribution as one characterized by "a [probability distribution function] whose [moment generating function] is finite." Nordhaus (2012) defines a fat-tail distribution as a distribution that follows a power law, which is a "distribution in which the probability is proportional to a value to a power or an exponent."

[17] For clarification purposes, medium-tailed distributions are sometimes referred to as thin-tailed distributions. This paper follows the convention laid out in Nordhaus (2012).

[18] Weitzman (2011) states that the "recipe" for fat tails is "deep structural uncertainty about the unknown unknowns of what might go very wrong ... coupled with essentially unlimited downside liability on possible planetary damages." In other words "the operation of taking 'expectations of expectations' or 'probability distributions of probability distributions' spreads apart and fattens the tails of the reduced-form compounded posterior-predictive PDF (Weitzman 2009)."

[19] Weitzman argues that existing IAMs underestimate the decrease in welfare-equivalent output for extremely high changes in global temperature. The DICE-2010 model, for example, predicts that a 10°C increase in the mean global temperature would result in a 19 percent loss in global welfare equivalent output. Weitzman contends that for very large increases in global temperature damage functions lose much of their predictive ability as complications in spatial and temporal averaging as well as a priori conjecture compound (Weitzman 2011). This implies that there is considerable uncertainty over climate damages at high temperature levels.

[20] Using the value of civilization, Weitzman (2009) calculates a lower bound on consumption (i.e., survival level of consumption), and demonstrates that it is decreasing in the value of civilization.

[21] Citing Yohe & Tirpak (2008) and Tol (2008), Mastrandrea (2009) states that "while there certainly may be unassessed positive impacts from climate change, such summaries suggest that they are likely to be outweighed by unassessed negative impacts."

[22] The choice of functional form determines how climate damages are projected to higher temperatures and does not determine which damages are accounted for and which are omitted.

[23] IAM damage functions are usually calibrated with one point estimate (i.e., at one temperature level), though DICE-1999 is calibrated with two point estimates (i.e., at two temperature levels). In both cases, the lack of damage estimates from climate change at high temperatures makes results unreliable at high temperature (Kopp & Mignone 2012). On the one hand, if analysts use a point estimate (i.e., damage estimates at a particular temperature increase) to calibrate damage functions, the functional form determines damages at high future temperatures. However, without estimates at higher temperatures, analysts cannot determine the correct functional form (Kopp & Mignone 2012). On the other hand, if analysts use multiple point estimates, analysts must extrapolate low temperature damage estimates to high temperatures; this requires a multitude of assumptions, as in DICE-1999, making damage estimates at high temperature unreliable. There are several alternatives. One alternative, utilized by Ackerman & Stanton (2012), is to assume that climate damages reach 100 percent of GDP at a particular temperature level based on the Weitzman argument that humans cannot live at 12 degrees Celsius higher. Another alternative, utilized by Hope (2006; 2011), is to conduct sensitivity analysis over the calibration temperature and damage value.

[24] FUND calibrates sector damage functions to a one degree Celsius increase in temperature. Unlike DICE and PAGE, which assume that climate damages are power functions of temperature increases, Tol assumes sector-specific equations of motion (equations that specify how damages evolve over time based on how physical systems, emissions, income, and population underlying these damages change over time) to extrapolate damage estimates to higher temperatures (and time periods). These equations rely on various assumptions about physical and economic processes, and rely heavily on parameter calibration.

[25] In terms of author discretion, all three IAMs rely heavily on author discretion. However, this reliance has declined with newer versions of the models.

[26] In addition to the default versions of these IAMs, various other versions of these models exist in publication where analysts (including the original developers) modify the default versions to capture differing growth paths or other potential variations.

[27] Whether the damage functions have a linear term, which allows for initial benefits from climate change, in addition to the quadratic term, depends on the version of the model. Only DICE-1999 and DICE-2010 include these linear terms, while Nordhaus sets this parameter equal to zero in DICE-2007 and DICE-2013.

[28] The regions in the DICE-1999 model are: United States, China, Japan, OECD Europe, Russia, India, other high income, high-income OPEC, Eastern Europe, middle income, lower middle income, Africa, and low income.

[29] Because the DICE-1999 climate damages are a function of temperature and temperature squared, two data points are necessary to calibrate the damage equation: damage estimates at 2.5 degrees and 6 degrees Celsius. Damage estimates for a 2.5 degree Celsius increase are available in the literature. Due to unavailability of damage estimates at 6 degrees, damage estimates at 2.5 degrees Celsius are extrapolated to 6 degrees Celsius.

[30] Nordhaus makes several updates to the damage estimates because some regions had climate benefits for high temperatures and catastrophic damages could have been calibrated more carefully in DICE-2000. First, Nordhaus calibrates the damage function using agricultural damage estimates drawn from "Cline's agricultural studies." However, it is unclear which of Cline's papers were used. Second, he no longer accounts for risk aversion when calculating catastrophic damages. This adjustment lowers catastrophic damage estimates. Third, Nordhaus utilizes updated regional GDP estimates to aggregate regional damage estimates to the global scale. In addition, Nordhaus drops the linear term from the quadratic

damage function (Nordhaus, 2008). Fourth, though not mentioned in Nordhaus (2008), Nordhaus does not extrapolate damages from low levels to high levels as discussed in Nordhaus and Boyer (2000); this is possible because Nordhaus eliminates the linear temperature term in the damage function. Last, Nordhaus changes the regions in the model to: the United States, Western Europe/European Economic Zone, Other-High Income, Russia, Eastern Europe/Former Soviet Union, Japan, China, India, Middle Eastern, Sub-Saharan Africa, Latin America, and Other Asian. See Table 6 for DICE-2007 region-sector specific damage estimates.

31 Anthoff and Tol (2013a) states that "FUND does not assume that there is a probability of disastrous impacts of climate change. Rather, we vary all parameters randomly and it so happens that particular realizations are catastrophic."

32 Again, this discussion refers to the default version of PAGE09.

33 According to Hope (2006), in PAGE02, the economic and non-economic damage estimates for 2.5 degree Celsius increase in temperature is based on pages 940 and 943 of the IPCC (2001a) and the tipping point damages are based on pages 947 and 952 of the IPCC (2001a). The combined market and non-market damage estimates on page 940, i.e., Table 19-4, include Pearce et al. (1996), Tol (1999), Mendelsohn et al., (2000), and Nordhaus and Boyer (2000), and the estimates on page 943, i.e., Figure 19-4, include Tol (2002a), Mendelsohn & Schlesinger (1997), and Nordhaus & Boyer (2000). Because the IPCC (2001a) cites only global damage estimates for Pearce et al., (1996) in Table 19-4 and it does not include estimates for Pearce et al., (1996) in Figure 19-4, it is likely that Hope (2006) does not base his regional damage estimates on this source. Similarly, because the IPCC(2001a) does not cite European climate damage estimates for Mendelsohn et al., (2000) in Table 19-4 and cites different estimates from Mendelsohn, i.e., Mendelsohn & Schlesinger (1997), in Figure 19-4 , it is again likely that Hope (2006) does not base his damages estimates on this source. Furthermore, the damage estimate of a 1.23 percent decline in GDP (with a range of -0.1 percent to 2.5 percent) used in PAGE2002 for Europe for a 2.5 degree Celsius increase in temperature do not match the damage estimates from Tol (1999) of a 3.7 percent increase in GDP for Europe with a standard deviation of 2.2 percent and a -2.8 percent decline in European GDP from a 2.5 degree Celsius increase in temperature; see Tables 10 and 11. Instead the damage estimates are closer to the Nordhaus & Boyer (2000) damage estimates. However, the Hope (2006) damage estimates do not replace Nordhaus & Boyer (2000). Similarly, it is unclear what source Hope (2006) uses to breakdown damage estimates between his market and non-market sectors. The market and non-market damage estimates, including their distribution parameters and breakdown between the two sectors, are best described as based on author's judgment informed by Nordhaus & Boyer (2000), Tol (1999), and Tol (2002a).

34 In Page2002, only Eastern Europe could potentially reap climate benefits from temperature increases.

35 For market damages, this temperature threshold increases with adaptation.

36 Hope (2006) calibrates his discontinuous damage function parameters based on discussions in the IPCC (2001a) on pages 947 and 952. Specifically, Hope (2006) calibrates the parameters corresponding to the percentage GDP loss in Europe for a discontinuity and the tolerable temperature risk using general statements about discontinuous damages in the IPCC (2001a). This implies that Hope (2006) utilized his discretion to calibrate the discontinuous damage function parameters.

37 See footnote 12 for a discussion of revealed and stated preference.

38 Ecosystem services and secondary social effects (such migration) are for the most part excluded from IAMs.

39 Note that FUND implicitly accounts for catastrophic damages; see footnotes 15 and 31. As a consequence, FUND may implicitly capture market and non-market catastrophic damages to the extent that the assumed probability distribution functions for uncertain parameters capture tipping points.

40 With respect to FUND 3.6, Tol (2013) explicitly states: "Some impacts are missing altogether – air quality, violent conflict, labour productivity, tourism, and recreation. Weather variability is poorly accounted for, and potential changes in weather variability ignored. The model assumes that there are few barriers to adaptation. There are no interactions between the impact sectors, and therefore are no higher order effects on markets or development."

41 Ocean acidification, wildfires, and pests, pathogens, and weeds affect the market sector via agriculture, forestry, and or fisheries and the non-market sector via biodiversity, ecosystem services, human health, and/or human settlements.

42 In many of the enumerative studies that do include fisheries, fisheries are abstractly captured under "other market" damages.

43 See footnote 8 for a discussion of the enumerative and statistical approaches to estimating climate damages.

44 Given the uncertainty of the effect of climate change on fisheries, Sumaila et al., (2011) argues that fisherman may increase their current fishing efforts given the possibility of lower future fishing stocks.

45 Phytoplankton are essential to the ocean food web and the global climate system. In terms of the latter, "Marine phytoplankton are responsible for [approximately] 50 percent of the CO2 that is fixed annually worldwide (Toseland et al., 2013)."

46 For example, ozone emissions from fuels lower crop yields (Ackerman and Stanton 2011).

47 Ozone impacts are counted separately in BCA analysis as traditional pollutants, not caused by climate change.

48 The CO_2 fertilization effect in FUND 3.6 is drawn from studies that assume a fertilization effect based on enclosure experiments, as do the studies behind DICE-2013 that account for this effect. However, DICE-1999, and therefore to some extent PAGE09, and several of the other studies behind DICE-2013 exclude the CO_2 fertilization effect altogether.

49 As discussed in Koetse and Rietveld (2009), some research casts doubt on the possibility of the Northwest Passage being a valid future shipping route.

50 Due to lower water levels, substantial increases of inland water-way transportation costs are possible. High water levels due to heavy precipitation events can also result in river closures (Koetse and Rietveld, 2009).

51 Network effects are delays, detours, and cancellations due to disruptions in the transportation network. In other words, transportation costs may be incurred in areas not directly affected by an extreme event due the propagation of costs throughout the network. These costs may be substantial (Koetse and Rietveld, 2009).

52 Bigano et al. (2007) state that "world aggregate expenditures hardly change, first rising slightly and then falling slightly." However, there is a considerable noise in the resulting estimates.

53 As noted, DICE-2013 uses a combination of enumerative and statistical studies. While the statistical studies may capture some dynamic effects indirectly, all of these studies are cross-sectional in nature.

54 As a consequence, Moyer et al., (2013) argues that DICE assumes a weak propagation of damages on growth.

55 The modified version of DICE used by the IWG eliminates the potential effect of climate change on economic growth through how it models changes in the savings rate.

56 The intuition is that mitigation spending in the present is equivalent to asking the current generation earning approximately $50,000 per household to transfer money to a future generation in 2300 earning $1.5 million per household (Moyer et al., 2013).

57 This point is made by Dasgupta (2006) with respect to Nordhaus' DICE model. "Despite the serious threats to the global economy posed by climate change, little should be done to reduce carbon emissions … [Norhduas'] idea is not that climate change shouldn't be taken seriously, but that it would be more equitable (and efficient) to invest in physical and human capital now, so as to build up the productive base of economies (including, especially, poor countries), and divert funds to meet the problems of climate change at a later year. These conclusions are reached on the basis of an explicit assumption that global GDP per capita will continue to grow over the next 100 years and more even under business as usual, an assumption that the [Stern] Review would appear to make as well." Given that the Stern Review utilized PAGE02, Dasgupta is in a sense making this point about PAGE as well.

58 According Hope, it is possible in PAGE09 for climate change damages to be large enough to negatively affect consumption growth, such that the discount rate becomes negative (personal correspondence with Hope, 2014).

59 While the Dell, Jones, & Olken (2012) estimate relies on annual data rather than medium-run or long-run average of temperature and precipitation, the authors do provide medium-run estimates that compare average growth rates between 1979 and 1985 and from 1985 to2000. In these medium-run cases, they again find negative effects of higher temperatures on the growth rates of poor nations.

60 Butkiewicz and Yanikkaya (2005) do find that the costs of social-political instability increase the higher the level of national income and democracy of a nation.

61 Higher temperatures require workers to take more breaks, work fewer hours, and/or decrease work intensity (i.e., slow down) (Kjellstrom et al., 2009).

62 While not discussed here, it is possible that as vector-borne diseases spread, more countries could become mired in poverty-disease traps, such as in current sub-Saharan Africa (Fankhauser and Tol, 2005).

[63] "The impacts on labor supply are non-trivial. If temperatures were to rise by 5 degrees Celsius in the United States by the end of the coming century and no adaptation occurs, U.S. labor supply would fall by roughly 0.6 hours per week in high-exposure industries, representing a 1.7 percent decrease in hours worked and thus earnings. In developing countries, where industrial composition is generally skewed toward climate-exposed industries and prevailing temperatures are already hotter than those in most of the United States, the economic impacts are likely to be much larger (Zivin & Neidell, 2010)."

[64] Modeling such changes in DICE may be difficult. On the one hand, Hall & Behl (2006) argue that "with irregular flickering between climate states, characteristic of past climatic transitions, we would expect the destruction of capital stock. If the flickering is forced by human activity, then policy or lack thereof results in the destruction of capital stock and a discontinuity of the rate of return on capital, violating the equilibrium condition." On the other hand, computer general equilibrium models, including ICES and ENVISAGE, have no such problem. ICES and ENVISAGE do not model capital losses as shocks, but instead use expected losses (Bosello et al., 2012; Roson & van der Mensbrugghe, 2010).

[65] The simplicity of the Cass-Koopmans model is particularly useful for making generalizations about the impact of climate change on factor productivity and economic growth. However, this simplicity also ignores certain empirical realities of economic growth (Lecocq & Shalizi, 2007). For example, the Cass-Koopmans model assumes a single aggregate good, while economies consist of multiple industries that are possibility affected differently by climate change. In another example, the Cass-Koopmans model assumes a production function with constant returns to scale, whereas, an economy characterized by increasing returns to scale may become "trapped" at a low growth rate if climate change causes large and frequent shocks to capital or labor productivity or stocks (Aziadaris & Stachurski, 2005).

[66] In DICE, it could be argued that declines in labor and capital productivity are already captured by their expression for "climate damages as fraction of output."

[67] Both the health and labor productivity damage sectors are effects on labor productivity. However, health effects are loss of labor productivity due to a decrease in labor stock through death and inability to work from disease, while the labor productivity damage sector accounts for decline in "on-the job" performance due to humidity and high temperatures.

[68] Like ENVISAGE, the authors of ICES model health damage as an effect on labor productivity.

[69] Environmental goods and services will become relatively scarcer than market goods and services due to climate change and other anthropomorphic drivers. As explained later in this subsection, because current damage estimates are estimated using willingness to pay estimates derived from data from the current time period, they fail to account for the future increases in the value of environmental goods relative to market goods due to the law of scarcity. By adopting structural modeling assumptions that also imply constant relative prices (i.e., that the relative value of non-market to market goods is constant over time), the developers of IAMs bias the SCC downward.

[70] Another example is disease regulation services, which are captured via health damage functions.

[71] Another example is air quality regulation, which is partially captured in PAGE09 via the DICE-1999 damage function. DICE-1999 captures the health effects of air pollution, which is omitted from FUND altogether. DICE-2013 mostly likely omits this damage because Nordhaus and Boyer (2000) is only one of 13 studies utilized to calibrate its damage function.

[72] Another example includes ecosystem services related to biochemicals, natural medicines, and pharmaceuticals.

[73] Another example is climate amenities, which includes cultural services, such as aesthetics, and outdoor leisure activities (i.e., non-market time use). Only earlier versions of DICE (i.e., DICE-1999 and DICE-2007) explicitly attempt to capture these services via Nordhaus' estimate of non-market amenities. However, DICE-1999 only captures outdoor leisure activities, and omits all cultural values. However, even these estimates have come under considerable fire from Hanemann (1998) and Ackerman (2010).

[74] The assessment of damages on ecosystem services depends on a valuation of those services based on public WTP. Boyd and Krupnick (2009) and others have compared ecological and economic production systems, arguing that valuation of ecosystem services implies a valuation of their respective outputs. These "outputs" (e.g., reduced flood risk, flourishing fish populations) can be reliably understood and valued by the public in ways that specific ecosystem services (e.g., nutrient cycling) cannot. Because an individual values the endpoint and not the process itself, when asked to value a specific ecosystem service, an individual will base his WTP for the service on his WTP for the "output" of that service. Stated preference valuation that focuses on the value of specific services (instead of outputs) often prove inaccurate because those surveyed assume ecological production factors that may not be consistent with each other or with reality (Boyd & Krupnick, 2009).

75 One such improvement could be to value the final outputs of species. In addition to their aesthetic and non-use values, analysis could estimate the value of the genetic material of species, an ecosystem service discussed in the previous subsection.

76 In addition to his own criticism of how FUND values biodiversity, the model has also come under criticism by other economists. They argue that assuming that biodiversity loss is a function of temperature change, instead of temperature level, is incorrect because it implies ecosystem adaptation to climate change (Warren et al., 2006). As a consequence, ecosystem damages decline in the long run as temperature increases level off (Warren et al., 2006).

77 This aggregate consumption good, often referred to as a numéraire, equals the combined economic values of all market and non-market goods divided by the global population.

78 Constant relative prices imply that a decline in the supply of a consumption good (market or non-market) does not affect its price relative to all other goods and services. If the relative price of the good were to increase in response to this decline in supply, there would be no demand for the good because consumers could obtain more utility (i.e., welfare) by switching their expenditure to all other goods and services (due to the perfectly substitutable assumption). This would put downward pressure on the good's price until it reached its original value relative to all other prices.

79 Discussions about changing relative prices date back to earlier literatures. Neumayer (1999) calls this argument the Krutilla-Fisher rationale from Krutilla and Fisher (1975). In the context of manufactured and public goods, Baumol (1967) describes a similar phenomenon called Baumol's disease. The discussion of changing relative prices also has roots in the earlier literatures of weak sustainability and strong sustainability.

80 In this context, the elasticity of substitution measures the ease at which market goods can be substituted for non-market goods. An elasticity of substitution less than one implies that market goods and non-market goods are complements in the long run. In the extreme, perfect complements are when market goods cannot be substituted at any level to make up for the loss of non-market goods. An example would be subsistent water levels, where no amount of a market good can replace its value. An elasticity greater than one implies that market goods and non-market goods are substitutes (Heal, 2009). In the extreme, perfect substitutes are when market goods can be substituted at a constant rate to make up for a loss of non-market goods, regardless of the level of non-market goods available.

81 In the language of sustainability, an elasticity less than one implies strong sustainability in the long run. An elasticity greater than one implies weak sustainability in the long run.

82 It should be unsurprising that the discount rate requires updating because growth rates of man-made and environmental goods and services differ. In addition, the rationale for discounting, i.e., that the future will be better off due to continued economic growth, is weakened with the elimination of the perfect substitutability assumption.

83 For example, the results can also apply to agricultural and non-agricultural goods. Heal (2009) argues that food shortages could result in the relative value of agricultural goods increasing from its currently insignificant level in most developed nations.

84 Initially, Sterner and Persson (2008) assume that elasticity of substitution is equal to 0.5, 10 percent of current utility comes from non-market goods, and that 50 percent of damages are attributable to non-market goods. The remaining parameters follow the standard assumptions of DICE.

85 The utility function chosen in Sterner and Persson (2008) assumes a constant elasticity of substitution, and implies only that a positive level of environmental services is essential (i.e., not zero).

86 A small example of the possible magnitude of these relocation costs are Alaskan native villages. In the case of relocating three villages (Kivalina, Shishmaref, & Newtok), the cost is estimated by the U.S. Army Corps of Engineers to be between $275 million and $455 million. While these costs are high, they should be interpreted as an upper bound on costs due to the remoteness of these villages (Lynn & Donoghue, 2011).

87 A decline in income may also decrease the opportunity cost of engaging in violence and civil conflict (Dell, Jones, & Olken, 2013).

88 There is an argument in the literature that higher temperatures and extreme weather may not actually cause conflict, but actually just shifts future conflicts to the period of higher temperatures or more extreme weather. Hsiang, Meng, and Crane (2011) demonstrate that climate change will actually cause "new" conflicts, rather than just shifting the time periods of "existing" conflicts.

89 While the studies vary in their focus over time and space, all 60 studies rely on the same general panel or time-series model. Cross-sectional studies and studies that control for confounding factors are avoided because these confounding factors are potential avenues through which climate can affect conflict. These 60 studies utilize 45 different conflict datasets. Two-thirds of these studies have been published since 2009.

90 The number of inter-personal conflicts far exceeds inter-group conflicts. Thus, a smaller percentage increase in inter-personal conflicts than inter-group conflicts can result in a far greater increase in the number of inter-personal conflicts than inter-group conflicts.

91 Violence on an individual scale, such as increased aggression in the police force, can result in more inter-group conflict. Thus, these two types of conflicts are correlated, such that an increase in interpersonal violence can increase the possibility of intergroup conflict.

92 These 60 studies find that: an increase in temperature raises violent crime faster than it increases property crime; increases in precipitation increase personal and intergroup violence in poorer, agricultural-dependent communities; low and high temperatures and low water availability lead to organized political conflicts; windstorms and floods affect the level of civil conflicts; institutional breakdowns occur in developing economies when they become sufficiently climate stressed.

93 These mechanisms include: decreased supply of resources leads to disagreements over their allocation; climate change makes conflict more appealing with regards to achieving a stated objective; declines in labor productivity make conflict relatively more desirable; declining state capacity reduces the ability of government institutions to suppress crime and provides incentives for competitors to increase the conflict; increased pressure for a redistribution of assets because of increased social and income inequality; increases in food prices; increasing migration and urbanization leading to conflict over geographically stationary non-climate related resources; changes in the logistics of human conflict increases incentives for conflict; a physiological response with respect to cognition, attribution, and/or aggression resulting from higher temperatures increases human propensity for conflict.

94 Certainty equivalent catastrophic damages are the guaranteed magnitude of catastrophic climate damages that humanity finds equally desirable as (that is, is indifferent to) risky (that is, the unknown magnitude of) catastrophic damages that we currently face. Due to humanity's general aversion to risk, humans are willing to pay a premium to avoid risk.

95 In DICE-2013, Nordhaus excluded damages from tipping points. Only two out of the 13 studies used include catastrophic damages. One of these studies, Hope (2006), does so at temperatures above the temperature used to calibrate the DICE-2013 damage function, that is, 2.5 degrees Celsius. As a consequence, the meta-analysis really only includes one study that accounts for tipping points. To rectify this shortcoming and *other omitted damages*, Nordhaus and Sztorc (2013) refit the damage curve after multiplying the damage estimates in Tol (2009) by 1.25. Specifically, Nordhaus and Sztorc (2013) state that "current studies generally omit several important factors (the economic value of losses from biodiversity, ocean acidification, and political reactions), extreme events (sea level rise, changes in ocean circulation, and accelerated climate change), impacts that are inherently difficult to model (catastrophic events and very long-term warming), and uncertainty (of virtually all components from economic growth to damages)." Comparing the unadjusted and adjusted damage estimates (that is, estimates that do not and do assume a 25 percent increase in damages, respectively), Nordhaus and Sztorc (2013) implicitly assume omitted damages of 0.34 percent of GDP at 2.5 degree Celsius and 1.94 percent of GDP at 6 degree Celsius. In contrast, catastrophic damages in DICE-1999 are 1.02 percent at 2.5 degrees Celsius and 6.94 percent degrees Celsius according to Nordhaus and Boyer (2000), while they are 1.16 percent at 2.5 degrees Celsius and 4.72 percent at 6 degrees Celsius in DICE-2007; DICE-2010 makes the same assumption as DICE-2007. To achieve the levels of catastrophic damages observed in DICE-1999, Nordhaus and Sztorc (2013) would have used an adjustment of between 77 percent and 91 percent. Similarly, to achieve the catastrophic damages observed in DICE-2007, the authors would need to have chosen an adjustment of between 62 percent and 87 percent. Therefore, if we believe that the certainty equivalent measure of catastrophic damages is anywhere near the scale proposed in these earlier versions of DICE, the 25 percent increase by Nordhaus is nowhere near sufficient to account for the potential cost of tipping points in the climate system, let alone the *other omitted damages*.

96 Nordhaus and Sztorc (2013), which is the source code for the default version of DICE-2013, specifies that the damage function is

where is the percentage loss in GDP from climate tipping points and T is the global average surface temperature. However, the tipping point damage is turned off in the default version, implying that it is excluded in the catastrophic damage function. In Nordhaus (2013), the tipping-point damage function in his recent book (Chapter 18 – footnote 5) is

This appears to only be used in a very limited analysis, and Nordhaus (2013) states that this damage function is "at the outer limit of what seems plausible and have no solid basis in empirical estimates of damages, so that should be interpreted as illustrating how tipping points might affect the analysis."

[97] The first scenario could be driven by the accelerated increase in atmospheric GHG concentrations driven by the release of greenhouse gas stocks or by the reduced albedo (i.e., the reflectivity of the Earth's surface) due to melting ice sheets. In either case, the rate of radiative forcing per unit of CO_2 is greater. The second tipping-point scenario is motivated by increased GHG atmospheric longevity due to the degradation of carbon sinks (e.g., forests, algae, and agricultural crops). Climate-driven dieback of trees in boreal and tropical forests or algae deaths would reduce Earth's capacity to sequester carbon, effectively increasing the amount of time carbon lingers in the atmosphere by decreasing the decay rate of atmospheric carbon. More persistent carbon would then place carbon sinks under increased pressure, presumably decreasing the decay rate further.

[98] Anthoff and Tol (2013a) states that "FUND does not assume that there is a probability of disastrous impacts of climate change. Rather, we vary all parameters randomly and it so happens that particular realizations are catastrophic."

[99] "A Monte Carlo simulation will run an integrated assessment model thousands of times, each time randomly picking the value of uncertain parameters from a probability distribution function, i.e., a function that assigns a probability to each possible parameter value. For example, the Working Group ran 10,000 Monte Carlo simulations for each of the three IAMs and five socio-economic scenarios, randomizing the value of climate sensitivity, i.e., the change in average global temperature associated with a doubling of CO_2, and all other uncertain parameters in the IAMs by the original authors. For each randomly drawn set of values, the IAM estimated the associated damages, with the final SCC estimate equaling the average value across all 10,000 runs, five socio-economic scenarios, and then across all three models. Therefore, each SCC estimate is calculated using 150,000 runs (EDF, NRDC, Policy Integrity, and UCS comments, 2013)."

[100] These distributions, according to Anthoff and Tol (2013a), "are occasionally derived from meta-analyses of published estimates, but more often based on 'expert guesses'."

[101] Specifically, Anthoff and Tol (2013a) state that "the fat tails found in the Monte Carlo analyses in FUND are a result, rather than an assumption."

[102] Pycroft et al., (2011) uses similar definitions of thin, medium, and fat tails as discussed earlier. To summarize, Pycroft et al., (2011) state that "thin-tailed probabilities, declining exponentially or faster; fat-tailed probabilities, declining polynomially or slower; intermediate-tailed probabilities, declining slower than exponentially but faster than polynomially."

[103] Considering only the change in the climate-sensitivity parameter distribution from the default assumption in PAGE09 (i.e., the triangular distribution) to the three modified distributions, the PAGE09 SCC estimate increases from $102 to $131 (thin), $146 (medium), and $188 (fat); even larger percentage increases are observed for the 95th and 99th percentile SCC estimates. After accounting for a decline in the PAGE09 SCC estimate from $102 to $76 from turning off the catastrophic damage function, the SCC increases from $76 to $99 (thin), $94 (medium), and $114 (fat) when considering only changes in the distributions of the damage function exponents.

[104] See footnote 8 for a discussion of the enumerative and statistical approaches to estimating climate damages.

[105] Yohe and Hope (2013) emphasize this concern. They warn that "to beware of analyses that are so narrow that they miss a good deal of the important economic ramifications of the full suite of manifestations of climate change; i.e., that they miss interactions in the climate system that allow climate change, itself, to be a source of multiple stress even within one particular sector."

[106] Tol (2009) states that "In the enumerative studies, effects are usually assessed independently of one another, even if there is an obvious overlap—for example, losses in water resources and losses in agriculture may actually represent the same loss."

[107] See footnote 8 for a discussion of the enumerative and statistical approaches to estimating climate damages.

[108] In the statistical approach, analysts estimate climate damages using econometric techniques. While there are several identification strategies, which differ in method and types of climate damages captured, all econometric methods rely on current observations of the climate to estimate future climate damages.

[109] While trade is not a positive spillover per se, it is an inter-regional benefit that is only captured through the modeling of connections between regions.

[110] Tradable goods represent only a fraction of market goods. They do not include market services, non-market goods and services, or market goods with prohibitively high transportation costs.

[111] Tol (2009) states: "In Bosello, Roson, and Tol (2007) and Darwin and Tol (2001), my coauthors and I show that sea level rise would change production and consumption in countries that are not directly affected, primarily through the food market (as agriculture is affected most by sea level rise through land loss and saltwater intrusion) and the capital market (as sea walls are expensive to build). Ignoring the general equilibrium effects probably leads to only a small negative bias in the global welfare loss, but differences in regional welfare losses are much greater."

[112] Technology spillovers between nations do not guarantee that the worldwide cost of mitigation and adaptation will decrease.

[113] In FUND 3.6, the number of migrants from the loss of dry land is equal to the product of land loss and average population density. The number of migrants between two regions is assumed to be a constant proportion of the overall number of migrants from the origin (sending) region: migrants from developed regions (United States, Canada, Western Europe, Japan and South Korea, Australia and New Zealand, Central and Eastern Europe, and the former Soviet Union) all resettle within their region of origin; 90 percent of migrants from developing regions (Middle East, Central America, South America, South Asia, Southeast Asia, China plus other nearby nations, North Africa, and sub-Saharan Africa) resettle within their region of origin, and the remaining 10 percent of migrants emigrate to developed regions; migrants from small island nations resettle in other regions: developed and developing (Anthoff and Tol, 2010).

[114] Cline (1992) cites data showing that state and local government spending in 1989 was approximately $3,000 per capita and assumes that immigrants do not pay taxes for their first 18 months in the United States and subsequently cover their share in state and local government expenditures. This yields an estimated cost per migrant of $4,500, which was approximately 25 percent of U.S. per capita income in 1990; a 40 percent cost per migrant, as assumed by FUND, however, would correspond to a $7,200 cost per migrant in the U.S. scenario. The average non-agricultural wage in the United States was $17,994 in 1990 (Economic Report of the President, February 1991, 336 from Cline, 1992). The 40 percent figure likely comes from Fankhauser (1995; 50), who cites Cline (1992) in assuming that global warming will increase immigration by 17 percent worldwide; this figure from Cline (1992), however, was simply an illustration of the cost of migration to the United States and was hardly a "guesstimate," as stated by Fankhauser. Further, Fankhauser applies the $4,500 cost per migrant from Cline (1992) to estimate cost of migration to OECD countries, and follows Ayres and Walter (1991) in assuming a $1,000 cost per migrant to non-OECD regions (Fankhauser, 1995; 51). The latter figure is based on foregone output a person would have produced had he or she not migrated. These assumptions are used to estimate a global cost of migration of $4.33 billion (Fankhauser, 1995; 50), which is likely the source of the estimated cost of migration used in FUND.

[115] See http://www.economist.com/news/europe/21590946-bulgaria-struggling-cope-syrian-refugees-nightmare-all.

[116] See http://www.bbc.co.uk/news/world-23813975.

[117] Freeman and Guzman (2009) state that "In addition to ecological changes, several of the other factors which contribute to the emergence of new diseases will very likely be exacerbated by global warming, including migration (as noted above) and breakdowns in public health infrastructures. It is impossible to say with certainty that climate change will result in new diseases—such emergences are highly complex, multi-factored developments—but it is very clear that climate change will substantially increase this risk."

[118] The United Nations' Millennium Ecosystem Assessment states that "The loss of species and genetic diversity decreases the resilience of ecosystems, which is the level of disturbance that an ecosystem can undergo structure or functioning. In addition, growing pressures from drivers such as overharvesting, climate change, invasive species, and nutrient loading push ecosystems toward thresholds that they might otherwise not encounter. ... The most important direct drivers of change in ecosystems are habitat change (land use change and physical modification of rivers or water withdrawal from rivers), overexploitation, invasive alien species, pollution, and climate change."

[119] There are many threats to future water supplies other than climate change. First, many regions in the United States are currently overpumping their ground water (http://ga.water.usgs.gov/edu/gwdepletion.html), In developing nations, water withdrawals are expected to increase over the next 50 years (Millennium Ecosystem Assessment). Furthermore, water pollution and increased water demand due to a growing population are also issues.

[120] Given that gross revenue of marine captured fisheries (i.e., excluding aquaculture) equals approximately $80 billion to $85 billion annually globally (Sumaila et al., 2011), the effect on U.S. shellfish is small.

[121] For example, the agricultural damage estimates used by Nordhaus include the benefits of farmer adaptation to climate change; see forthcoming Appendix A.

[122] The adaptation assumptions underlying PAGE09 are more conservative than PAGE02. As a consequence, this downward bias is likely less significant for PAGE, as it is for the other two IAMs (Hope, 2006; Hope, 2011).

[123] This paper uses FUND 3.6 instead of FUND 3.8 as mentioned earlier; at the time this report was researched, documentation for FUND was only available up until FUND 3.6. Tol only made minor changes between versions 3.6 and 3.8. For the purposes of this report, no additional damages were included by the author.

[124] DICE-1999 and FUND 3.6, and PAGE09 as a consequence of being greatly informed by these two IAMs, exclude the value of firewood. The studies underlying the forestry damage estimates, i.e., Perez-Garcia et al., 1997; Sohngen et al., 2001, focus on industrial products manufactured from wood, but do not consider the use of wood for fuel. Perez-Garcia et al. (1997) note that fuel uses of wood accounted for roughly half of all timber harvests at the time of the study. Additionally, non-timber aspects of forests (e.g., recreation, water, wildlife, etc.) are only considered to the extent that they are captured in other sectors.

[125] It should be noted, however, that some of these categories also have damages associated with them that are omitted, such as increased energy supply costs due to increased weather variability and extreme events.

[126] Tol (2009) believes that unless a fundamental shift in the literature occurs, improving estimates of willingness to pay for biodiversity and ecosystem services will not affect the SCC. Citing Pearce and Moran (1994), he states that individuals are limited in their willingness to pay for conservation.

[127] This argument is based on statements by David Anthoff at the Cost-Benefit Analysis and Issue Advocacy Workshop on October 28, 2013 at New York University School of Law.

[128] This type of analysis does not represent new data or methodologies as discussed in the previous paragraph.

[129] Only DICE and FUND fail to account for the uncertainty in the functional form of damage equation.

[130] By utilizing the Ramsey discount rate equation, the three IAMs allow for declining discount rates resulting from declining economic growth rates. However, the 2010 and 2013 IWG estimates impose an external assumption of constant discount rates.

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Exhibit D

In the

United States Court of Appeals

For the Seventh Circuit

Nos. 14-2147, 14-2159, & 14-2334

ZERO ZONE, INC., et al.,

Petitioners,

v.

UNITED STATES DEPARTMENT OF ENERGY, et al.,

Respondents.

On Petitions for Review of Final Regulations of the
United States Department of Energy.
Agency No. EERE-2010-BT-STD-0003 &
Agency No. EERE-2013-BT-TP-0025

ARGUED SEPTEMBER 30, 2015 — DECIDED AUGUST 8, 2016

Before BAUER, RIPPLE, and ROVNER, *Circuit Judges*.

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RIPPLE, *Circuit Judge*. The United States Department of Energy ("DOE") published two final rules aimed at improving the energy efficiency of commercial refrigeration equipment ("CRE").[1] The first rule adopted new energy efficiency standards for CRE. 79 Fed. Reg. 17,726 (Mar. 28, 2014) (the "New

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[1] "Commercial refrigeration equipment" includes refrigerators and freezers sold to restaurants and other industries. The term specifically is defined as refrigeration equipment which:

> (i) is not a consumer product … ;
>
> (ii) is not designed and marketed exclusively for medical, scientific, or research purposes;
>
> (iii) operates at a chilled, frozen, combination chilled and frozen, or variable temperature;
>
> (iv) displays or stores merchandise and other perishable materials horizontally, semivertically, or vertically;
>
> (v) has transparent or solid doors, sliding or hinged doors, a combination of hinged, sliding, transparent, or solid doors, or no doors;

Standards Rule"). The second rule, issued a month later, clarified the test procedures that DOE uses to implement those standards. 79 Fed. Reg. 22,278 (Apr. 21, 2014) (the "2014 Test Procedure Rule").

Petitioners Zero Zone, Inc. ("Zero Zone"), a small business specializing in CRE, and Air-Conditioning, Heating and Refrigeration Institute ("AHRI"), a trade association of CRE manufacturers, petitioned for review of both rules. Petitioner North American Association of Food Equipment Manufacturers ("NAFEM"), another trade association of CRE manufacturers, petitioned for review of the first rule. AHRI and Zero Zone moved to consolidate the cases, and we granted the motion.[2]

> (vi) is designed for pull-down temperature applications or holding temperature applications; and
>
> (vii) is connected to a self-contained condensing unit or to a remote condensing unit.

42 U.S.C. § 6311(9)(A).

[2] The Energy Policy and Conservation Act ("EPCA") grants us jurisdiction to hear these cases:

> Any person who will be adversely affected by a rule prescribed under section 6293, 6294, or 6295 of this title may, at any time within 60 days after the date on which such rule is prescribed, file a petition with the United States court of appeals for the circuit in which such person resides or has his principal place of business, for judicial review of such rule.

42 U.S.C. § 6306(b)(1). The New Standards Rule was prescribed under § 6295. The 2014 Test Procedure Rule was prescribed under § 6314, which is covered by § 6306(b). *See id.* § 6316(a)(1) (explaining that "references to

Petitioners challenge both the decisionmaking process and the substance of the final rules. Upon review of those challenges, we conclude that DOE acted in a manner worthy of our deference. The New Standards Rule is premised on an analytical model that is supported by substantial evidence and is neither arbitrary nor capricious. DOE conducted a cost-benefit analysis that is within its statutory authority and is supported by substantial evidence. Its methodology and conclusions were not arbitrary or capricious. It also gave appropriate consideration to the rule's effect on small businesses and the role of other agency regulations. DOE similarly acted within its authority, and within reason, when it promulgated the 2014 Test Procedure Rule. For these reasons, we deny the petitions in their entirety.

I

BACKGROUND

A. Statutory and Regulatory Context

1. Energy Policy and Conservation Act

The Energy Policy and Conservation Act ("EPCA"), Pub. L. No. 94-163, §§ 321–339, 89 Stat. 871, 917–32 (1975) (codified as amended at 42 U.S.C. §§ 6201–6422) was enacted in part to improve the energy efficiency of specific types of equipment and appliances. § 2(5), 89 Stat. at 874. Congress enacted the EPCA in the wake of the 1973–1974 embargo of petroleum exports to the United States by the Organization of Arab Petroleum Exporting Countries. S. Rep. No. 94-26, at 26 (1975). It

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sections 6293, 6294, and 6295 of this title shall be considered as references to sections 6314, 6315, and 6313 of this title").

viewed the embargo as presenting a need for "legislation which would facilitate the reduction of the nation's petroleum consumption through energy conservation." *Id.* at 27; *see also* H.R. Rep. No. 94-340, at 1 (1975) ("This legislation is directed to the attainment of the collective goals of increasing domestic supply, *conserving and managing energy demand*, and establishing standby programs for minimizing this nation's vulnerability to major interruptions in the supply of petroleum imports." (emphasis added)).

As originally enacted, the EPCA authorized the Federal Energy Administration ("FEA")—the predecessor to DOE[3]—to implement voluntary "energy efficiency improvement target[s]" that would encourage manufacturers to decrease the energy consumption of their equipment. Pub. L. No. 94-163, § 325, 89 Stat. 923–26. However, Congress determined shortly thereafter that, "[u]nder the target approach, there would be little incentive by a manufacturer to exceed a target, and to do so might place a given manufacturer at a competitive disadvantage." H.R. Rep. No. 95-496, at 45 (1977). It therefore amended the EPCA to impose *mandatory* energy conservation standards. National Energy Conservation Policy Act, Pub. L. No. 95-619, § 422, 92 Stat. 3206, 3259 (1978). As amended, the EPCA directs DOE to review these standards and implement new ones when appropriate. 42 U.S.C. §§ 6313(c), 6316(e), 6295(m).

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[3] The Department of Energy Organization Act of 1977 established the Department of Energy and transferred the responsibilities of the Federal Energy Administration into DOE. *Id.* § 7151(a).

When establishing new energy conservation standards, DOE must follow certain statutory requirements. First, standards may not "increase[] the maximum allowable energy use" of any individual unit. *Id.* § 6295(o)(1). Second, standards must be "designed to achieve the maximum improvement in energy efficiency" and be "technologically feasible and economically justified." *Id.* § 6295(o)(2)(A). The EPCA explains that:

> In determining whether a standard is economically justified, the Secretary shall, after receiving views and comments furnished with respect to the proposed standard, determine whether the benefits of the standard exceed its burdens by, to the greatest extent practicable, considering—
>
> (I) the economic impact of the standard on the manufacturers and on the consumers of the products subject to such standard;
>
> (II) the savings in operating costs throughout the estimated average life of the covered product in the type (or class) compared to any increase in the price of, or in the initial charges for, or maintenance expenses of, the covered products which are likely to result from the imposition of the standard;
>
> (III) the total projected amount of energy, or as applicable, water, savings likely to result directly from the imposition of the standard;
>
> (IV) any lessening of the utility or the performance of the covered products likely to result from the imposition of the standard;

> (V) the impact of any lessening of competition, as determined in writing by the Attorney General, that is likely to result from the imposition of the standard;
>
> (VI) the need for national energy and water conservation; and
>
> (VII) other factors the Secretary considers relevant.

Id. § 6295(o)(2)(B)(i). The EPCA further explains that, for the purposes of determining anticompetitive effects, the Attorney General must submit his or her opinion in writing "not later than 60 days after the publication of a proposed rule" and that "[a]ny such determination and analysis shall be published by the Secretary in the Federal Register." *Id.* § 6295(o)(2)(B)(ii).

The EPCA also charges DOE with establishing test procedures for measuring the energy use of covered equipment. *Id.* § 6314. Manufacturers must use these test procedures when determining whether their equipment complies with the applicable energy conservation standards. *Id.* §§ 6295(s), 6316(e)(1). According to the EPCA:

> (1) The Secretary shall, not later than 3 years after the date of prescribing a test procedure under this section (and from time to time thereafter), conduct a reevaluation of such procedure and, on the basis of such reevaluation, shall determine if such test procedure should be amended. In conducting such reevaluation, the Secretary shall take into account such information as he deems relevant, including techno-

> logical developments relating to the energy efficiency of the type (or class) of covered equipment involved.
>
> (2) If the Secretary determines under paragraph (1) that a test procedure should be amended, he shall promptly publish in the Federal Register proposed test procedures incorporating such amendments and afford interested persons an opportunity to present oral and written data, views, and arguments. Such comment period shall not be less than 45 days' duration.

Id. § 6314(c).

2. Energy Policy Act of 2005

Congress amended the EPCA in 2005, and in doing so added CRE to the industrial equipment category. Energy Policy Act of 2005, Pub. L. No. 109-58, § 136, 119 Stat. 594, 638–39 (codified at 42 U.S.C. § 6313(c)(2)–(3)) ("EPACT"). The EPACT prescribed standards for six different classes of CRE. § 136, 119 Stat. at 639.[4] It also required DOE to set standards for additional classes of CRE that were not yet covered by the EPCA. *Id.*

[4] Specifically, the EPACT prescribed standards for refrigerators with solid doors, refrigerators with transparent doors, freezers with solid doors, freezers with transparent doors, refrigerator-freezers with solid doors, and self-contained condensing units with transparent doors designed for pull-down temperature applications. *Id.* § 6313(c)(2)–(3).

3. 2009 Final Rule

Accordingly, DOE published a final rule on January 9, 2009, that prescribed energy conservation standards for thirty-eight additional equipment classes. 74 Fed. Reg. 1092. These classes were defined by a combination of the equipment's geometry (vertical, semivertical, or horizontal), door type (solid, transparent, or open), condensing-unit configuration (self-contained or remote-condensing), and operating temperature (medium, low, or ice-cream).[5]

4. American Energy Manufacturing Technical Corrections Act

Congress made an additional amendment to the statute in January 2012, which prescribed a specific standard for self-contained commercial refrigerators with transparent doors. American Energy Manufacturing Technical Corrections Act, Pub. L. No. 112-210, § 4, 126 Stat. 1514, 1516 (codified as amended at 42 U.S.C. § 6313(c)(4)) ("AEMTCA"). As a result, the existing energy conservation standards for CRE at the time of this rulemaking had been established by three separate sources: the EPACT, the AEMTCA, and DOE's 2009 Final Rule.

B. The New Standards Rule

DOE published a sixty-page framework document in 2010, which discussed the relevant issues and processes in de-

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[5] For example, a unit could be in the "vertical open, remote condensing, medium temperature equipment class." *See* 79 Fed. Reg. 17,726, 17,732 (Mar. 28, 2014). This class is identified by DOE as "VOP.RC.M." *Id.*

termining whether to amend the CRE energy efficiency standards. 75 Fed. Reg. 24,824, 24,824–25 (May 6, 2010); App. R.6, Admin. R.2. DOE then published a notice of proposed rulemaking for new CRE energy efficiency standards on September 11, 2013. 78 Fed. Reg. 55,890. The notice of proposed rulemaking listed new standards for forty-nine classes of CRE. *See id.* at 55,890–92. DOE also made available a technical support document for the proposed rule. App. R.6, Admin. R.51. On October 3, 2013, DOE held a public meeting in Washington, D.C. to solicit comments and provide some preliminary responses. App. R.6, Admin. R.62. DOE also permitted the public to submit further comments until a November 12, 2013 deadline, although a few comments were submitted after that date. On March 28, 2014, DOE published the New Standards Rule, the rule before us in this proceeding.

The New Standards Rule establishes energy conservation standards for forty-nine classes of CRE. 79 Fed. Reg. at 17,727. Just as in DOE's earlier 2009 Final Rule, the classes were defined by a combination of the equipment's geometry, door type, condensing-unit configuration, and operating temperature. *Id.* at 17,743. For each class, the maximum daily energy consumption is determined by a function of either the unit's refrigerated volume ("V") or the unit's total display area ("TDA"). *Id.* at 17,727.[6] For eight equipment classes, DOE made no changes from the 2009 Final Rule. *Id.* at 17,728. For the remaining forty-one equipment classes, DOE set forth a

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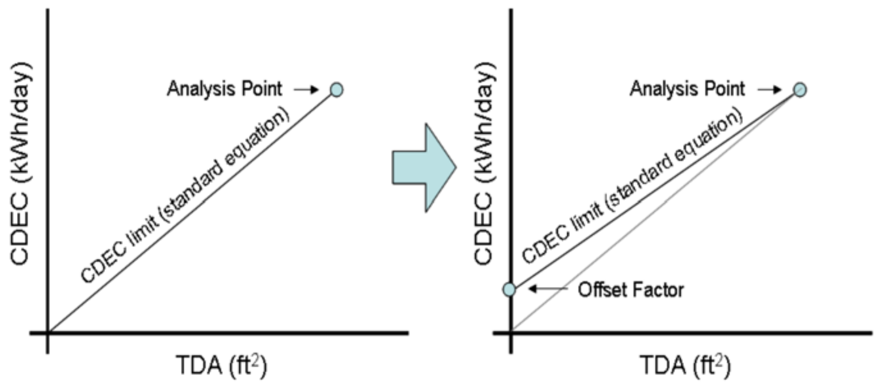
[6] For example, a CRE in the vertical, open, remote-condensing, medium temperature class has a maximum daily energy consumption of (0.64 x TDA + 4.07) kilowatt-hours. 79 Fed. Reg. at 17,727. Therefore, if a CRE in this equipment class had a total display area of ten square feet, its maximum allowable energy consumption would be 6.47 kilowatt-hours/day.

higher standard that it determined was both technologically feasible and economically justified. *Id.* at 17,727–30. DOE estimated that the revised standards were likely to result in a savings of 2.89 quadrillion British thermal units of energy in 2014—an "annualized energy savings equivalent to 0.5 percent of total U.S. commercial primary energy consumption in 2014." *Id.* at 17,728, 17,736–37.

To determine the appropriate standard for each class of equipment, DOE used a design-option engineering analysis. *Id.* at 17,745; Final Technical Support Document, App. R.6, Admin. R.102 at 5-41 to 5-68. In that analysis, DOE chose a representative unit from each class of CRE. App. R.6, Admin. R.102 at 5-1 to 5-2. DOE intentionally chose a unit that "was toward the larger end of the equipment available within that class." *Id.* at 5-68. DOE then, using an analytical model, estimated the cost to manufacturers of implementing more efficient components into that unit, as well as the "calculated daily energy consumption" ("CDEC") that would result from implementing those components. *Id.* at 5-1 to 5-3, 5-13 to 5-41. This analysis included modeling the effect of more efficient lighting, compressors, and insulation. *Id.* at 5-13 to 5-41. DOE then ranked the components in order of cost, and drew a cost-efficiency curve that illustrated a feasible maximum energy consumption level for a unit of that size. *Id.* at 5-2 to 5-3.

This maximum energy consumption level served as an "analysis point" for DOE, which it used to establish an equation for determining a CRE unit's maximum energy consumption level. *Id.* at 5-68. DOE's method for establishing this equation is illustrated in the graphs below:



Id. As the graph to the left shows, DOE first plotted the analysis point on a graph measuring the relationship between a CRE unit's CDEC and its TDA (or, in some cases, CDEC and refrigerated volume). *Id.* DOE then drew a line from the analysis point to the origin. Under the scheme contemplated by the left graph, a CRE unit would need to have a CDEC at or below that line. *Id.*

DOE originally had intended to employ this scheme in its 2009 Final Rule, but it had received comments about the effects of such an equation on smaller equipment. *Id.* As the comments pointed out, drawing a line from the origin assumed that a small CRE unit with a TDA approaching zero could consume energy at a level close to zero. *Id.* DOE therefore chose to include an "offset" factor for each class, which allowed smaller equipment to consume more energy under the standards. *Id.* The offset "represent[s] energy consumption end effects inherent in equipment operation regardless of the size of the equipment." *Id.* at 5-3. As shown in the graph above on the right, the offset serves as the y-intercept for the CDEC equation. *Id.* at 5-68.[7]

The resulting energy conservation standards do not compel manufacturers to use any particular components to achieve improved efficiency. Instead, as DOE explained, "should manufacturers value some features over others, they are free to use different design paths in order to attain the performance levels required." 79 Fed. Reg. at 17,750.

DOE then considered whether its new standards were economically justified. *Id.* at 17,737. It developed five potential "trial standard levels" of energy efficiency requirements for each class and considered the costs and benefits at each level. *Id.* at 17,738, 17,803–11. DOE initially proposed that the standards be set at the second-highest level. 78 Fed. Reg. at 55,948.

[7] NAFEM commented before the agency and submits in its brief that DOE offset factors are ill conceived because they are based on only forty-nine classes of equipment and are illogical in their structure. We have considered this submission on the basis of the briefs and have studied the record, including the engineering report compiled by DOE during its study of these standards. It is clear to us that DOE undertook a study of industry patterns, compared those patterns to the ones that it had encountered in earlier rulemaking, and concluded that the categories that it implemented were an accurate reflection of the current industry situation. NAFEM has countered with no data or other information demonstrating that DOE's conclusion is not supported by substantial evidence or that its approach to the problem is arbitrary or capricious. Since this argument is underdeveloped by NAFEM, we see no reason for further discussion in our later analysis.

However, after the notice and comment period, DOE determined that the third-highest level "will offer the maximum improvement in efficiency that is technologically feasible and economically justified and will result in the significant conservation of energy." 79 Fed. Reg. at 17,810.

As part of this economic analysis, DOE requested a letter on September 24, 2013 from the United States Department of Justice ("DOJ") that would assess the rule's anticompetitive effect. DOJ did not respond until November 25, 2013, when the Assistant Attorney General for Antitrust sent a letter to DOE. App. R.6, Admin. R.106. According to DOJ, the new rule would not have anticompetitive effects. *Id.* DOE added this letter to the record on June 17, 2014—several months after the public hearing on the rule. *See id.* DOE also published this letter in the Federal Register on July 28, 2015—over a year after the Final Rule had been published and one day before it filed its appellate brief in this case. 80 Fed. Reg. 44,892.

After receiving the DOJ letter and other sources, DOE concluded in the Final Rule, published on March 28, 2014, that the new standards would result in lower energy use and thus produce a net benefit to consumers between $4.93 and $11.74 billion. 79 Fed. Reg. at 17,728, 17,810. In addition, DOE noted the monetary benefits of the reductions in greenhouse gas emissions. *Id.* at 17,811. DOE then determined that the development of new CRE would cost manufacturers between $93.9 and $165 million. *Id.* at 17,810. DOE concluded that the benefits outweighed the costs and that the standards therefore would be economically justified. *Id.* at 17,810–11.

C. The 2014 Test Procedure Rule

The New Standards Rule noted that "[t]he test procedure amendments established in the 2012 test procedure final rule are required to be used in conjunction with the amended standards promulgated in this … final rule." 79 Fed. Reg. at 17,735. In that 2012 Test Procedure Rule, DOE incorporated the method for calculating the TDA of CRE required by statute. 77 Fed. Reg. 10,292, 10,318 (Feb. 21, 2012). As shown above, the maximum allowable daily energy consumption for some units is dependent on their TDA.

To measure the TDA of a CRE unit, one must take certain measurements of the unit and enter those measurements into a general equation.[8] One of those measurements is the "Length of Commercial Refrigerated Display Merchandiser" ("L"). 79 Fed. Reg. at 22,299. Under DOE's energy efficiency standards, "L" is directly proportional to a CRE unit's maximum energy consumption level: the longer the display on a CRE unit, the more energy a CRE unit is allowed to consume on a daily basis. Therefore, the precise definition of "L" will impact the energy efficiency standards. However, the 2012 Test Procedure "contain[ed] no figures or illustrations instructing a user how to perform this measurement." *Id.*

DOE issued a notice of proposed rulemaking on October 28, 2013, which proposed a clarification on the meaning of "L" in the 2012 Test Procedure Rule. 78 Fed. Reg. 64,296, 64,309–

[8] According to DOE, TDA = D_h x L + A_e. "D_h" stands for "Dimension of projected visible product." "L" stands for "Length of Commercial Refrigerated Display Merchandiser." "A_e" stands for "Projected area from visible product through end walls." 79 Fed. Reg. 22,278, 22,299 (Apr. 21, 2014).

12.[9] That definition would have corresponded to the total length of the transparent area on CRE but would have not included any opaque or non-transparent areas. *Id.* at 64,309–10. Several companies, however, submitted comments, contending that the "industry has always treated the length 'L' as the 'length of the commercial refrigerated display merchandiser' from inside wall to inside wall, disregarding the presence of non-transparent mullions[10] and door frames." 79 Fed. Reg. at 22,300.

A little less than a month after the CRE standards were published, on April 21, 2014, DOE published a CRE test procedure that clarified how energy efficiency was to be measured. *Id.* at 22,278. In light of the comments it received, DOE departed from its proposed rule and published a CRE test procedure that was "consistent with and clarifie[d] current industry practice and the existing provisions of the DOE test procedure." *Id.* at 22,301. According to this final rule, "L" was defined "as the interior length of the CRE model, provided no more than 10 percent of that length consists of non-transparent material." *Id.* The rule provided further clarification on measuring "L" for units where more than ten percent of the surface was not transparent. *Id.*

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[9] DOE issued this notice of proposed rulemaking *after* it issued the notice of proposed rulemaking for the New Standards Rule on September 11, 2013.

[10] A mullion is the vertical bar between the panes in a window, door, or screen.

D. Petitions for Review

NAFEM timely filed a petition for review on May 23, 2014, challenging the New Standards Rule. Four days later, on May 27, 2014, AHRI and Zero Zone filed a petition similarly challenging the New Standards Rule. AHRI and Zero Zone then filed a petition challenging the 2014 Test Procedure Rule on June 19, 2014. Upon AHRI's and Zero Zone's motion, we consolidated the petitions.

II

DISCUSSION

The petitioners raise a series of procedural and substantive challenges to DOE's final rules pertaining to energy efficiency standards. We will consider, in turn, the challenges to: (1) DOE's engineering analysis; (2) DOE's economic analysis; (3) DOE's regulatory flexibility analysis, which considered the effect of the new standards on small businesses; (4) DOE's assessment of the cumulative regulatory burden; and (5) the 2014 Test Procedure Rule.

Pursuant to the Administrative Procedure Act ("APA"), we will "hold unlawful and set aside agency action, findings, and conclusions" that are:

> (A) arbitrary, capricious, an abuse of discretion, or otherwise not in accordance with law;
>
> (B) contrary to constitutional right, power, privilege, or immunity;
>
> (C) in excess of statutory jurisdiction, authority, or limitations, or short of statutory right;

> (D) without observance of procedure required by law; [or]
>
> (E) unsupported by substantial evidence in a case subject to sections 556 and 557 of this title … .[11]

5 U.S.C. § 706(2). When determining whether an agency's decision is arbitrary or capricious, we ask whether the agency

> has relied on factors which Congress had not intended it to consider, entirely failed to consider an important aspect of the problem, offered an explanation for its decision that runs counter to the evidence before the agency, or is so implausible that it could not be ascribed to a difference in view or the product of agency expertise.

Nat'l Ass'n of Home Builders v. Defs. of Wildlife, 551 U.S. 644, 658 (2007) (quoting *Motor Vehicle Mfrs. Ass'n v. State Farm Mut. Auto. Ins. Co.*, 463 U.S. 29, 43 (1983)) (internal quotation marks omitted). "Substantial evidence," we have explained, "means 'such relevant evidence as a reasonable mind might accept as adequate to support the conclusion'" reached by the agency. *Local 65-B, Graphic Commc'ns Conference of Int'l Bhd. of Teamsters v. NLRB*, 572 F.3d 342, 347 (7th Cir. 2009) (quoting *Huck Store Fixture Co. v. NLRB*, 327 F.3d 528, 533 (7th Cir. 2003)); *see also Consol. Edison Co. v. NLRB*, 305 U.S. 197, 229 (1938) (explaining that the agency must produce "more than a mere scintilla" of evidence).

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[11] The EPCA states that "no rule under" the statutory provisions applicable to this case "may be affirmed except by substantial evidence." 42 U.S.C. § 6306(b)(2).

In our review, "[w]e give great deference to an agency's predictive judgments about areas that are within the agency's field of discretion and expertise." *W. Fuels-Ill., Inc. v. ICC*, 878 F.2d 1025, 1030 (7th Cir. 1989) (internal quotation marks omitted); *see also Pub. Citizen, Inc. v. NHTSA*, 374 F.3d 1251, 1260–61 (D.C. Cir. 2004). "[W]hen reviewing an agency's scientific and technical determinations, 'a reviewing court must generally be at its most deferential.'" *Indiana v. EPA*, 796 F.3d 803, 811 (7th Cir. 2015) (quoting *Balt. Gas & Elec. Co. v. NRDC*, 462 U.S. 87, 103 (1983)). However, we also note that the Supreme Court "has stressed the importance of not simply rubber-stamping agency factfinding." *Dickinson v. Zurko*, 527 U.S. 150, 162 (1999). Further, "[t]he reviewing court should not attempt itself to make up for … deficiencies" in the agency's reasoning; "'we may not supply a reasoned basis for the agency's action that the agency itself has not given.'" *Motor Vehicle Mfrs. Ass'n*, 463 U.S. at 43 (quoting *SEC v. Chenery Corp.*, 332 U.S. 194, 196 (1947)).

For those of petitioners' challenges based on the statutory language of the EPCA, our review is structured by *Chevron, U.S.A., Inc. v. Natural Resources Defense Council, Inc.*, 467 U.S. 837 (1984). At the first step of *Chevron* review, we ask whether Congress has spoken directly on the precise question of interpretation. *Chevron*, 467 U.S. at 842 ("If the intent of Congress is clear, that is the end of the matter … ."). When there is a statutory ambiguity, we then move to the second step of *Chevron* review and ask whether the agency's interpretation is "arbitrary or capricious in substance." *Mayo Found. for Med. Educ. & Research v. United States*, 562 U.S. 44, 53 (2011) (internal quotation marks omitted). As the Supreme Court has noted, this second step of *Chevron* is functionally equivalent to traditional arbitrary and capricious review under the APA. *Judulang v. Holder,* 132 S. Ct. 476, 483 n. 7 (2011). For those of petitioners' challenges based on the language of DOE regulations, we will uphold DOE's interpretations of its own regulation "unless plainly erroneous or inconsistent with the regulation." *Auer v. Robbins*, 519 U.S. 452, 461 (1997) (internal quotation marks omitted); *see also Joseph v. Holder*, 579 F.3d 827, 833 (7th Cir. 2009).[12]

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[12] The Supreme Court has explained that:

> Although *Auer* ordinarily calls for deference to an agency's interpretation of its own ambiguous regulation, even when that interpretation is advanced in a legal brief, see *Chase Bank USA, N.A. v. McCoy*, 562 U.S. —, —, 131 S.Ct. 871, 880, 178 L.Ed.2d 716 (2011); *Auer*, 519 U.S., at 461–462, 117 S.Ct. 905, this general rule does not apply in all cases. Deference is undoubtedly inappropriate, for example, when the agency's interpretation is "'plainly erroneous or inconsistent with the regulation.'" *Id.,* at 461, 117 S.Ct. 905 (quoting *Robertson v. Methow Valley Citizens Council*, 490 U.S. 332, 359, 109 S.Ct. 1835, 104 L.Ed.2d 351 (1989)). And deference is likewise unwarranted when there is reason to suspect that the agency's interpretation "does not reflect the agency's fair and considered judgment on the matter in question." *Auer*, *supra,* at 462, 117 S.Ct. 905; see also, *e.g., Chase Bank*, *supra,* at —, 131 S.Ct. at 881. This might occur when the agency's interpretation conflicts with a prior interpretation, see, *e.g., Thomas Jefferson Univ. v. Shalala*, 512 U.S. 504, 515, 114 S.Ct. 2381, 129 L.Ed.2d 405 (1994), or when it appears that the interpretation is nothing more than a "convenient litigating position," *Bowen v. Georgetown Univ. Hospital*, 488 U.S. 204, 213, 109 S.Ct. 468, 102 L.Ed.2d 493 (1988), or a "'*post hoc* rationalizatio[n]' advanced by an agency seeking to defend past agency action against attack," *Auer*, *supra,* at

A. Engineering Analysis

The New Standards Rule was based in part on a "design option" engineering analysis. 79 Fed. Reg. at 17,763. To conduct this analysis, DOE defined a hypothetical "representative unit" from each class of CRE. App. R.6, Admin. R.102 at 5-1 to 5-2. The unit displayed the characteristics of that class of CRE, *id.*, but was "toward the larger end of equipment available for that class," *id.* at 5-68. DOE then, using an analytical model, estimated the cost to manufacturers of implementing more efficient components into that unit, as well as the "calculated daily energy consumption" that would result from implementing those components. *Id.* at 5-1 to 5-3, 5-13 to 5-41. This analysis included, for example, modeling the effect of more efficient lighting, compressors, and insulation. *Id.* at 5-13 to 5-41. From this model, DOE determined an appropriate energy consumption level for a unit of that size, *id.* at 5-2 to 5-3, and then extrapolated from those results to create an equation for determining the energy consumption level for the rest of the class, *id.* at 5-68.[13]

The petitioners raise several procedural and substantive challenges to DOE's engineering analysis. We will discuss each in turn.

> 462, 117 S.Ct. 905 (quoting *Bowen, supra,* at 212, 109 S.Ct. 468; alteration in original).

Christopher v. SmithKline Beecham Corp., 132 S. Ct. 2156, 2166–67 (2012).

[13] A more detailed explanation of the engineering analysis can be found *supra* Part I.B.

1. Notice and Comment

NAFEM contends that DOE failed to provide a meaningful opportunity for notice and comment of an "engineering spreadsheet" that compiled all the data that was used in DOE's analysis. *See* App. R.6, Admin. R.98. Early in the promulgation of the standards rule, DOE provided two technical support documents that explained its planned analysis. App. R.6, Admin. R.2; App. R.6, Admin. R.30. On August 29, 2013—two weeks before the publication of the notice of proposed rulemaking—DOE published a more complete technical support document that further spelled out its engineering analysis and included all the relevant raw data. *See* App. R.6, Admin. R.51 at 5-1 to 5A-17. However, at that time, DOE did *not* provide the engineering spreadsheet that it used. After receiving questions about the spreadsheet at a public hearing on October 3, 2013, a DOE representative stated that DOE would make the spreadsheet publicly available. App. R.6, Admin. R.62 at 337. DOE subsequently published the spreadsheet on October 8, 2013. App. R.6, Admin. R.59. Several members of the public provided assessments of that spreadsheet in their submissions before the November 12, 2013 deadline for public comments.[14] Nevertheless, NAFEM now contends that the engineering spreadsheet was not provided early enough in the process and that the spreadsheet lacks certain information.

We previously expressed "reluctan[ce] to approve a regulation where … much of the information in support of the proposed rule was kept secret until after the hearing," *Granite*

[14] *See* App. R.6, Admin. R.65-A1 at 6; App. R.6, Admin. R.75-A1 at 4; App. R.6, Admin. R.85-A1 at 3.

City Steel Co. v. EPA, 501 F.2d 925, 927–28 (7th Cir. 1974), but we have never held that petitioners have a right to full notice and comment of the scientific data relied upon by the agency. Several of our sister circuits have held that "[a]mong the information that must be revealed for public evaluation are the technical studies and data upon which the agency relie[d]." *Chamber of Commerce v. SEC*, 443 F.3d 890, 899 (D.C. Cir. 2006) (internal quotation marks omitted); *Lloyd Noland Hosp. & Clinic v. Heckler*, 762 F.2d 1561, 1565 (11th Cir. 1985); *Wash. Trollers Ass'n v. Kreps*, 645 F.2d 684, 686 (9th Cir. 1981); *United States v. Nova Scotia Food Prods. Corp.*, 568 F.2d 240, 251–52 (2d Cir. 1977).[15]

This case presents no occasion for us to determine whether we ought to join these circuits. Here, an examination of the proceedings before the agency makes clear that the petitioners received adequate notice of the engineering spreadsheet. NAFEM first criticizes DOE for only providing the spreadsheet a month before final comments were due. However, NAFEM and the rest of the public had access to all of the spreadsheet's underlying data almost three months earlier when the technical support document was published. *See* App. R.6, Admin. R.51 at 5-1 to 5A-17. The spreadsheet simply organized this information in a different manner. We note as well that several members of the public provided meaningful

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15 *Cf. Am. Radio Relay League, Inc. v. FCC*, 524 F.3d 227, 246 (D.C. Cir. 2008) (Kavanaugh, J., concurring) (asking whether this requirement can "be squared with the text of § 553 of the APA" and *Vermont Yankee Nuclear Power Corp. v. Natural Resource Defense Council, Inc.*, 435 U.S. 519, 524 (1978)).

commentary in direct response to the spreadsheet by the November deadline.[16] NAFEM received sufficient notice of the applicable data and, consequently, had adequate opportunity to comment on that spreadsheet. *See* App. R.6, Admin. R.98.

NAFEM also submits that DOE was obliged to provide a spreadsheet that could be "manipulated" to permit manufacturers to ascertain how DOE's analysis would apply to specific products in their present or future inventories. In NAFEM's view, DOE should have been required to provide manufacturers with the capacity to insert data about their own units into the spreadsheet, so that they could "predict how [their] individual products would perform under the same analysis."[17] According to NAFEM, it should have been possible for manufacturers to manipulate the spreadsheet to account for volumes and total display areas different from the hypothetical model actually studied by DOE.

At the most fundamental level, this contention fails because it asks the DOE spreadsheet to perform a function different from the one for which it was designed. As we have noted earlier, DOE designed the spreadsheet to calculate the efficiency level of one specific hypothetical "representative unit," of a specific size, for each class of refrigeration equipment. App. R.6, Admin R.102 at 5-1 to 5-2. Relying on the data from its testing of the hypothetical unit, it then created a formula for determining the efficiency level of units of other sizes in the same class. *Id.* at 5-2 to 5-3. In creating that formula, DOE did *not* apply the calculations on the spreadsheet

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[16] *See supra* note 14.

[17] NAFEM Br. at 36.

to units of differing sizes. *See id.*

In any event, if a manufacturer wanted to determine the accuracy of the calculations in the engineering spreadsheet, it could have compared the spreadsheet's results for a given type of refrigeration product to units of the same type and size in its own product line. *See* App. R.6, Admin. R.98. Moreover, if a manufacturer wished to go further and test the accuracy of DOE's overall analysis, including the results that the analysis would produce for units of varying sizes, it could have looked to the actual energy efficiency standards provided by DOE in the notice of proposed rulemaking. *See* 78 Fed. Reg. at 55,892. If the manufacturer's product, when altered to conform to the energy standards proposed by DOE, could not reach those standards, the manufacturer would have cause to believe that DOE's underlying computations on the hypothetical model could not be replicated in the real world or were otherwise faulty. Petitioners were provided with a sufficient opportunity to see and comment upon technical data. There is no basis here for our disturbing the agency's decision.

2. Compressors

We now turn to the substance of DOE's engineering analysis. As we have discussed earlier, DOE modeled the effect of different component designs on energy efficiency in order to determine a technologically feasible energy consumption level for each class of CRE. NAFEM challenges DOE's modeling of one of those components: compressors.

DOE concluded "that two levels of technology were applicable for the compressor design option:" "standard single-speed hermetic compressors" and "high-efficiency single-speed hermetic compressors." App. R.6, Admin. R.102 at 5-33.

DOE could obtain "publicly-available performance data for standard single-speed hermetic compressors." *Id.* However, DOE pointed out, "[a]lthough several compressor manufacturers produce high-efficiency compressors, little data are currently available on their performance." *Id.* at 5-34.

Despite this absence of data, DOE initially estimated that high-efficiency compressors could achieve an efficiency level that was ten percent above the standard level. 79 Fed. Reg. at 17,760. According to the technical support document that was provided alongside the notice of proposed rulemaking, "DOE developed this multiplier through its own research, consultation with outside experts, and verification through discussion with commercial refrigeration equipment manufacturers." App. R.6, Admin. R.51 at 5-30; *see also* App. R.6, Admin. R.62 at 71 ("A general market-vetted, industry-vetted assumption of a ten percent improvement in compressor EER being feasible across the board at a five percent cost premium was used based on the input that we got from the industry."). However, subsequent comments from several manufacturers persuaded DOE to abandon its optimism and to expect lower performance during the compliance period. Several manufacturers suggested there could only be meager product improvement on the basis of present technology, and one manufacturer, the Danfoss group, suggested that only a two percent improvement in efficiency was realistic. 79 Fed. Reg. at 17,760. Accordingly, DOE estimated that a switch to high-efficiency compressors would yield energy savings only two percent above the standard model. *Id.*

This revision was not an "eyeball guesstimate." In altering its decision, DOE had the benefit of its earlier research as well as the commentary of the manufacturers. It therefore was confronted with significant warning that the state of the technology made its earlier estimation unrealistic. In short, the primary purpose of the notice and comment period functioned as it should have, and the agency was apprised of responsible opinions contrary to its own. "[A]n agency's change of course, so long as generally consistent with the tenor of its original proposals, indicates that the agency treats the notice-and-comment process seriously, and is willing to modify its position where the public's reaction persuades the agency that its initial regulatory suggestions were flawed." *Am. Med. Ass'n v. United States*, 887 F.2d 760, 767 (7th Cir. 1989).[18]

We also cannot fault DOE for placing significant weight on the view of the Danfoss group that "it would be reasonable to assume either continued use of efficient compressors available today, or alternatively a 1% to 2% efficiency improvement." App. R.6, Admin. R.61-A1 at 2; 79 Fed. Reg. at 17,760. The agency had a basis for considering this manufacturer to be a major supplier of CRE and one with significant institutional experience.[19] Moreover, in its letter, Danfoss stated its

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[18] *See also Kern Cty. Farm Bureau v. Allen*, 450 F.3d 1072, 1076 (9th Cir. 2006).

[19] NAFEM relatedly claims that DOE should have provided the public with an opportunity to respond to the Danfoss comment. We cannot accept this argument. "[T]he public gets to comment on the proposed rules, not on the agency's response to earlier public comments." *Nat. Res. Def. Council v. Jackson*, 650 F.3d 662, 666 (7th Cir. 2011). We would only entertain such an argument if "the revisions materially change the text, adding features that the commentators could not have anticipated." *Id.* Here, DOE initially proposed that some compressors could achieve an efficiency level that was *ten percent higher* than the standard compressor. The public clearly was on notice that DOE might issue a rule which assumed that

belief that the compressor technology available was "mature." App. R.6, Admin. R.61-A1 at 2. DOE therefore could conclude that product development on the basis of "existing technologies," 79 Fed. Reg. at 17,767, could be expected to be very slow during the compliance period. Relying on present technology would yield marginal improvement in compressor performance.

NAFEM nevertheless submits that the two percent increase is inconsistent with DOE's statement in the final rule "that existing technologies should be the basis of its engineering analysis." *Id.* We believe that is an uncharitable and unrealistic reading of the administrative record in its entirety. DOE simply concluded that the current state of the technology, including the increased use of high-efficiency compressors, would yield at least an incremental improvement. Such an incremental improvement "reflect[s] the options available to manufacturers of commercial refrigeration equipment." *Id.* at 17,760. DOE's decision may be questionable in the minds of some, but its decision is supported by substantial evidence and was reached through a reasoned decisionmaking process. "[O]ur role is limited; we require only that the agency acknowledge factual uncertainties and identify the considerations it found persuasive." *Rural Cellular Ass'n v. FCC*, 588 F.3d 1095, 1105 (D.C. Cir. 2009).

3. Insulation Foam Thickness

The petitioners also submit that DOE acted arbitrarily and capriciously when it modeled another component: insulation. DOE explained that increasing insulation foam thickness by a

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compressors could achieve an efficiency level that was *two percent higher* than the standard model.

half-inch was a viable design option for eight primary equipment classes of CRE. 79 Fed. Reg. at 17,749; App. R.6, Admin. R.102 at 5-43 to 5-67. However, the petitioners contend that increasing insulation is not an available design option because the "footprint" of a refrigerator or freezer is sometimes fixed due to limited floor space. In their view, increasing insulation either will decrease a unit's internal volume (which could prevent the storage of industry-standard sheets and pans at restaurants) or will increase its external dimensions (which could lead to narrower walkways and restrict the ability to move CRE units through doorways).

In promulgating the final rule, however, DOE explained that it had conducted manufacturer interviews during the rulemaking period and that the manufacturers had agreed that an extra half-inch of insulation was feasible. 79 Fed. Reg. at 17,749–50. DOE also noted that a number of models currently on the market were already using this thickness of insulation, which suggested that a product with this thickness of insulation was useful and marketable to consumers. *Id.* at 17,750. "DOE believe[d] that this serves as a proof of concept and that the resulting changes … would be of minimal impact to end users." *Id.* We must conclude that DOE's investigation of the situation clearly justifies its conclusion. The determination is supported by substantial evidence and certainly cannot be characterized as arbitrary and capricious.

Moreover, in promulgating the rule, DOE stated explicitly that manufacturers were "free to use different design paths in order to attain the performance levels required by today's rule," should they decide that increasing the thickness of insulation would not be a viable option for some of their consumers. *Id.* DOE noted, for example, that if a manufacturer determines that adding insulation is not a possible or desirable way to enhance energy performance, the manufacturers can instead implement enhanced evaporator coils, high-efficiency reciprocating compressors, and more effective vacuum insulated panels. *See* App. R.6, Admin. R.102 at 5-27, 5-32 to 5-34.

The petitioners point out that these recommended alternatives are not viable options for at least one class of CRE. *See id.* at 5-51, 10B-3 (describing the available design options for horizontal self-contained freezers without doors). They also contend that, for other classes, alternatives such as evaporator coils can result in frost buildup; that high-efficiency reciprocating compressors are noisy, expensive, and unreliable; and that vacuum insulated panels are prohibitively expensive. Even if these design options have their faults, however, they are still alternative solutions that manufacturers can choose in order to increase energy efficiency for the vast majority of CRE units. That one energy-saving solution is not feasible in one class of CRE does not prevent DOE from including it among the energy-saving devices that might be employed by the industry as a whole. Similarly, drawbacks in the other energy-saving devices do not prevent DOE from concluding that, for units in other classes, the industry may have to settle for a less-than-optimum situation to achieve the necessary conservation goals. In short, DOE was on solid ground in concluding that increasing the thickness of insulation was a feasible design option. That conclusion is worthy of deference.

AHRI and Zero Zone also contend that DOE acted capriciously by failing to address directly a comment submitted by AHRI during the rulemaking process. *See* App. R.6, Admin. R.75 at 5. The comment noted that the estimated costs related to improving the insulation of CRE were dramatically different from DOE's estimated costs of insulation in 2009. *Id.* We believe that DOE's response was entirely reasonable. It explained in the final rule that it "estimated the conversion costs associated with increases in foam thickness based on direct input from the industry in interviews, as well as through analysis of production equipment that is part of the engineering cost model." 79 Fed. Reg. at 17,775. The analysis, DOE noted, "included capital conversion costs, including … tooling costs and production line upgrades, and product conversion costs, including redesign efforts, testing costs, industry certifications, and marketing changes." *Id.* DOE's conclusions were based on *new* data; there was no reason to provide further justification for departing from the estimates it had made in 2009. There was a solid basis for DOE's determination. It was based on substantial evidence and can hardly be characterized as arbitrary or capricious.

4. Validation

Finally, the petitioners contend broadly that DOE's engineering analysis is not based on real-world application and therefore must be verified by testing actual equipment. This submission is governed by some basic principles. "That a model is limited or imperfect is not, in itself, a reason to remand agency decisions based upon it." *Appalachian Power Co. v. EPA*, 249 F.3d 1032, 1052 (D.C. Cir. 2001); *see also In re Polar Bear Endangered Species Act Listing & Section 4(d) Rule Litig.—MDL No. 1993*, 709 F.3d 1, 13 (D.C. Cir. 2013). Rather, we will remand only if the model "bears no rational relationship to the reality it purports to represent" or if the agency fails to "provide a full analytical defense" when the model is challenged. *Columbia Falls Aluminum Co. v. EPA*, 139 F.3d 914, 923 (D.C. Cir. 1998) (internal quotation marks omitted).

Our previous discussions go a long way toward answering this broad-brush assault on DOE's general manner of proceeding. As we have demonstrated throughout our earlier discussion, DOE provided a complete analytical defense to each of the challenges that were raised during the notice and comment period. Our review of the record gives us a high level of confidence that DOE was fully aware of the inherent difficulties of formulating regulations for real-world situations on the basis of a model. DOE correctly noted that "[i]nputs to the model included data from tangible sources such as manufacturer literature, manufacturer interviews, production facility tours, reverse engineering and teardown of existing products on the market, and tests of commercial refrigeration equipment and components." 79 Fed. Reg. at 17,763. DOE explained that its present analytical model was consistent with models used in at least three other final rules—including the 2009 CRE Standards Rule. *Id.* Indeed, in many respects, this process can be characterized as a continuing dialogue with the industry before the backdrop of DOE's earlier regulations.

The petitioners nevertheless contend that DOE acted arbitrarily and capriciously by failing to test its conclusions against a full range of actual CRE equipment. As an initial matter, we note that an agency need not "'justify [its] model on an *ad hoc* basis for every [unit] to which the model is applied.'" C*olumbia Falls Aluminum Co.*, 139 F.3d at 923 (quoting *Chemical Mfrs. Ass'n v. EPA*, 28 F.3d 1259, 1265 (D.C. Cir.

1994)). In any event, DOE performed validation testing on a representative sample of units:

> In response to the comments … that DOE perform validation testing to confirm the veracity of its model, at the final rule stage DOE procured a number of commercial refrigeration units currently on the market, including high-performance units featuring advanced designs. It gathered physical test data on each unit from certification directories and, in some cases, from independent laboratory tests conducted by DOE on the units. DOE then performed physical teardowns and inspection of the units to quantify the features and design attributes included in each model. Then, DOE used this empirically-determined data as inputs into its engineering model, allowing the model to simulate these specific manufacturer models as closely as possible. The results showed good alignment between the model outputs and the physical test results across a range of equipment classes and efficiencies, validating the abilities of the model.

79 Fed. Reg. at 17,763; *see also* App. R.6, Admin. R.102 at 5-40 to 5-41 ("The results of the energy consumption model were compared against the performance data gathered through testing or certification, and the two showed sound agreement, with the energy consumption model generally being slightly conservative (modeling the units as using slightly more energy than they consumed as tested)."). Further, "DOE utilized information from the ENERGY STAR and California Energy

Commission appliance databases as a point of comparison to its engineering analysis results." 79 Fed. Reg. at 17,763 (footnotes omitted). Although DOE did not provide data or further details of its validation testing, DOE did publish the web addresses for the appliance databases, which included the "certified data" that "DOE compared its results against … as a check." *Id.*

This is not a close call. We are convinced that DOE's engineering analysis, including its use of an analytical model, was neither arbitrary nor capricious.

B. Economic Analysis

The EPCA requires that efficiency standards be "economically justified." 42 U.S.C. § 6295(o)(2)(A). In addressing this statutory mandate, DOE established five different "trial standard levels," and determined which "level" would be economically and technologically feasible. *See* 79 Fed. Reg. at 17,738, 17,803. It originally proposed that the benefits of the second-highest level of standards would outweigh the costs. 78 Fed. Reg. at 55,948. After receiving public comment, it determined that the third-highest level would be more appropriate. 79 Fed. Reg. at 17,810. DOE concluded that this level of standards would produce a net benefit to consumers between $4.93 and $11.74 billion and reduce greenhouse gas emissions. *Id.* at 17,728–29, 17,780–11. Conversely, the new standards would cost manufacturers between $93.9 and $165 million. *Id.* at 17,795–96. DOE determined therefore that the standards were justified. *Id.* at 17,810–11. The petitioners fault DOE's economic analysis in several ways. We now address each of those arguments.

1. Elasticity

The petitioners first contend that DOE acted arbitrarily and capriciously when it assumed that the new standards would not result in significant changes in purchasing behavior. DOE essentially treated CRE as "price inelastic," meaning that an increase in the price of CRE would not impact the amount of CRE purchased. *See* 79 Fed. Reg. at 17,770. The petitioners object to that assumption, noting that consumers could refurbish used equipment or switch to cheaper, less-efficient models of CRE.

Our review of the record convinces us that DOE's consideration of this issue was certainly more balanced and careful than the petitioners suggest. DOE explained in the New Standards Rule that it "did not have enough information on CRE customer behavior to explicitly model" the effects of the new standards on demand, and therefore it had to make a prediction about the market for CRE. *Id.*[20] In its technical support document, DOE reasoned:

> In general, when the data are available[,] DOE incorporates a purchase price elasticity into the shipments model. This allows for the possibility that total shipments will fall under a standard, due to a rise in the first cost of the equipment. For commercial refrigeration equipment, DOE

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[20] DOE made clear, during a public hearing, that more information was needed to measure price elasticity, and told industry leaders that "if you can supply that information, then we can incorporate that into our models." App. R.6, Admin. R.62 at 220–21. That information was never provided. 79 Fed. Reg. at 17,770.

> did not have access to any data that would allow the estimation of purchase price elasticities. Therefore the total shipments in the standards case scenarios are the same as the total shipments in the base case scenario. As most users of this equipment are subject to health codes and other regulations, it is not very likely that a business owner would forego the purchase of needed equipment even under a price increase. Price sensitivity is more likely to occur in the form of increased equipment lifetimes. However, equipment lifetimes for food sales and service are driven primarily by the remodeling cycle, and so are unlikely to be affected on the average by a standard.

App. R.6, Admin. R.102 at 9-8 to 9-9.

DOE's analysis hardly is arbitrary and capricious. A business must store food at a proper temperature in order to comply with health code regulations. Consequently, in DOE's view, restaurants and other businesses will purchase CRE regardless of its price. A refrigerator cannot easily be substituted. DOE reasonably concluded that CRE is a "necessity" for restaurants and other businesses, which makes demand relatively inelastic.[21] That conclusion is worthy of our deference.

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[21] *See Crystal Semiconductor Corp. v. TriTech Microelecs. Int'l, Inc.*, 246 F.3d 1336, 1359 (Fed. Cir. 2001) ("[I]f substitution of a product were impossible and the product were a necessity, elasticity of demand would be zero … .").

The petitioners note that businesses could refurbish used equipment and that this ability to "substitute" proves that the market for CRE is elastic. Indeed, in the New Standards Rule, "DOE acknowledge[d] that increases in price due to amended standards *could* lead to more refurbishing of equipment (or purchase of used equipment)." 79 Fed. Reg. at 17,770 (emphasis added). DOE simply decided "that the extent of refurbishing would not be so significant as to change the ranking of the [trial standard levels] considered for today's rule." *Id.* DOE has the authority "to make such a prediction about the market it regulates, and a reasonable prediction deserves our deference notwithstanding that there might also be another reasonable view." *Envtl. Action, Inc. v. FERC*, 939 F.2d 1057, 1064 (D.C. Cir. 1991); *see also White Eagle Coop. Ass'n v. Conner*, 553 F.3d 467, 475 (7th Cir. 2009).

The petitioners also suggest that businesses could switch to more affordable and less efficient CRE. The trend in the CRE market has been towards more efficient "closed" equipment with transparent doors and away from "open" equipment that does not have doors. *See* 79 Fed. Reg. at 17,770. The petitioners contend that the new standards will reverse that trend, as closed equipment will lose its utility. DOE acknowledged this concern in the New Standards Rule. DOE pointed out that at least one manufacturer "had not observed a reversal of the trend toward closed units in response to previous efficiency standards." *Id.* DOE also responded to one of the stakeholders' major concerns that the use of triple-pane coated glass would reduce the visibility of objects in a CRE unit and thus decrease the utility of a closed unit. *Id.* DOE explained that the new standards "do not require triple-pane coated glass." *Id.* DOE thus concluded that the new standards would not reverse the consumer trend toward closed equipment. *Id.*

Without evidence that contradicts DOE's assumptions, we cannot conclude that DOE's conclusions were "so implausible that it could not be ascribed to a difference in view or the product of agency expertise." *Nat'l Ass'n of Home Builders*, 551 U.S. at 658 (internal quotation marks omitted); *see also USA Grp. Loan Servs., Inc., v. Riley*, 82 F.3d 708, 714 (7th Cir. 1996); *W. Fuels-Ill., Inc.*, 878 F.2d at 1030. The petitioners have failed to show that DOE acted arbitrarily or capriciously when it determined that CRE was price inelastic.

2. Environmental Benefits

DOE considered the environmental benefits of the amended standards when determining whether the New Standards Rule was "economically justified." 79 Fed. Reg. at 17,738. In particular, DOE employed "an estimate of the monetized damages associated with an incremental increase in carbon emissions in a given year," known as the Social Cost of Carbon ("SCC"). *Id.* at 17,777.[22] The petitioners contend that the EPCA does not allow DOE to consider environmental factors and that DOE abused its discretion when it considered them. In the alternative, the petitioners contend that DOE's analysis of the SCC was itself arbitrary and capricious.

We turn first to DOE's statutory authority under the EPCA. An agency decision is arbitrary and capricious when

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22 The estimate "include[s] (but is not limited to) changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services." 79 Fed. Reg. at 17,777.

the agency "has relied on factors which Congress had not intended it to consider." *Nat'l Ass'n of Home Builders*, 551 U.S. at 658 (internal quotation marks omitted). Here, however, the EPCA specifically *requires* DOE to consider "the need for national energy … conservation." 42 U.S.C. § 6295(o)(2)(B)(i)(VI). In the New Standards Rule, DOE explained that the "Need of the Nation to Conserve Energy" includes the "potential environmental benefits" which would result. 79 Fed. Reg. at 17,738 (citing the Rule's subsection on SCC). To determine whether an energy conservation measure is appropriate under a cost-benefit analysis, the expected reduction in environmental costs needs to be taken into account.[23] We have no doubt that Congress intended that DOE have the authority under the EPCA to consider the reduction in SCC.[24]

Alternatively, AHRI and Zero Zone contend that DOE's calculation of SCC was irredeemably flawed. They submit that DOE failed to address three concerns about these calculations raised by the Chamber of Commerce in a letter during

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[23] This argument is highlighted by an amicus brief submitted by the Institute for Policy Integrity at New York University School of Law. The petitioners argue that we should strike the amicus brief from the record. That motion is denied.

[24] Although we need not reach these questions today, DOE probably also had the authority to consider environmental benefits under 42 U.S.C. § 6295(o)(2)(B)(i)(I), which allows the agency to consider "the economic impact of the standard on the manufacturers and on the consumers of the products subject to such standard." Environmental benefits have an economic impact. Further, DOE would have the authority to consider environmental benefits under 42 U.S.C. § 6295(o)(2)(B)(i)(VII), which allows DOE to consider "other factors the Secretary considers relevant."

the notice and comment period. *See* App. R.6, Admin. R.79-A2.[25] That letter complained that: (1) who exactly worked on the SCC analysis had not been made public, *id.* at 5–7; (2) the inputs to the models were not peer reviewed, *id.* at 7–9; and (3) the "damages functions," or variables based on problems like sea level rise, were determined in an arbitrary manner, *id.* at 12. DOE responded to the letter in general, noting that it "acknowledge[d] the limitations in the SCC estimates." 79 Fed. Reg. at 17,779. DOE then referenced letters from multiple parties that supported the SCC values, a 2010 interagency group report on the discount rates used, and the OMB's Final Information Quality Bulletin for Peer Review. *Id.* Although DOE did not respond to the specific points laid out in the Chamber of Commerce letter, it did respond to the Chamber of Commerce's general concerns and made clear that, despite those concerns, the calculation of SCC could be used. *See St. James Hosp. v. Heckler*, 760 F.2d 1460, 1469 (7th Cir. 1985). DOE's determination of SCC was neither arbitrary nor capricious.

3. Cost-Benefit Analysis

The petitioners raise a series of objections to DOE's general approach to weighing the costs and benefits of its new standards. In their view, DOE's analysis overestimated the benefits of the new rule and underestimated its costs.

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[25] AHRI and Zero Zone frame this issue as a violation of the Information Quality Act. *See* 44 U.S.C. § 3516 note (a). However, "almost every court that has addressed an Information Quality Act challenge has held that the statute 'creates no legal rights in any third parties.'" *Miss. Comm'n on Envtl. Quality v. EPA*, 790 F.3d 138, 184 (D.C. Cir. 2015) (quoting *Salt Inst. v. Leavitt*, 440 F.3d 156, 159 (4th Cir. 2006)). That being said, the APA still affords the petitioners the right to bring this challenge.

The petitioners first contend that DOE arbitrarily considered indirect *benefits* like carbon reduction over hundreds of years but ignored indirect *costs* like the long-term effects on displaced workers. DOE fully responded to that objection in the New Standards Rule:

> AHRI stated that DOE calculates the present value of the costs of standards to consumers and manufacturers over a 30-year period, but the SCC values reflect the present value of future climate related impacts well beyond 2100. AHRI stated that DOE's comparison of 30 years of cost to hundreds of years of presumed future benefits is inconsistent and improper. (AHRI, No. 84 at p.12)
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> For the analysis of national impacts of the proposed standards, DOE considered the lifetime impacts of equipment shipped in a 30-year period. With respect to energy and energy cost savings, impacts continue past 30 years until all of the equipment shipped in the 30-year period is retired. With respect to the valuation of CO_2 emissions reductions, the SCC estimates developed by the interagency working group are meant to represent the full discounted value (using an appropriate range of discount rates) of emissions reductions occurring in a given year. DOE is thus comparing the costs of achieving the emissions reductions in each year of the analysis, with the carbon reduction value of the emissions reductions in those same years. Nei-

> ther the costs nor the benefits of emissions reductions outside the analytic time frame are included in the analysis.

79 Fed. Reg. at 17,779. DOE further explained in the technical support document that these standards "should lead to upward pressure on wages and a shift in employment away from electricity generation towards consumer goods. Note that in long-run equilibrium there is no net effect on total employment since wages adjust to bring the labor market into equilibrium." App. R.6, Admin. R.102 at 16-3.[26] DOE therefore found that the reduction of carbon over thirty years would have long-term effects on the environment but that the increased costs over thirty years would not have long-term effects on employment. The petitioners may disagree with the merits of DOE's conclusion, but DOE's analysis is neither arbitrary nor capricious.

AHRI and Zero Zone next contend that DOE arbitrarily considered the *global* benefits to the environment but only considered the *national* costs. They emphasize that the EPCA only concerns "national energy and water conservation." 42 U.S.C. § 6295(o)(2)(B)(i)(VI). In the New Standards Rule, DOE did not let this submission go unanswered. It explained that climate change "involves a global externality," meaning that carbon released in the United States affects the climate of the entire world. 79 Fed. Reg. at 17,779. According to DOE, national energy conservation has global effects, and, therefore, those global effects are an appropriate consideration when looking at a national policy. *Id.* Further, AHRI and Zero Zone

[26] *See also* 79 Fed. Reg. at 17,780 (referring to this section of the technical support document).

point to no global costs that should have been considered alongside these benefits. Therefore, DOE acted reasonably when it compared global benefits to national costs.

Finally, AHRI and Zero Zone criticize DOE's determination of discount rates for CRE in its cost estimate. DOE used the "Capital Asset Pricing Model" ("CAPM") to estimate the cost of equity financing. The CAPM assumes that the cost of equity is proportional to the amount of systemic risk of failure associated with a company. The model therefore estimates the overall risks and returns for all of a firm's capital, rather than the risks and returns associated with one specific asset. The petitioners, however, believe that DOE should have used a model specific to the risks and returns of CRE. They contend that DOE did not adequately respond to a comment from the Mercatus Center at George Mason University, which urged DOE to adopt an analysis of capital costs that was particular to CRE.[27] However, DOE addressed the Mercatus comment in the New Standards Rule in sufficient detail:

> The cost of capital is commonly used to estimate the present value of cash flows to be derived from a typical company project or investment, and the CAPM is among the most widely

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[27] Specifically, the Mercatus comment urged that a more particularized model was appropriate because (1) CRE has a higher depreciation rate than other products (meaning it will decrease in value quicker), and (2) CRE has a lower salvage value than other products (meaning that it cannot be resold as easily). App. R.6, Admin. R.72-A1 at 2–3. If CRE decreases in value at a faster rate than the average product, and if CRE cannot be resold as easily as the average product, then a company may be less willing to purchase CRE at a higher price than other products at a higher price.

> used models to estimate the cost of equity financing. The types of risk mentioned by Mercatus may exist, but the cost of equity financing tends to be high when a company faces a large degree of systemic risk, and it tends to be low when the company faces a small degree of systemic risk. DOE's approach estimates this risk for the set of companies that could purchase [CRE].

Id. at 17,767. DOE considered the point and concluded that the cost of equity financing is commonly determined at the firm-wide level rather than unit-by-unit. *Id.* Therefore, the CAPM provided an appropriate estimate of the cost of equity financing. DOE's choice of economic model was neither arbitrary nor capricious.[28]

4. Anticompetitive Effects

The petitioners contend that DOE's consideration of anticompetitive effects was both substantively and procedurally arbitrary and capricious. In its cost-benefit analysis, DOE

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[28] When discussing the Mercatus comment, AHRI and Zero Zone also contend that DOE was required to identify a "market failure" that justified the amended efficiency standards. AHRI Br. 30; AHRI Reply Br. 22. The petitioners rely on *Schurz Commc'ns, Inc. v. FCC*, 982 F.2d 1043 (7th Cir. 1992) for this proposition. In *Schurz*, however, the agency had previously ruled that it could "not intervene in the market except where there is evidence of a market failure." *Id.* at 1053 (internal quotation marks omitted). The agency therefore was bound by its previous ruling. *Id.* Here, the EPCA merely requires DOE to promulgate standards which are "technologically feasible and economically justified." 42 U.S.C. § 6295(o)(2)(A). The petitioners point to no statute or agency rule that requires DOE to identify a market failure. Therefore, their argument is without merit.

must consider the anticompetitive effects of its proposed rule "as determined in writing by the Attorney General." 42 U.S.C. § 6295(o)(2)(B)(i)(V). Pursuant to this provision, the Assistant Attorney General for the Antitrust Division, acting on behalf of the Attorney General, sent DOE a letter (the "DOJ letter"). The letter stated that "the proposed energy conservation standards for commercial refrigeration equipment [we]re unlikely to have a significant adverse impact on competition." 80 Fed. Reg. at 44,892. DOE relied on this letter in the New Standards Rule and considered the Attorney General's determination in its cost-benefit analysis. 79 Fed. Reg. at 17,803. The petitioners contend that the DOJ letter does not articulate adequately the reasoning behind the Attorney General's determination. They also contend that both the DOJ letter's submission to DOE and its publication to the Federal Register were untimely.

As originally enacted, the EPCA instructed the rulemaking agency (then the FEA, now DOE) to consider anticompetitive effects in its cost-benefit analysis. Pub. L. No. 94-163, § 325, 89 Stat. at 924–25.[29] However, the rulemaking agency

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[29] The EPCA originally read:

> (D) For purposes of subparagraph (B), improvement of energy efficiency is economically justified if it is economically feasible the benefits of reduced energy consumption, and the savings in operating costs throughout the estimated average life of the covered product, outweigh—
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> …
>
> (iii) any negative effects on competition.

was not given the authority to determine anticompetitive effects on its own. Instead, only the Attorney General could determine the extent of a regulation's impact on competition. § 625, 89 Stat. at 925. The Attorney General would only make such a determination "on request of the Administrator, the Commission, or any person, or on his own motion." *Id.* If the Attorney General decided not to submit a letter with his or her assessment of anticompetitive effects, then the agency could not consider anticompetitive effects at all.

Three years after the EPCA's enactment, these clauses were amended to their current form. Pub. L. No. 95-619, § 422, 92 Stat. at 3259–60. Under the EPCA as amended, the Attorney General always makes a determination about a proposed rule's anticompetitive effects.[30] That determination is submit-

> (E) For purposes of subparagraph (D)(iii), the Administrator shall not determine that there are any negative effects on competition, unless the Attorney General (on request of the Administrator, the Commission, or any person, or on his own motion) makes such determination and submits it in writing to the Administrator, together with his analysis of the nature and extent of such negative effects. The determination of the Attorney General shall be available for public inspection.

Energy Policy and Conservation Act, Pub. L. No. 94-163, § 325, 89 Stat. 871, 924–25 (1975).

[30] According to the EPCA:

> (i) In determining whether a standard is economically justified, the Secretary shall, after receiving views and comments furnished with respect to the proposed standard, determine whether the benefits of the standard exceed its

ted to DOE within sixty days of the publication of the proposed rule. 42 U.S.C. § 6295(o)(2)(B)(ii). DOE must then consider the "lessening of competition, as determined in writing by the Attorney General," in its overall cost-benefit analysis. *Id.* § 6295(o)(2)(B)(i)(V). DOE then publishes the letter in the Federal Register. *Id.* § 6295(o)(2)(B)(ii). Just like its predecessor, the amended EPCA does not grant DOE the authority to alter DOJ's conclusions or to determine anticompetitive effects on its own.

The petitioners contend that the DOJ letter provided insufficient reasoning and that DOE therefore erred in relying on this letter. We cannot accept this argument. DOE's reliance on the DOJ letter was clearly consistent with its secondary

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> burdens by, to the greatest extent practicable, considering—
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> > …
> >
> > (V) the impact of any lessening of competition, as determined in writing by the Attorney General, that is likely to result from the imposition of the standard;
> >
> > …
>
> (ii) For purposes of clause (i)(V), the Attorney General shall make a determination of the impact, if any, of any lessening of competition likely to result from such standard and shall transmit such determination, not later than 60 days after the publication of a proposed rule prescribing or amending an energy conservation standard, in writing to the Secretary, together with an analysis of the nature and extent of such impact. Any such determination and analysis shall be published by the Secretary in the Federal Register.

42 U.S.C. § 6295(o)(2)(B).

role under this provision of the EPCA. DOE's statutory duty under the EPCA is to defer to the Attorney General. The New Standards Rule makes clear that DOE acted in complete accordance with the statute:

> EPCA directs DOE to consider any lessening of competition that is likely to result from standards. It also directs the Attorney General of the United States (Attorney General) to determine the impact, if any, of any lessening of competition likely to result from a proposed standard and to transmit such determination to the Secretary within 60 days of the publication of a proposed rule and simultaneously proposed rule, together with an analysis of the nature and extent of the impact. (42 U.S.C. 6295(o)(2)(B)(i)(V) and (B)(ii)) To assist the Attorney General in making a determination for CRE standards, DOE provided the Department of Justice (DOJ) with copies of the [notice of proposed rulemaking] and the [technical support document] for review. DOE received no adverse comments from DOJ regarding the proposal.

79 Fed. Reg. at 17,803. DOE did exactly what the EPCA instructs. Once it published the notice of proposed rulemaking, it awaited the Attorney General's assessment of the effect on competition. In fact, DOE provided the Attorney General with additional information—in a technical support document—so that it could receive a more informed determination. After reviewing this document, the transcript of the public meeting, and other "supplementary information," DOJ provided a response that articulated enough information to

allow DOE to adequately consider anticompetitive effects. *See* 80 Fed. Reg. at 44,892. DOE then considered this "relevant factor[]," among the other statutory factors, in its cost-benefit analysis. *Citizens to Preserve Overton Park v. Volpe*, 401 U.S. 402, 416 (1971); *see also* 42 U.S.C. § 6295(o)(2)(B)(i)(V). Under the EPCA, DOE could do no more. We are convinced that DOE's approach was neither arbitrary nor capricious. *Motor Vehicle Mfrs. Ass'n*, 463 U.S. at 43.

We must also determine whether the submission and publication of the DOJ letter were "without observance of procedure required by law." 5 U.S.C. § 706(2)(D). AHRI and Zero Zone contend that the DOJ letter was submitted to DOE after the EPCA's deadline. They also contend that the DOJ letter was untimely published in the Federal Register.

Under the EPCA, the Attorney General is required to submit its letter "not later than 60 days after the publication of a proposed rule." 42 U.S.C. § 6295(o)(2)(B)(ii). However, the Assistant Attorney General for Antitrust did not respond to DOE until *75 days* after the notice of proposed rulemaking. 80 Fed. Reg. at 44,892. Although DOJ erred when it submitted the letter fifteen days late, the error was harmless. "[D]ue account shall be taken of the rule of prejudicial error." 5 U.S.C. § 706. "[I]f we are sure that the agency would if we remanded the case reinstate its decision—if in other words the error in its decision was harmless—a reversal would be futile … ." *People of the State of Ill. v. ICC*, 722 F.2d 1341, 1348 (7th Cir. 1983); *see also Spiva v. Astrue*, 628 F.3d 346, 353 (7th Cir. 2010). Further, "[w]e will not invalidate [an agency] decision based on procedural error unless the errors alleged could have affected the outcome." *Zevallos v. Obama*, 793 F.3d 106, 115 (D.C. Cir. 2015). The DOJ letter was submitted on November 25,

2013. *See* 80 Fed. Reg. at 44,892. The final rule was not published until several months later, on March 28, 2014. 79 Fed. Reg. at 17,726. DOE had enough time to consider fully the Attorney General's determination of anticompetitive effects and to factor that determination into its cost-benefit analysis. Indeed, DOE fully considered the DOJ letter in its final rule. *Id.* at 17,803.

The petitioners note that the DOJ letter was submitted thirteen days after the period for public comment had closed; the public therefore was denied the opportunity to respond to the Attorney General's analysis. However, this lack of time for public comment does not render the procedural error harmful. Under the EPCA, the notice and comment period shall last "not less *than 60 days*" after publication of the notice of proposed rulemaking. 42 U.S.C. § 6295(p)(2) (emphasis added). However, the DOJ must submit its letter within sixty days of the publication of the notice of proposed rulemaking. *Id.* § 6295(o)(2)(B)(ii). Had Congress intended the public to have the opportunity to respond to the DOJ letter, it would have imposed its deadline for submission of the letter *before* the end of any notice and comment period. Instead, Congress imposed a deadline that ensured DOE—but not necessarily the public—had enough time to consider the letter. We are convinced that this procedural error did not impair DOE's ability to consider anticompetitive effects and we will not reverse on this basis.

The EPCA also states that "[a]ny such determination and analysis shall be published by the Secretary in the Federal Register." *Id.* Here, DOE did not publish the DOJ letter until July 28, 2015, which the petitioners contend was untimely.

However, the EPCA does not impose a deadline for publication. In the absence of any statutory language imposing such a requirement, we cannot hold that the delayed publication of this letter was "without observance of procedure required by law." 5 U.S.C. § 706(2)(D).

C. Regulatory Flexibility Analysis

The petitioners' concerns about the New Standards Rule's anticompetitive effects also were addressed, in part, by DOE's discussion of the standards' impact on small businesses. The Regulatory Flexibility Act ("RFA"), 5 U.S.C. § 601 *et seq.*, requires agencies to assess the effect of their rules on small entities. Under the RFA, "[w]hen an agency promulgates a final rule under section 553 of this title, … the agency shall prepare a final regulatory flexibility analysis." 5 U.S.C. § 604(a). Accordingly, DOE included such an analysis in its final rule. 79 Fed. Reg. at 17,812–14. In that analysis, DOE acknowledged that "[s]mall firms would likely be at a disadvantage," but it determined that no alternative program would be viable. *Id.* at 17,814.

The petitioners contend that DOE's final regulatory flexibility analysis failed to comply with the RFA. The RFA requires a final regulatory flexibility analysis to include, in relevant part:

> [A] description of the steps the agency has taken to minimize the significant economic impact on small entities consistent with the stated objectives of applicable statutes, including a statement of the factual, policy, and legal reasons for selecting the alternative adopted in the final

> rule and why each one of the other significant alternatives to the rule considered by the agency which affect the impact on small entities was rejected.

5 U.S.C. § 604(a)(6). At the outset, we note that "the Act does not require rules that are less burdensome for small businesses;" it instead requires that "agencies … explain why any such alternatives were rejected." *Council for Urological Interests v. Burwell*, 790 F.3d 212, 226 (D.C. Cir. 2015). When reviewing an agency's compliance with the RFA, we ask whether the agency's analysis "demonstrat[es] a 'reasonable, good-faith effort to carry out [the RFA's] mandate.'" *U.S. Cellular Corp. v. FCC*, 254 F.3d 78, 88 (D.C. Cir. 2001) (quoting *Alenco Commc'ns, Inc. v. FCC*, 201 F.3d 608, 625 (5th Cir. 2000).[31]

In its final regulatory flexibility analysis, DOE identified thirty-two CRE manufacturers that met the definition of a small business, and it interviewed four of those manufacturers. 79 Fed. Reg. at 17,813. DOE concluded that "small businesses will likely have greater increases in component costs than large businesses," and "may have greater difficulty obtaining credit." *Id.* After reaching this conclusion, DOE considered several different policy alternatives, including: "(1) [n]o change in the standard; (2) consumer rebates; (3) consumer tax credits; (4) manufacturer tax credits; (5) voluntary energy efficiency targets; and (6) bulk government pur-

[31] *See also Ranchers Cattlemen Action Legal Fund United Stockgrowers of Am. v. U.S. Dep't of Agric.*, 415 F.3d 1078, 1101 (9th Cir. 2005); *Associated Fisheries, Inc. v. Daley*, 127 F.3d 104, 114 (1st Cir. 1997).

chases." *Id.* at 17,814. Those policy alternatives were discussed in detail in the technical support document.[32] After considering each alternative, "DOE determined that the energy savings of these alternatives are significantly smaller than those that would be expected to result from adoption of the amended standard levels," and it opted not to adopt any of the alternatives. *Id.*

The petitioners nevertheless note that DOE failed to consider an exemption for small businesses in its final regulatory flexibility analysis. Under § 604 of the RFA, an agency must discuss "each one of the other significant alternatives" in its final regulatory flexibility analysis. 5 U.S.C. § 604. The RFA does not require that an agency "address every alternative, but only that it address significant ones." *Associated Fisheries, Inc. v. Daley*, 127 F.3d 104, 115 (1st Cir. 1997); *see also Ranchers Cattlemen Action Legal Fund United Stockgrowers of Am. v. U.S. Dep't of Agric.*, 415 F.3d 1078, 1102 (9th Cir. 2005). In the petitioners' view, a small business exemption constitutes a significant alternative and must be considered.

Section 604 does not define what the RFA considers to be "significant" alternatives. *See* 5 U.S.C. § 604. However, when describing an agency's duty to write an *initial* regulatory flexibility analysis, § 603 states that:

> Consistent with the stated objectives of applicable statutes, the analysis shall discuss *significant alternatives* such as—
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> (1) the establishment of differing compliance or reporting requirements or timetables that

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[32] App. R.6, Admin. R.66 at 17-1 to 17-A-20.

> take into account the resources available to small entities;
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> (2) the clarification, consolidation, or simplification of compliance and reporting requirements under the rule for such small entities;
>
> (3) the use of performance rather than design standards; and
>
> (4) *an exemption from coverage of the rule*, or any part thereof, *for such small entities*.

Id. § 603(c) (emphases added). According to the petitioners, agencies must also consider all four of these "significant alternatives" in their *final* regulatory flexibility analysis. Therefore, the petitioners contend, by not considering one of the alternatives listed in § 603 during its final analysis, DOE failed to comply with its obligation under § 604 of the RFA.[33]

Section 603 of the RFA limits the definition of a "significant alternative" to one which is "[c]onsistent with the stated

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[33] To the extent that the petitioners are raising a specific claim that DOE failed to comply with § 603 of the RFA, we note that their claim is not reviewable:

> Section 611(c) of the RFA provides that "[c]ompliance or noncompliance by an agency with the provisions of this chapter shall be subject to judicial review *only* in accordance with this section." 5 U.S.C. § 611(c) (emphasis added). Section 611(a)(2) grants this court "jurisdiction to review any claims of noncompliance with sections 601, 604, 605(b), 608(b), and 610." 5 U.S.C. § 611(a)(2).

Nat'l Ass'n of Home Builders v. EPA, 682 F.3d 1032, 1041 (D.C. Cir. 2012); *see also Allied Local & Reg'l Mfrs. Caucus v. EPA*, 215 F.3d 61, 79 (D.C. Cir. 2000).

objectives of applicable statutes." *Id.* § 603(c). Therefore, to determine the merits of petitioners' argument, we must first consider the objectives of the EPCA. One of the EPCA's stated "purposes" is to "provide Federal energy conservation standards applicable to covered products." 42 U.S.C. § 6295(a)(1). The EPCA contemplates exemptions for small manufacturers. *Id.* § 6295(t). However, those exemptions are temporary, lasting for a "period not longer than the 24-month period beginning on the date such rule becomes effective." *Id.* § 6295(t)(1). In addition, an exemption will only be made "on application of [the] manufacturer" and only after DOE investigates the unique circumstances of that manufacturer. *Id.* Further, the exemption can only be provided after DOE "makes a finding, after obtaining the written views of the Attorney General, that a failure to allow an exemption … would likely result in a lessening of competition." *Id.* § 6295(t)(2). These provisions make clear that the EPCA's objective is to impose consistent, national standards for each class of covered product. Exceptions to those standards are only allowed for short periods of time, and only after consultation with the Attorney General. A blanket exemption—made without any temporal limitation, any applications from manufacturers, or any input from the Attorney General—would be "[inc]onsistent with the stated objectives of" the EPCA. *See* 5 U.S.C. § 603(c). Therefore, a blanket exemption for small businesses was not a significant alternative that DOE needed to consider.

DOE made a "good-faith effort" to describe both the impact of its amended standard on small businesses and the significant alternatives it considered. *U.S. Cellular Corp.*, 254 F.3d at 88. Therefore, its final regulatory flexibility analysis fully complied with the RFA.

D. Cumulative Regulatory Burden

The petitioners contend that DOE failed to properly consider the impact of two other regulatory burdens on CRE manufacturers: EPA's Significant New Alternatives Policy ("SNAP") Rule and the ENERGY STAR Program. According to DOE Process Rule 10(g), DOE must consider the cumulative impacts of other federal regulations. 10 C.F.R. pt. 430, subpt. C, app. A, at 10(g) (2016). DOE decided that neither the SNAP rule nor the ENERGY STAR Program warranted a change in its regulations. 79 Fed. Reg. at 17,754, 17,798. Therefore, we must determine whether DOE has "articulate[d] a satisfactory explanation for its action including a rational connection between the facts found and the choice made." *Motor Vehicle Mfrs. Ass'n*, 463 U.S. at 43 (internal quotation marks omitted).

1. EPA Significant New Alternatives Policy Program

We first turn to EPA's proposed SNAP rulemaking. At the time of DOE's rulemaking, EPA was reviewing the refrigerants R404 and R134a and was considering removing those refrigerants from commercial refrigeration applications. 79 Fed. Reg. at 17,754.[34] Both R404 and R134a were used in DOE's en-

[34] EPA published its final rule on refrigerants more than a year after the New Standards Rule. *See* 80 Fed. Reg. 42,870 (July 20, 2015). In the rule, EPA noted that:

> We do, however, consider issues such as technical needs for energy efficiency (*e.g.,* to meet DOE standards) in determining whether alternatives are "available." EPA recognizes that the energy efficiency of particular models of

gineering analysis. *Id.* NAFEM contends that, based on a potential SNAP rule that EPA was considering, DOE should have considered refrigerants other than R404 and R134a.

Responding to this critique, DOE explained that "there are currently no mandatory initiatives such as refrigerant phase-outs," *id.*, and that "DOE does not include the impacts of pending legislation or unfinalized regulations in its analyses, as any impact would be speculative," *id.* at 17,775. Indeed, EPA did not even issue a notice of proposed rulemaking regarding the SNAP program until months after DOE's final rule. *See* 79 Fed. Reg. 46,126 (Aug. 6, 2014). "In circumstances involving agency predictions of uncertain future events, complete factual support in the record for [an agency's] judgment or prediction is not possible or required since a forecast of the direction in which future public interest lies necessarily involves deductions based on the expert knowledge of the

> equipment is a significant factor when choosing equipment. We also recognize that the energy efficiency of any given piece of equipment is in part affected by the choice of refrigerant and the particular thermodynamic and thermophysical properties that refrigerant possesses. Although we cannot know what energy efficiency will be achieved in future products using a specific acceptable refrigerant, we can point to both actual equipment and testing results that show promise and often better results than the equipment using the refrigerants that we are finding unacceptable.

Id. at 42,921. After assessing the impact of the New Standards Rule, EPA went on to extend the "change of status" date for certain units. *See id.* at 42,908, 42,916–17.

agency." *Rural Cellular Ass'n*, 588 F.3d at 1105 (internal quotation marks omitted). DOE's determination that the SNAP rulemaking might not come to fruition is entirely reasonable, and it is certainly within its discretion.[35]

Further, DOE explained that even if it assumed the SNAP rulemaking would become binding, it did not have adequate "publicly-available data on the design, construction, and operation of equipment featuring alternative refrigerants to facilitate the level of analysis of equipment performance which would be needed." 79 Fed. Reg. at 17,754. NAFEM finds this rationale inadequate; it contends that DOE should have relied on data regarding the use of alternative refrigerants in Europe. However, NAFEM does not point to any comment that raised this issue before the agency during the notice and comment period. Further, DOE notes that the basic design of CRE in Europe differs from CRE in the United States, making that data unreliable. In light of the deference due to DOE, *White Eagle Coop. Ass'n*, 553 F.3d at 474, DOE's decision to ignore the EPA SNAP rulemaking was not arbitrary or capricious.[36]

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[35] As part of their objection to DOE's consideration of carbon benefits, AHRI and Zero Zone criticize DOE's decision to ignore the impact of the EPA's proposed power plant rule on greenhouse gas emissions. For the same reasons noted above, DOE was entirely within reason to disregard the impact of this pending regulatory action.

[36] We observe that DOE provided a remedy for any CRE manufacturers that are unduly impacted by the burden of subsequent regulation. In the New Standards Rule, DOE explained that "[i]f a manufacturer believes that its design is subjected to undue hardship by regulations, the manufacturer may petition" DOE, which "has the authority to grant … relief on a case-by-case basis." 79 Fed. Reg. at 17,754.

2. ENERGY STAR Program

NAFEM also contends that DOE failed to take account of the ENERGY STAR program. ENERGY STAR is a program that provides voluntary certifications and ratings to energy efficient products as a way to incentivize manufacturers. 79 Fed. Reg. at 17,739. DOE noted that the program was "voluntary for manufacturers. As such, [it is] not part of DOE's consideration of cumulative regulatory burden." *Id.* at 17,798. That determination was entirely reasonable. DOE's decision not to consider ENERGY STAR was neither arbitrary nor capricious.

In sum, DOE satisfied its duty laid out in Process Rule 10(g). 10 C.F.R. pt. 430, subpt. C, app. A. Neither the possibility of a SNAP rulemaking nor the ENERGY STAR program needed to be considered by DOE.

E. 2014 Test Procedure Rule

We now consider AHRI's and Zero Zone's challenges to the 2014 Test Procedure Rule, a rule published after the New Standards Rule. As discussed above, DOE encountered an interpretive difficulty when measuring the total display area ("TDA") of a CRE unit.[37] Determining the TDA of a unit is essential to calculating the maximum allowable energy consumption level for certain CRE units. 79 Fed. Reg. at 22,299. According to DOE, the 2014 Test Procedure Rule clarified how CRE manufacturers should measure a specific aspect of the TDA: "L," otherwise known as the "Length of Commercial Refrigerated Display Merchandiser." *Id.* AHRI and Zero

37 *See supra* Part I.C.

Zone now contend, however, that the clarified definition of "L" is contrary to law, substantively arbitrary and capricious, and was promulgated in an impermissible manner. They further submit that if the 2014 Test Procedure Rule is ruled invalid, the New Standards Rule—which incorporates the definition of "L"—must fall as well.

1. Conformity to Industry Standards

AHRI and Zero Zone first contend that the 2014 Test Procedure's definition of "L" is contrary to the EPCA's definition of "L." As previously mentioned, "L" is a variable in the function for determining the TDA of a CRE unit. The EPCA states that "'TDA' means the total display area (ft^2) of the refrigerated case, *as defined in AHRI Standard 1200*." 42 U.S.C. § 6313(c)(1)(D) (emphasis added). Therefore, the definition of "L" employed by DOE must align with this industry standard. According to AHRI and Zero Zone, however, DOE's clarified definition of "L" deviated from AHRI Standard 1200. Specifically, AHRI and Zero Zone believe that DOE employed an impermissible "compromise" between the industry standard and DOE's own definition. *See* 79 Fed. Reg. at 22,300 ("As a compromise, DOE is adopting … this final rule … .")

We cannot accept petitioners' understanding of the "compromise" DOE made when defining "L." As DOE explained in its notice of proposed rulemaking for the 2014 Test Procedure Rule, AHRI Standard 1200 does not define or illustrate the meaning of "L." 78 Fed. Reg. at 64,309–12. Because the promulgation and enforcement of energy standards required a precise definition of the term "L," DOE undertook to define the term in a manner that, while remaining faithful to the statutory language, would provide both the regulator and the industry with a workable metric. DOE proposed a definition of

"L" that was consistent with AHRI Standard 1200's stated definition of the TDA: "the sum of the projected area(s) *for visible product*." 79 Fed. Reg. at 22,299 (emphasis added). DOE reasoned that if the TDA was defined as only consisting of the visible area on a CRE unit, then a variable of the TDA also must only consist of the visible area on a CRE unit. *Id.* After considering comments from the industry, however, DOE determined "that defining TDA as strictly the total length of transparent area may be inconsistent with the method used by industry to calculate TDA today." *Id.* at 22,300. That method typically included non-transparent areas like door frames and mullions. DOE therefore chose what it termed, somewhat imprudently and improvidently, a "compromise" value. *See id.* "L" would be defined

> as the internal length of the CRE model, provided no more than 10 percent of that length consists of non-transparent material. For those cases with greater than 10 percent of non-transparent area, L shall be determined as the projected linear dimension(s) of visible product plus 10 percent of non-transparent area.

Id. at 22,301.

Contrary to AHRI and Zero Zone's contention that DOE created a "compromise" between the department's desired standard and the AHRI standard, DOE actually crafted a more precise definition of "L"—one not fully articulated in the *text* of the AHRI Standard but found in the *method* of implementing the AHRI Standard. *Id.* at 22,299–301. DOE's definition of "L" therefore conforms to AHRI Standard 1200 and complies with the mandate of the EPCA. *See* 42 U.S.C. § 6313(c)(1)(D).

2. Operation of the Rule

AHRI and Zero Zone next raise a series of challenges to the operation of the new test procedure. When issuing the 2014 Test Procedure Rule, DOE concluded that the clarified definition of "L" will "not change the measured energy consumption of covered equipment" and therefore will not change the expected impact of the amended standards on the CRE industry. 79 Fed. Reg. at 22,301. AHRI and Zero Zone disagree with this conclusion and contend that DOE's definition of "L" in the 2014 Test Procedure Rule will result in smaller maximum energy consumption levels for CRE units than the previously enforced definition. In their view, DOE acted arbitrary and capriciously when it modeled the new standards on a less stringent definition of "L." More significantly, they contend that DOE failed to adhere to the EPCA's requirement that it "determine, in the rulemaking carried out with respect to prescribing such procedure, to what extent, if any, the proposed test procedure would alter the measured energy efficiency [or] measured energy use … of any covered product as determined under the existing test procedure." 42 U.S.C. § 6293(e)(1).

This contention has no merit. Our review confirms that DOE did explain why the definition of "L" in the 2014 Test Procedure Rule was consistent with the definition it had previously employed. DOE referred back to its engineering analysis for the New Standards Rule, and it explained that the calculation for the length of the relevant model of CRE was based "upon the continuous length of transparent area of the CRE model, which included mullions and door frames, but excluded any additional case wall present on the front face of the unit. In other words, DOE included the entire length of the transparent doors, including minor non-transparent areas." 79 Fed. Reg. at 22,300; *see also* App. R.6, Admin. R.102 at 5A-6 (displaying the length of the doors and TDA for the CRE models); App. R.13, Admin. R.13-A1 at 2–3 (comment from Hillphoenix noting that mullion and door frame widths were included in DOE's calculation). DOE stated that the "10 percent of non-transparent area that may be included in the dimension L" was consistent with its consideration of the mullions and door frames during the engineering analysis. 79 Fed. Reg. at 22,301. DOE adequately explained how it reached the conclusion "that this amendment should not change the measured energy consumption of covered equipment." *Id.*

We note that multiple manufacturers—including AHRI—believed that an even *more* stringent definition of "L" would have been consistent with prior practice. They suggested in comments that DOE only account for door mullion and door frame widths of five inches or less; any non-transparent area greater than five inches would be excluded from the calculation of "L."[38] DOE noted in response that "the 10 percent threshold [it adopted] is less stringent than the 5-inch threshold recommended by manufacturers. That is, a threshold of 10 percent accommodates greater amounts of non-transparent area in the dimension 'L' for a majority of CRE models." *Id.* None of the petitioners have disputed DOE's assertion that its clarified definition is more favorable to manufacturers than their proposal of a five-inch threshold for non-transparent area, and we find that assertion entirely reasonable. DOE

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[38] App. R.13, Admin. R.11-A1 at 4 (comment from Hussman); App. R.13, Admin. R.13-A1 at 3–4 (comment from Hillphoenix); App. R.13, Admin. R.15-A1 at 3 (comment from AHRI).

adequately explained that its clarification to the definition of "L" would have no discernable impact on the application of the new standards.

3. Procedural Challenges

AHRI and Zero Zone also object to the timing of both the proposal and the publication of the 2014 Test Procedure Rule. The Rule was proposed after the New Standards Rule was proposed and published after the New Standards Rule was published.[39] The petitioners submit that this timeline violated both the EPCA and DOE's own Process Rules.

We begin with the challenge under the EPCA. According to the EPCA, "[a]ny new or amended energy conservation standard prescribed under this section *shall include*, where applicable, *test procedures*." 42 U.S.C. § 6295(r) (emphases added). The petitioners contend that DOE therefore was obligated under the EPCA to include the *2014* Test Procedures in the New Standards Rule. DOE did not fulfill this statutory mandate, they contend, because the 2014 Test Procedures were not published at the time of the publication of the New Standards Rule. In response, DOE contends that it satisfied the EPCA by including the *2012* Test Procedures in its New Standards Rule.[40]

39 The notice of proposed rulemaking for the New Standards Rule was issued on September 11, 2013. The notice of proposed rulemaking for the 2014 Test Procedure Rule was issued on October 28, 2013. The publication of the New Standards Rule occurred on March 28, 2014. The publication of the 2014 Test Procedure Rule occurred on April 21, 2014.

40 The New Standards Rule notes that "[t]he test procedure amendments established in the 2012 test procedure final rule are required to be used in

We agree with DOE's interpretation: the inclusion of the 2012 Test Procedures satisfies § 6295(r). The EPCA clearly contemplates that DOE will amend and proscribe test procedures independent of energy conservation standards. Indeed, the EPCA states that "[i]f [DOE] determines that the amended test procedure will alter the measured efficiency or measured use, [DOE] shall amend the applicable energy conservation standard during the rulemaking carried out with respect to such test procedure." *Id.* § 6293(e)(2). It naturally follows that if DOE determines that the amended test procedures will *not* alter efficiency standards—as DOE did here—DOE does *not* need to amend the applicable efficiency standards during that rulemaking.[41] Therefore, DOE acted well within the bounds of the EPCA when it included the 2012 Test Procedures in the New Standards Rule and then clarified the meaning of those test procedures in a subsequent rule.

We now turn to the challenges under DOE's own process rules. DOE Process Rule 7(b) explains that "[a]ny necessary modifications [to test procedures] will be proposed before issuance of an [advance notice of proposed rulemaking]." 10 C.F.R. pt. 430, subpt. C, app. A. DOE Process Rule 7(c) further explains that "[f]inal, modified test procedures will be issued prior to the [notice of proposed rulemaking] on proposed standards." *Id.* The petitioners submit that DOE violated both

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conjunction with the amended standards promulgated in this … final rule." 79 Fed. Reg. at 17,735.

[41] *See King v. Burwell*, 135 S. Ct. 2480, 2489 (2015) ("[W]hen deciding whether the language is plain, we must read the words 'in their context and with a view to their place in the overall statutory scheme.'" (quoting *FDA v. Brown & Williamson Tobacco Corp.*, 529 U.S. 120, 133 (2000)).

of these Process Rules because the 2014 Test Procedures were not even proposed until the notice of proposed rulemaking for the New Standards Rule. DOE responds that the 2014 Test Procedures are merely "clarifying amendments" that are not covered by either Process Rule.[42] DOE Process Rule 7(b) refers to "necessary modifications" and DOE Process Rule 7(c) refers to a "modified test procedure." *Id.* In DOE's view, *clarifying* the meaning of a procedure is not equivalent to *modifying* the procedure itself.

DOE created these Process Rules, so we will affirm DOE's interpretation of those rules "unless plainly erroneous or inconsistent with the regulation." *Auer*, 519 U.S. at 461 (internal quotation marks omitted); *see also Whetsel v. Network Prop. Servs., LLC*, 246 F.3d 897, 901 (7th Cir. 2001). Here, DOE's interpretation is worthy of such deference. The Supreme Court has explained that an "interpretation" of a rule, which is meant to ascertain the meaning of text, is not the same as an "amendment" of a rule, which is meant to change the text. *Perez v. Mortg. Bankers Ass'n*, 135 S. Ct. 1199, 1207–08 (2015) ("One would not normally say that a court 'amends' a statute when it interprets its text. So too can an agency 'interpret' a regulation without 'effectively amend[ing]' the underlying source of law." (alteration in original)). Similarly, a *clarification* of a rule, which is also meant to ascertain the meaning of text, can be distinguished from a *modification* of a rule, which, according to the Supreme Court, "connotes moderate change." *MCI Telecomms. Corp. v. AT&T Co.*, 512 U.S. 218, 228 (1994). DOE determined that "L," as defined in its previous

42 DOE Br. at 16.

test procedure rules, was ambiguous. By clarifying the meaning of "L" in the 2014 Test Procedure Rule, DOE acted within its authority and did not violate any regulatory or statutory provisions.

Conclusion

For the foregoing reasons, we deny the petitions for review in their entirety.

PETITIONS DENIED

Exhibit E

Nos. 14-2147, 14-2159 & 14-2334 (consolidated)

**IN THE UNITED STATES COURT OF APPEALS
FOR THE SEVENTH CIRCUIT**

ZERO ZONE, INC., *et al.*,
Petitioners,

v.

U.S. DEPARTMENT OF ENERGY, *et al.*,
Respondents,

On Petition for Review of Final
Rules of the Department of Energy

BRIEF OF THE INSTITUTE FOR POLICY INTEGRITY AT NEW YORK UNIVERSITY SCHOOL OF LAW AS AMICUS CURIAE IN SUPPORT OF RESPONDENTS

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July 29, 2015

APPEARANCE & CIRCUIT RULE 26.1 DISCLOSURE STATEMENT

Appellate Court No: 14-2147

Short Caption: Zero Zone, Inc. v. U.S. Department of Energy (and consolidated cases 14-2159 and 14-2334)

To enable the judges to determine whether recusal is necessary or appropriate, an attorney for a non-governmental party or amicus curiae, or a private attorney representing a government party, must furnish a disclosure statement providing the following information in compliance with Circuit Rule 26.1 and Fed. R. App. P. 26.1.

The Court prefers that the disclosure statement be filed immediately following docketing; but, the disclosure statement must be filed within 21 days of docketing or upon the filing of a motion, response, petition, or answer in this court, whichever occurs first. Attorneys are required to file an amended statement to reflect any material changes in the required information. The text of the statement must also be included in front of the table of contents of the party's main brief. **Counsel is required to complete the entire statement and to use N/A for any information that is not applicable if this form is used.**

[ ] **PLEASE CHECK HERE IF ANY INFORMATION ON THIS FORM IS NEW OR REVISED AND INDICATE WHICH INFORMATION IS NEW OR REVISED.**

(1) The full name of every party that the attorney represents in the case (if the party is a corporation, you must provide the corporate disclosure information required by Fed. R. App. P 26.1 by completing item #3):

Institute for Policy Integrity

(2) The names of all law firms whose partners or associates have appeared for the party in the case (including proceedings in the district court or before an administrative agency) or are expected to appear for the party in this court:

n/a

(3) If the party or amicus is a corporation:

i) Identify all its parent corporations, if any; and

The Institute for Policy Integrity has no parent companies.

ii) list any publicly held company that owns 10% or more of the party's or amicus' stock:

No publicly held company owns an interest of 10% or more in the Institute for Policy Integrity.

Attorney's Signature: s/ Richard L. Revesz Date: 07/28/2015

Attorney's Printed Name: Richard L. Revesz

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Attorney's Signature: s/ Denise A. Grab Date: 07/28/2015

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Attorney's Signature: s/ Jayni Foley Hein   Date: 07/28/2015

Attorney's Printed Name: Jayni Foley Hein

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Attorney's Signature: s/ Jason A. Schwartz Date: 07/28/2015

Attorney's Printed Name: Jason A. Schwartz

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INTEREST OF AMICUS CURIAE

Pursuant to the consent of all of the parties[1] in these consolidated cases, the Institute for Policy Integrity at New York University School of Law[2] ("Policy Integrity") files this *amicus curiae* brief in support of Respondents, the Department of Energy ("DOE"), *et al*. In particular, Policy Integrity supports DOE's use of the social cost of carbon ("SCC") in conducting its economic analysis of the energy conservation standards at issue.

Policy Integrity is dedicated to improving the quality of government decisionmaking through advocacy and scholarship in administrative law, economics, and public policy. Policy Integrity is a collaborative effort of faculty; a full-time staff of attorneys, economists, and policy experts; law students; and a Board of Advisors comprised of leaders in public policy, law, and government.

Policy Integrity has produced extensive scholarship on the use of economic analysis in regulatory decisionmaking. An area of special concern for Policy Integrity is the development and use of the SCC for analyzing the climate impacts of proposed regulations. Policy Integrity's economists and legal scholars are among the nation's leading experts on the economic analysis underlying the SCC and its application in different regulatory contexts, having published numerous papers,

[1] Under Federal Rule of Appellate Procedure 29(c), the Institute for Policy Integrity states that no party's counsel authored this brief in whole or in part, and no party or party's counsel contributed money intended to fund the preparation or submission of this brief. No person—other than the amicus curiae, its members, or its counsel—contributed money intended to fund the preparation or submission of this brief.

[2] No part of this brief purports to present New York University School of Law's views, if any.

reports, and comments on these topics. Petitioners' briefs have questioned DOE's treatment of the SCC, and Policy Integrity has a significant interest in supporting DOE's appropriate use of the SCC in this rulemaking.

SUMMARY OF ARGUMENT

The Department of Energy ("DOE")'s energy conservation standards for commercial refrigeration equipment ("the Rule"), 79 Fed. Reg. 17,726 (Mar. 28, 2014), will reduce carbon pollution, help mitigate climate change, and so generate billions of dollars in quantifiable benefits to economic welfare, public health, national security, and environmental quality. DOE quantified those benefits by applying the "social cost of carbon" ("SCC"), a framework for estimating the monetized, global damages caused by releasing an additional ton of carbon dioxide anywhere into the atmosphere. DOE relied on the SCC estimates developed by a rigorous interagency process over many years, in which DOE actively participated.

In opposing DOE's energy conservation standards, Petitioners AHRI and Zero Zone (collectively "AHRI"), take aim at nearly every aspect of the SCC's development and its application to this Rule. This amicus brief defends the development and application of the SCC as rigorous, rational, and consistent with statutory requirements, regulatory best practices, and case law.

First, AHRI launches a wholesale attack on DOE's statutory authority to consider any environmental effects of its energy conservation standards. AHRI overlooks the clear statutory instructions in the Energy Policy and Conservation Act ("EPCA") to weigh "the need for national energy conservation," which courts and agencies have repeatedly interpreted to include environmental, economic, and national security effects.

Next, AHRI disparages the interagency process that developed the SCC values. That process, in fact, was transparent and open to repeated public comments; it was rigorously grounded in the best available, peer-reviewed scientific and economic literature; and it properly addressed the uncertainties of climate science without becoming paralyzed by them. Though the SCC should be continually updated with the latest information, DOE properly relied in this Rule on the 2013 estimates from the interagency process. Indeed, ensuring that all regulatory agencies use consistent values derived by a consensus-driven, interagency process is essential to harmonizing climate policy and cost-benefit analysis across the federal executive branch.

Finally, AHRI misleadingly suggests that DOE improperly expanded the geographic and temporal scope of its calculation of climate benefits. AHRI is incorrect. DOE deliberately selected a global perspective for the SCC values because a global perspective directly advances U.S. national interests. A domestic-only view of climate change, by contrast, would prevent DOE from setting conservation standards at economically efficient levels, and would risk impeding international climate actions that directly benefit U.S. welfare. With respect to timespan, DOE assessed both the costs and benefits accruing over time due to refrigerators sold for 30 years following the Rule. DOE properly accounted for the fact that most of the Rule's costs occur sooner than the climate benefits, by using economic techniques to value more highly the effects that occur sooner, and DOE properly considered uncertainty and adaptation to climate change over time. In doing so, DOE acted in accordance with economic and regulatory best practices.

ARGUMENT

I. The Energy Policy and Conservation Act Allows DOE to Consider Climate Change in Setting and Justifying Energy Conservation Standards

AHRI alleges that DOE lacks "environmental regulatory power" under the Energy Policy and Conservation Act ("EPCA"), and therefore attacks DOE's consideration of the Rule's billions of dollars of climate benefits. AHRI Br. 23. AHRI both misinterprets EPCA's grant of regulatory authority and overlooks climate change's serious economic and national security dimensions. While Respondents explain that the Rule's stringency ultimately did not turn on climate considerations, Resp'ts Br. 33-34, DOE has clear statutory authority to weigh climate effects in calibrating the Rule's stringency and detailing its economic justification.

This Rule's large social benefits from mitigating carbon emissions and other pollution were evaluated by DOE under the sixth of EPCA's seven factors for determining the economic justification of appliance efficiency standards: specifically, "the need for national energy . . . conservation," 42 U.S.C. § 6295(o)(2)(B)(vi). *See* 79 Fed. Reg. at 17,738 (labeling the factor as "the need of the nation to conserve energy," and listing environmental benefits along with energy security and reliability). The key statutory term "need" is not defined, *see* 42 U.S.C. § 6291, and DOE generally deserves deference in interpreting such ambiguous language. *See Chevron U.S.A. Inc. v. Natural Res. Def. Council, Inc.*, 467 U.S. 837, 842-45 (1984). As courts and agencies have repeatedly determined, environmental, economic, health, and foreign policy effects can be important aspects of "the need for national energy conservation," and EPCA certainly does not bar their consideration.

For example, EPCA gives the Department of Transportation nearly identical instructions to weigh "the need of the United States to conserve energy" in setting motor vehicle efficiency standards. 49 U.S.C. § 32,902(f). In defining that language, DOT has explained:

> As courts of appeal have noted in three decisions stretching over the last 20 years, [DOT] defined the "need of the Nation to conserve energy" in the late 1970s as including ". . . environmental, and foreign policy implications . . . ." In 1988, [DOT] included climate change concepts in its [vehicle efficiency standards] . . . . Since then, [DOT] has considered the benefits of reducing tailpipe carbon dioxide emissions . . . pursuant to the statutory requirement to consider the nation's need to conserve energy by reducing fuel consumption.

77 Fed. Reg. 62,624, 62,669-70 (Oct. 15, 2012). In 1988, the D.C. Circuit highlighted that DOT interprets the language as "*requir[ing]* consideration of . . . environmental . . . implications." *See Pub. Citizen v. Nat'l Highway Traffic Safety Admin.*, 848 F.2d 256, 263 n.27 (D.C. Cir. 1988) (R.B. Ginsburg, J.) (quoting 42 Fed. Reg. 63,184, 63,188 (Dec. 15, 1977), adding emphasis to the word *requires*, and explaining that EPCA contains no statutory command prohibiting environmental considerations). More recently, in 2008, the Ninth Circuit indicated that, due to advancements in "scientific knowledge of climate change and its causes," "[t]he need of the nation to conserve energy is even more pressing today than it was at the time of EPCA's enactment." *Ctr. for Biological Diversity v. Nat'l Highway Traffic Safety Admin.*, 538 F.3d 1172, 1197-98 (9th Cir. 2008). The court held that DOT's failure to monetize climate benefits explicitly in its economic assessment of vehicle efficiency standards was arbitrary and capricious. *Id.* at 1203. Here, DOE rationally recognized climate change as an important aspect of "the need for national energy

conservation," and monetized the economic, health, security, and environmental effects to the extent possible. 79 Fed. Reg. at 17,803-05.

From among the earliest energy conservation standards that DOE issued following EPCA's 1987 amendments—and consistently since then, under administrations of both political parties—DOE has considered the economic and other effects of avoided carbon emissions when assessing the national need for energy conservation. Under President George H.W. Bush's administration in 1989, DOE agreed with public commenters that "environmental effects," including the "national security" implications of "mitigating global warming and pollution," counted toward the "economic justification" for efficiency standards, under the "need of the nation to conserve energy" prong. 54 Fed. Reg. 47,916, 47,924, 47,937, 47,940 (Nov. 17, 1989). Less than two years later, again at the behest of commenters, DOE not only "quantified"—"to the extent DOE had data"—the "social benefits" of environmental effects like "global warming" to help justify the selected standards, but further noted that environmental effects "have also been considered in the development of the selected standard levels." 56 Fed. Reg. 22,250, 22,259 (May 14, 1991).

These practices—particularly, quantifying climate effects to the extent possible—continued through subsequent presidential administrations. Under President Clinton's administration, DOE elaborated that the "need of the nation to save energy" included "improv[ing] the Nation's energy security, strengthen[ing] the economy, and reduc[ing] the environmental impacts of energy production." 62 Fed.

Reg. 50,122, 50,143 (Sept. 24, 1997). And starting in 2008, under President George W. Bush, DOE began estimating a range of monetary benefits for carbon reductions. 73 Fed. Reg. 58,772, 58,814 (Oct. 7, 2008).

Longstanding agency interpretations and court rulings thus support DOE's statutory authority to consider climate change in setting and justifying energy conservation standards. In fact, as recently as 2010, commenting on this very rulemaking's framework document, AHRI agreed: "This is not the first time the Department has considered the benefits to the nation of potential CO_2 emissions reductions in an appliance efficiency standards rulemaking, *and we agree that it is an important factor to consider*." AHRI 2010 Comments, No. 15 at 6 (emphasis added).

II. DOE Reasonably Applied the Interagency Working Group's Social Cost of Carbon Values to Evaluate Climate Effects

In this Rule, DOE reasonably used the social cost of carbon ("SCC") to evaluate the monetary benefits of reducing carbon dioxide ("CO_2") emissions. *See* 79 Fed. Reg. at 17,777. The SCC was developed by an Interagency Working Group ("IWG") comprised of economic and scientific experts from the White House and multiple federal agencies—including DOE—that regularly met to review technical literature, consider public comments, and discuss relevant inputs and assumptions. *Id*. Contrary to Petitioners' claims, AHRI Br. 25-27, the SCC values were developed through open and transparent processes, with significant public input, and using the best peer-reviewed science and economic methods available.

The IWG was convened by the White House to develop a single range of SCC estimates for all federal agencies to use consistently in their regulatory impact analyses. Final Technical Supporting Document [hereinafter "Final TSD"], No. 102 at 14A-4 (appending the IWG's 2010 Technical Support Document [hereinafter "2010 IWG"]). Courts have long recognized "the basic need of the President and his White House staff to monitor the consistency of executive agency regulations with Administration policy. . . . The authority of the President to control and supervise executive policymaking is derived from the Constitution; the desirability of such control is demonstrable from the practical realities of administrative rulemaking." *Sierra Club v. Costle*, 657 F.2d 298, 405-06 (D.C. Cir. 1981). Before the 2009 interagency process, different agencies used different SCC estimates in their regulatory analyses—if they estimated the SCC at all. *See* 2010 IWG, No. 102, at 14A-4. Such inconsistency risked sending mixed signals to the American public, American industry, and foreign countries about the U.S. administration's policy on climate change, and led to inconsistent cost-benefit analyses across agencies and regulatory proceedings. By convening a consensus-driven interagency process, the White House ensured that all agencies would account for climate benefits in a rational and consistent manner. *See* Richard L. Revesz, *Quantifying Regulatory Benefits*, 102 Cal. L. Rev. 1423, 1439-41, 1454-55 (2014).

DOE acted reasonably and in accordance with longstanding executive orders, agency guidance, and case law in using the SCC to estimate this Rule's economic benefits. Executive Orders instruct agencies to "use the best available techniques to quantify anticipated present and future benefits and costs as accurately as possible." Exec. Order No. 13,563 § 1(c), 76 Fed. Reg. 3821, 3821 (Jan. 18, 2011); *accord* Exec. Order No. 12,866 § 6(a)(3)(C), 58 Fed. Reg. 51,735, 51,741 (Oct. 4, 1993) (requiring economic analysis). The Office of Management and Budget ("OMB") under President George W. Bush issued Circular A-4, which instructs agencies in the use of best practices for cost-benefit analysis. Office of Mgmt. & Budget, *Circular A-4* at 1 (2003) [hereinafter "Circular A-4"]. And courts have held that agencies cannot assign a zero dollar value to the social costs of climate change, even if those impacts are difficult to quantify. *See Ctr. for Biological Diversity*, 538 F.3d at 1200. Moreover, it is well-established that DOE can rely on interagency economic values; for example, federal agencies have long relied on discount rates developed by OMB in conducting regulatory impact analyses. *See, e.g.*, Office of Mgmt. & Budget, *Circular A-94* at 8-11 (1992) (recommending discount rates for regulatory impact analyses); Circular A-4 at 31–37; *see also Ohio v. Dept. of Interior*, 880 F.2d 432, 465 (D.C. Cir. 1989) (holding that the agency did not act unreasonably when it followed OMB guidance for discount rates).

A. The Social Cost of Carbon Values Were Derived Through a Transparent and Open Interagency Process

The IWG's analytical process in developing the SCC was transparent and open, designed to solicit public comment and incorporate the most recent scientific analysis.

First, the process was transparent. Beginning in 2009, OMB and the Council of Economic Advisers established the IWG, composed of scientific and economic experts from the White House, Environmental Protection Agency, and Departments of Agriculture, Commerce, Energy, Transportation, and Treasury, to develop a rigorous method of valuing CO_2 reductions resulting from federal regulations. 2010 IWG, No. 102 at 14A-3. In February 2010, the IWG released estimated SCC values, developed using the three most widely cited climate economic impact models (known as integrated assessment models). These models were each developed by outside experts, and published and extensively discussed in peer-reviewed literature. *See* 79 Fed. Reg. at 17,779. An accompanying Technical Support Document released by the IWG discussed the models, their inputs, and the assumptions used in generating the SCC estimates. 2010 IWG, No. 102 at 14A-1 to 14A-52. In May 2013, after all three underlying models had been updated and used in peer-reviewed literature, the IWG released revised SCC values, with an accompanying Technical Support Document. Final TSD, No. 102 at 14-B-i to 14-B-18 (appending the IWG's 2013 Technical Support Document with minor modifications [hereinafter "2013 IWG"]).

Both the 2010 and 2013 Technical Support Documents are comprehensive and rigorous in explaining the IWG's sources of data, assumptions, and analytic methods. The Government Accountability Office recently examined the IWG's process, and found that it was consensus-based, relied on academic literature and modeling, disclosed relevant limitations, and was designed to incorporate new information via public comments and updated research. Gov't Accountability Office, *Regulatory Impact Analysis: Development of Social Cost of Carbon Estimates* (2014).

Petitioners complain that the IWG did not name specific personnel who worked on the SCC estimates. *See* AHRI Br. 25. But neither Circular A-4 nor federal standards for internal control mandate personnel lists. *See generally* Circular A-4; Gov't Accountability Office, *Standards for Internal Control in the Federal Government*, (2014). Further, Petitioners' argument that the IWG failed to disclose the role of outside consultants is misleading. *See* AHRI Br. 25-26. For example, the IWG described consultation "with several lead authors" of the Fourth Assessment Report of the U.N. Intergovernmental Panel on Climate Change. 2010 IWG, No. 102 at 14A-13 to 14A-14.[3]

Second, the IWG's process was and continues to be open, soliciting public comments at multiple stages. Before it even released the 2010 SCC values, the IWG considered public comments on prior federal agency efforts to monetize climate effects. *See* 79 Fed. Reg. at 17,777; 2010 IWG, No. 102 at 14A-3. Next, in 2013, OMB requested public comments on all aspects of the SCC and its updated Technical Support Document. *See* 79 Fed. Reg. at 17,779 (citing 78 Fed. Reg. 70,586 (Nov. 26, 2013)). Over the 90-day comment period, OMB received at least 140 unique comments and thousands of form letters covering a range of topics; and OMB, through the IWG, responded to these comments. *See* 2015 Response to Comments 4-6.

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[3] In addition, the IWG responded to public comments in July 2015, and explained that for the 2013 IWG—i.e., the SCC estimates used by DOE for this Rule—the IWG staff ran all models themselves and did not use a consultant. Interagency Working Grp. on Social Cost of Carbon, U.S. Gov't, *Response to Comments: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* at 37 (2015) [hereinafter "2015 Response to Comments"].

In addition, between February 2010 and May 2013, numerous federal agencies proposed rules that used the SCC and provided opportunities for public comment on all aspects of the SCC values and their development, including comment periods on several DOE energy conservation standards.[4] These comments informed the IWG's revised SCC values released in May 2013. *See* 2013 IWG, No. 102 at 14-B-1. And as the comments cited in AHRI's brief demonstrate, AHRI Br. 28-29, interested parties continued to submit comments to DOE on the SCC during this very rulemaking.

In short, the IWG worked transparently and openly to develop and update the SCC values, and DOE's use of these values has been similarly transparent and open.

B. The Social Cost of Carbon Values Are Based on Peer-Reviewed Science and Economics

The SCC was developed with robust academic rigor, including peer review of both the integrated assessment models and the inputs used by the IWG. Petitioners' arguments to the contrary have no merit and fall far short of demonstrating that DOE was arbitrary and capricious in using the SCC to estimate the economic benefits from its energy conservation standards. *See* AHRI Br. 26-27.

The SCC values were developed using the three most widely cited climate economic impact models that link physical impacts to the economic damages of CO_2 emissions. Each of these integrated assessment models—known as DICE, FUND,

[4] *See, e.g.*, 77 Fed. Reg. 32,381 (May 31, 2012); 77 Fed. Reg. 18,478 (Mar. 27, 2012); 76 Fed. Reg. 74,854 (Dec. 1, 2011); 75 Fed. Reg. 74,152 (Nov. 30, 2010); 75 Fed. Reg. 59,470 (Sept. 27, 2010).

and PAGE[5]—has been extensively peer reviewed in the economic literature. *See* 79 Fed. Reg. at 17,779; 2010 IWG, No. 102 at 14A-4. The newest versions of the models—updated in 2013—were also published in peer-reviewed literature. *See* Final TSD, No. 102 at 14-3; 2013 IWG, No. 102 at 14-B-1; *see also* William Nordhaus, *Estimates of the Social Cost of Carbon: Concepts and Results from the DICE-2013R Model and Alternative Approaches*, 1 J. Ass'n Envtl. & Resource Economists 273 (2014). Each model translates emissions into changes in atmospheric carbon concentrations, atmospheric concentrations into temperature changes, and temperature changes into economic damages. 2010 IWG, No. 102 at 14A-6. The IWG gives each model equal weight in developing the SCC values. *Id* at 14A-5.

The IWG also used peer-reviewed inputs to run these models. *Id.* at 14A-5 to 14A-29. The IWG conducted an "extensive review of the literature . . . to select three sets of input parameters for these models: climate sensitivity, socio-economic and emissions trajectories, and discount rates." *Id.* at 14A-6. For example, to derive socioeconomic and emissions pathways, the IWG used results from the Stanford Energy Modeling Forum, all of which were peer-reviewed, published, and publicly available. *Id.* at 14A-16; *see also* Symposium, *International, U.S. and E.U. Climate Change Control Scenarios: Results from EMF 22*, 31 Energy Econ. S63 (2009). For

[5] More specifically: DICE (Dynamic Integrated Climate and Economy), developed by William Nordhaus; PAGE (Policy Analysis of the Greenhouse Effect), developed by Chris Hope; and FUND (Climate Framework for Uncertainty, Negotiation, and Distribution), developed by Richard Tol. *See* 2010 IWG, No. 102 at 14A-5 n.b.

each parameter, the IWG documented its inputs, all of which are based on peer-reviewed literature. *See* 2010 IWG, No. 102 at 14A-13 to 14A-24.

Further, the analytical methods that the IWG applied to its inputs, such as Monte Carlo analysis and the Roe Baker distribution to address climate sensitivity, were also peer reviewed. *See id.* at 14A-14 (citing Roe and Baker studies). Monte Carlo analysis is a powerful statistical technique used for decades in social science to account for uncertainty, which has been extensively applied to the SCC models.[6] Moreover, although there is no legal requirement that an agency's analysis itself be subject to peer review, the IWG's methods have been extensively discussed, often approvingly, in academic journals. *See, e.g.*, Michael Greenstone et al., *Developing a Social Cost of Carbon for US Regulatory Analysis: A Methodology and Interpretation*, 7 Rev. Envtl. Econ. & Pol'y 23 (2013); Frank Ackerman & Elizabeth Stanton, *Climate Risks and Carbon Prices: Revising the Social Cost of Carbon*, Econ.: The Open-Access, Open-Assessment E-Journal, Apr. 2012, at 6 (reviewing the IWG's methods and stating, "[T]he Working Group analysis is impressively thorough.").

C. The Interagency Working Group Properly Addressed Uncertainty in the Damage Functions Used to Calculate the Social Cost of Carbon

The damage functions used by the IWG are based on the best available information and transparently address uncertainty in a way that yields a

[6] *See, e.g.,* Simon Dietz & Nicholas Stern, *Why Economic Analysis Supports Strong Action on Climate Change: A Response to the* Stern Review*'s Critics*, 2 Rev. Envtl. Econ. & Pol'y 94, 103 (2008) (stating that integrated assessment models, including PAGE, use Monte Carlo procedures to estimate probabilities).

conservative assessment of the SCC. To argue that accounting for uncertainty makes the damage functions invalid, as Petitioners do, is wrong as a matter of both law and of economics. *See* AHRI Br. 27-28. Science by its nature is uncertain, and economists have developed tools to deal with uncertainty in climate damages. The question is not whether uncertainty exists, but whether the IWG used proper methods to account for uncertainty. The answer is resoundingly "yes."

The IWG comprehensively accounted for and disclosed uncertainty. First, recognizing different ways of modeling climate science and damages, the IWG used three different integrated assessment models. 79 Fed. Reg. at 17,779; 2010 IWG, No. 102 at 14A-4. Second, the IWG used sensitivity analysis over these models, applying three different discount rates and five different socio-economic scenarios. *See id.* at 14A-26. Third, the IWG conducted Monte Carlo analysis, producing a range of estimates based upon different outcomes that climate and social science research indicate are possible.[7] *Id.* at 14A-13 to 14A-18, 14A-28; *see also* Circular A-4 at 41-42 (describing the use of Monte Carlo simulations). Fourth, the IWG updated its damage estimates in 2013 to incorporate the most recent peer-reviewed versions of the integrated assessment models. 2013 IWG, No. 102 at 14-B-1. The scientific method requires continual examination of new evidence to improve the resulting analysis; the SCC was developed with the understanding that the IWG

[7] A Monte Carlo simulation will run an integrated assessment model thousands of times, each time randomly picking the value of uncertain parameters from a probability distribution function. The IWG ran 10,000 Monte Carlo simulations for each of the three models and five socio-economic scenarios, randomizing the value of climate sensitivity and all other uncertain parameters.

would regularly revisit the estimates to reflect the "growing body of scientific and economic knowledge." *Id.*

Petitioners cite work by Robert Pindyck, which discusses uncertainties inherent in SCC values. *See* AHRI Br. 27-28. Pindyck's central criticism, however, is that the models fail to adequately capture very high damages and catastrophic risks, and thus likely *underestimate* future damages. *See* Robert S. Pindyck, *Climate Change Policy: What Do the Models Tell Us?*, 51 J. Econ. Literature 860, 869-70 (2013) ("[E]ven if a large temperature outcome has low probability, if the economic impact of that change is very large, it can push up the SCC considerably."). Further, Pindyck explicitly endorses use of the 2013 SCC estimates as at least a minimum starting value. *Id.* at 870 ("My criticism of IAMs should *not* be taken to imply that, because we know so little, nothing should be done about climate change right now. . . . [E]ven though we don't have a good estimate of the SCC, it would make sense to take the Interagency Working Group's [current] number as a rough and politically acceptable starting point and impose a carbon tax (or equivalent policy) of that amount."). Other economists have endorsed the utility of the SCC in peer-reviewed publications. *See, e.g.*, John Weyant, *Integrated Assessment of Climate Change: State of the Literature*, 5 J. Benefit-Cost Analysis 377, 401 (2014) ("The models have provided important insights into many aspects of climate-change policy."); Richard L. Revesz et al., *Improve Economic Models of Climate Change*, 508 Nature 173, 174 (2014) ("[T]he current estimate for the social cost of carbon is useful for policy-making, notwithstanding the significant uncertainties.") (co-authored with Kenneth Arrow, among others). Moreover, recent work that was not taken into account in the IWG's analysis indicates that uncertainties with respect to the damage function suggest *higher* climate damages than currently captured in the models, not lower damages. *Id.* at 174 ("[C]limate-economic models need to be extended to include a wider range of social and economic impacts. . . . The future costs of climate change could be even higher . . . ."). The current damage functions are likely conservative estimates because they omit many climate damages, including ocean acidification, wildfires, and effects of climate change on economic growth, to name only a few. *See id.*; Peter Howard, *Omitted Damages: What's Missing From the Social Cost of Carbon* 2-45 (2014) (chronicling a host of impacts omitted from the damage functions, which contribute to "a downward bias to the federal SCC estimates"); *see also* Policy Integrity et al. Comments, No. 83 at 5.

Finally, uncertainty in benefits estimates does not mean that such benefits should be excluded from regulatory impact analyses. Courts have explicitly rejected this argument with respect to the SCC, and executive orders direct agencies to consider benefits even despite uncertainty. *See, e.g.*, *Ctr. for Biological Diversity,* 538 F.3d at 1200 (holding that "while the record shows that there is a range of values, the value of carbon emissions reduction is certainly not zero," despite agency protestations about uncertainty); Exec. Order No. 13,563 §§ 1(a)-(c), 76 Fed. Reg. at 3821 (instructing agencies to "use the best available techniques to quantify anticipated present and future benefits and costs as accurately as possible"). Notably, Congress's conference report on EPCA explained that, in assessing the statutory factors for "economic justification" of energy conservation standards, "where quantification is possible, it is expected that the Secretary will perform such quantification of individual factors *to the greatest extent practicable."* S. Rep. No. 95-1294, at 116 (1978) (emphasis added).

In all, the SCC values were developed through an open and transparent process, with significant public input, using the best science and economic methods available. It is reasonable for federal agencies to use a single SCC, determined by expert consensus. Petitioners point to no alternative SCC more widely accepted or developed through a more rigorous process. DOE reasonably used the SCC to estimate the total benefits of this Rule.

III. DOE's Use of the Social Cost of Carbon in Its Economic Analysis Was Proper

A. The Energy Policy and Conservation Act Allows DOE to Take a Global Perspective on Climate Benefits, Especially Because a Global Perspective Directly Advances National Interests

AHRI accuses DOE of violating EPCA by considering the global benefits of reduced carbon emissions, because AHRI argues that EPCA's purpose is to guarantee only U.S., not international, welfare. AHRI Br. 28-29. AHRI gets the argument backwards: it is precisely to advance U.S. welfare that DOE must consider the global dimensions of climate change. The United States will surely experience within its own borders its share of climate change's direct economic, health, security, and environmental damages. Yet a domestic-only view of climate change would prevent DOE from setting conservation standards at economically efficient levels, and would impede international climate actions that directly benefit U.S. welfare.

DOE assesses this Rule's climate benefits by using the IWG's SCC framework. Following the IWG's recommendations, 2010 IWG, No. 102 at 14A-11 to -12, DOE gives three reasons for using a global SCC value. First, climate change "involves a global externality." 79 Fed. Reg. at 17,779. Second, climate change is "a problem that the United States alone cannot solve." *Id.* Third, "[t]here is no *a priori* reason why domestic benefits should be a constant fraction of net global damages over time." *Id.* at 17,778 n.66. AHRI dismisses the first two reasons as "*non sequiturs*" and ignores the third. AHRI Br. 29. Yet DOE's three reasons precisely explain why EPCA necessarily permits evaluation of the full societal costs of climate pollution.

To avoid a global "tragedy of the commons" that could irreparably damage all countries, including the United States, every nation should set policy according to a global SCC value. *See* Policy Integrity et al. Comments, No. 83 at 10; Garrett Hardin, *The Tragedy of the Commons*, 162 Science 1243, 1244 (1968) ("[E]ach pursuing [only its] own best interest . . . in a commons brings ruin to all."). Climate and clean air are global common resources, meaning they are freely available to all countries, but any one country's use—i.e., pollution—imposes harms on the polluting country as well as the rest of the world. Because carbon pollution does not stay within geographic borders but rather mixes in the atmosphere and affects climate worldwide, each ton of carbon emitted by the United States not only creates domestic harms, but also imposes large externalities on the rest of the world.

Conversely, each ton of carbon abated in another country benefits the United States along with the rest of the world. *See* 79 Fed. Reg. at 17,779 (discussing carbon's "global externality").

If all countries set their carbon emission levels based on only domestic costs and benefits, ignoring the large global externalities, the aggregate result would be substantially sub-optimal climate protections and significantly increased risks of severe harms to all nations, including the United States. Thus, basic economic principles demonstrate that the United States stands to benefit greatly if all countries apply a global SCC value in their regulatory decisions. A rational tactical option in the effort to secure that economically efficient outcome is for the United States to continue using a global SCC value itself. *See* Robert Axelrod, *The Evolution of Cooperation* 10-11 (1st ed. 1984) (on repeated prisoner's dilemma games). The United States is engaged in a repeated strategic game of international negotiations and regulatory coordination, in which several significant players—including the United States, England, and France—have already adopted a global SCC framework. *See* Policy Integrity et al. Comments, No. 83 at 10-11. For example, Canada and Mexico have explicitly borrowed the U.S. estimates of a global SCC to set their own fuel efficiency standards.[8] For the United States to now depart from

[8] *See* Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations, 147 C. Gaz. pt. II, 450, 544 (Can.), *available at* http://canadagazette.gc.ca/rp-pr/p2/2013/2013-03-13/html/sor-dors24-eng.html ("The values used by Environment Canada are based on the extensive work of the U.S. Interagency Working Group on the Social Cost of Carbon."); Instituto Nacional de Ecología, Mexico, Regulatory Impact Analysis on *PROY-NOM-163-SEMARNAT-ENER-SCFI-2012, Emisiones de bióxido de carbono (CO_2) provenientes del escape y su equivalencia en términos de rendimiento de combustible, aplicable a vehículos*

this collaborative dynamic by reverting to a domestic-only SCC estimate could undermine the country's long-term interests in climate negotiations and could jeopardize emissions reductions underway in other countries, which are already benefiting the United States.

Negotiation is key to the President's constitutional foreign affairs powers, and the Supreme Court has "recognized the special importance of our nation speaking with one voice." *See Made in the USA Found. v. United States*, 242 F.3d 1300, 1317-18 (11th Cir. 2001) (explaining the Supreme Court's holding in *Baker v. Carr,* 369 U.S. 186, 211 (1962)). The development and analysis of U.S. regulations are essential parts of the dialogue between the United States and foreign countries about climate change. Through the IWG, the President has instructed all federal agencies to use a global SCC value as one important step in negotiations to encourage other countries to take reciprocal actions that also account for global externalities. As the IWG explained, "Emphasizing the need for a global solution to a global problem, the United States has been actively involved in seeking international agreements to reduce emissions. . . . When these considerations are taken as a whole, the interagency group concluded that a global measure of the benefits from reducing U.S. emissions is preferable." 2010 IWG, No. 102 at 14A-11 to -12; *see also* 79 Fed. Reg. at 17,779 (climate change is "a problem that the United States alone cannot solve"). If different agencies used different SCC values in setting regulatory policies, it would risk sending mixed signals to the international

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automotores nuevos de peso bruto vehicular de hasta 3857 kilogramos (July 5, 2012), *available at* http://207.248.177.30/mir/formatos/defaultView.aspx?SubmitID=273026.

community. The President's constitutional powers to negotiate international agreements would be seriously impaired if federal agencies were forced to stop relying on a single, harmonized, global SCC value.

Finally, a global SCC value is in the national interest because harms experienced by other countries could significantly affect the United States. Climate damages in one country could generate large spillover effects to which the United States is especially vulnerable. Policy Integrity et al. Comments, No. 83 at 11 n.36. As seen historically, economic disruptions in one country can cause financial crises that reverberate globally at a breakneck pace. Similarly, "national security analysts . . . increasingly emphasize that the geopolitical instability associated with climatic disruptions abroad poses a serious threat to the United States." *Id.* at 12 & n.37. A global SCC framework properly recognizes that climate change will threaten the United States with significant and shifting international spillover effects.

In short, even if AHRI were correct that EPCA focuses exclusively on national welfare, a global perspective on climate change *promotes* national welfare. EPCA instructs DOE to set "economically justified" standards after weighing the "need for national energy conservation," which, as explored above, includes economic, security, environmental considerations generally, and climate change particularly. To advance our own national interests, numerous strategic factors support the continued use a global SCC value in setting and evaluating energy conservation standards.

B. DOE Properly Assessed All Significant Costs and Benefits Likely to Result from the Rule over Time

In accordance with economic and regulatory best practices, DOE accounted for all significant benefits and costs likely to result from the Rule over time. Petitioners argue that DOE inappropriately analyzed the full stream of climate benefits but only part of the stream of costs, AHRI Br. 36-43, but DOE employed proper cost-benefit analysis techniques in assessing the rule's effects over time. Circular A-4 instructs that the timeframe for agencies' analyses "should cover a period long enough to encompass all the important benefits and costs likely to result from the rule." Circular A-4 at 15. DOE followed this approach.

Circular A-4 further explains that "[b]enefits and costs do not always take place in the same time period." *Id.* at 31. When "benefits or costs are delayed or otherwise separated in time from each other, the difference in timing should be reflected" in the agency's analysis. *Id.* Importantly, the "ending point" for economic analysis should be set "far enough in the future to encompass all the significant benefits and costs likely to result from the rule." *Id.* After identifying all significant regulatory benefits and costs likely to occur, the agency must then account for any differences in timing of costs and benefits by using a "discount rate." The discount rate accounts for the fact that "[b]enefits or costs that occur sooner are generally more valuable." *Id.* at 32. The further in the future the effects are, the "more they should be discounted" before considering them in the cost-benefit analysis. *Id.*

DOE followed these regulatory best practices in assessing this Rule. DOE first considered all significant benefits and costs stemming from all equipment projected to be sold under the standard between 2017 and 2046.[9] 79 Fed. Reg. at 17,728, 17,773, 17,779, 17,811. Then, DOE correctly employed discounting to account for the timing of each effect. *Id.* For costs, DOE conducted a discounted cash-flow analysis. *See, e.g.*, *id*. at 17,773 (pertaining to manufacturers' costs). Because costs occur early in the analytical time period, they were discounted far less—and therefore weighted proportionately more heavily in the analysis—than the climate benefits occurring later.

With respect to climate benefits, DOE considered only those carbon reductions occurring as a result of this Rule between 2017 and 2046. 79 Fed. Reg. at 17,779; Final TSD, No. 102 at 13-4 to 13-5. However, because carbon persists in the atmosphere for centuries, the climate benefits from reduced emissions over those 30 years will continue to accrue into the future. To account correctly for the timing of future climate benefits, the agency: (1) converted the SCC values into 2013 U.S. dollars to account for inflation, (2) multiplied emission reductions in Year X by the corresponding SCC in Year X, (3) applied the discount rate to calculate the present value of future emission benefits from reductions in Year X, and then (4) summed up the present value of emission benefits across all relevant years. 79 Fed. Reg. at 17,779; Final TSD, No. 102 at 14-2. As even Petitioners acknowledge, the climate benefits that DOE analyzes arise from reductions in carbon emissions that will

[9] In addition, DOE accounts for extra years of manufacturer costs toward the beginning of the Rule's operation, covering years 2013 to 2017, after announcement of the Rule but before the compliance date. Final TSD, No. 102 at 12-22.

occur in the first 30 years of the Rule's operation, the same time frame used for the analysis of the Rule's costs. *See* AHRI Br. 37-38.

Petitioners argue that DOE improperly failed to count future indirect costs, while counting hypothetical future climate benefits. *See* AHRI Br. 42. Contrary to Petitioners' claims, DOE did consider the potential future effects of increased manufacturing costs; the analysis accounts directly for the cash value of increased manufacturing costs when they are accrued. 79 Fed. Reg. at 17,773; Final TSD, No. 102 at 12-22. Petitioners argue that these increased manufacturing costs will lead to lower R&D spending and reduced future innovation, but they fail to account for how the discounting process works. Discounting incorporates these foregone investment opportunities. The discount rate accounts for the fact that "[r]esources that are invested will normally earn a positive return," by valuing "current consumption" as "more expensive than future consumption," because society is "giving up that expected return on investment" when it "consume[s] today." Circular A-4 at 32. Because the manufacturer costs are accrued toward the beginning of the analysis period, they are valued more highly when using a discount rate than future climate effects, which reflects the higher opportunity cost of losing access to resources in the short-term. Petitioners also argue that DOE failed to properly consider future effects of employment loss, but DOE did conduct an employment analysis and found the employment effects of the rule to be negligible on balance. *See* Final TSD, No. 102 at 12-26 to 12-27, 16-3 to 16-4.

Petitioners also take issue with the timespan of benefits reflected in the analysis, arguing that intervening factors may change climate outcomes. AHRI Br. 37, 39. However, the SCC models already account for potential adaptation to climate change, as well as uncertainty, and still find strong evidence that carbon emitted today will affect the climate for centuries. *See* Peter Howard, *Omitted Damages: What's Missing From the Social Cost of Carbon* 42-43 (2014); Sections II(B)-(C), *supra*.

Petitioners cite the proposed Clean Power Plan as an example of an intervening factor that may affect climate outcomes in a way not explored in the analysis. However, the Clean Power Plan had not even been proposed when this Rule was finalized on March 28, 2014. *See* 79 Fed. Reg. 34,830 (proposed June 18, 2014). DOE followed standard procedure by considering all *existing* federal and state regulations in developing the emissions baseline used in its analysis. *See* Final TSD, No. 102 at 13-1 ("The analysis of power sector emissions uses . . . DOE's NEMS-BT model, [which] . . . incorporates the projected impacts of . . . current Federal and State legislation and final implementation regulations in place as of the end of December 2012."); *see also* Circular A-4 at 15 (noting that the baseline used for comparison purposes in regulatory impact analysis "should reflect the future effect of current government programs and policies"). If and when the Clean Power Plan is finalized, it will be incorporated into the DOE baseline model for future rulemakings, like all other air emissions regulations. Before a rule is finalized (or even proposed, as in this case), its content may change significantly; DOE's decision to not include the Clean Power Plan in its emissions baseline was eminently reasonable.

In short, DOE conducted a comprehensive cost-benefit analysis that directly compared the present value of all significant benefits and costs resulting from 30 years of this Rule's operation, in accordance with regulatory best practices.

CONCLUSION

For the foregoing reasons, the Court should deny the petitions for review with respect to DOE's use of the social cost of carbon.

DATED: July 29, 2015

Respectfully submitted,

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CERTIFICATE OF COMPLIANCE WITH WORD LIMITATION

I hereby certify that this brief complies with the requirements of Fed. R. App. P. 32(a)(5) and (6) and Circuit Rule 32(b) because it has been prepared in 12-point Century Schoolbook, a proportionally spaced font. I further certify that, in accordance with Federal Rule of Appellate Procedure 32(a)(7)(C), the foregoing Brief of the Institute for Policy Integrity at New York University School of Law as Amicus Curiae In Support of Respondents contains 6,987 words, as counted by counsel's word processing system, and this complies with the applicable word limit established by the Court.

DATED: July 29, 2015

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CERTIFICATE OF SERVICE

I hereby certify that on July 29, 2015, I filed the foregoing Brief of the Institute for Policy Integrity at New York University School of Law as Amicus Curiae In Support of Respondents through the Court's CM/ECF system, which will send a notice of filing to all parties, because all parties are registered CM/ECF users.

DATED: July 29, 2015

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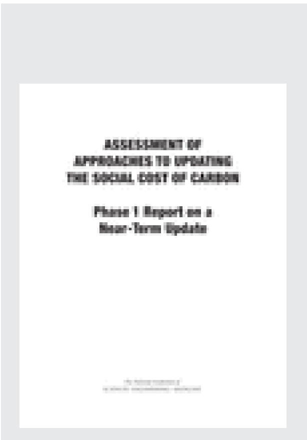
Exhibit F


ASSESSMENT OF APPROACHES TO UPDATING THE SOCIAL COST OF CARBON

Phase 1 Report on a Near-Term Update

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BOARD ON ENVIRONMENTAL CHANGE AND SOCIETY
2015-2016

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Academies of Sciences, Engineering, and Medicine's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We thank the following individuals for their participation in their review of this report:

Kenneth J. Arrow, Department of Economics, Stanford University;
James (Jae) Edmonds, Joint Global Change Research Institute, Pacific Northwest National Laboratory;
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Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions nor did they see the final draft of the report before its release. The review of this report was overseen by Elisabeth M. Drake, Massachusetts Institute of Technology, appointed by the Division of Behavioral and Social Sciences and Education, and Charles F. Manski, Northwestern University, appointed by the Report Review Committee, who were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

Acronyms

AR4	IPCC's Fourth Assessment Report
AR5	IPCC's Fifth Assessment Report
CH_4	Methane
CMIP3	Coupled Model Intercomparison Project Phase 3
CMIP5	Coupled Model Intercomparison Project Phase 5
CO_2	Carbon dioxide
DICE	Dynamic Integrated Climate-Economy Model
ECS	Equilibrium climate sensitivity
EgC	Exagram of carbon, 1 trillion tons of fossil carbon
EMF 22	Energy Modeling Forum's 22nd study
FUND	Climate Framework for Uncertainty, Negotiation and Distribution
Gt	Gigaton, 1,000,000,000 tons
IAM	Integrated assessment model
IPCC	Intergovernmental Panel on Climate Change
IPT	Initial pulse-adjustment timescale
IWG	Interagency Working Group on the Social Cost of Carbon
N_2O	Nitrous oxide
OMB	Office of Budget and Management
PAGE	Policy Analysis of the Greenhouse Effect
PETM	Paleocene-Eocene Thermal Maximum (in Figure 3-1)
ppm	Parts per million
RCP/ECP	Representative concentration pathway/extended concentration pathway
SCC	Social cost of carbon
SF_6	Sulfur hexafluoride
TCR	Transient climate response
TCRE	Transient climate response to cumulative carbon emissions
Tt C	Teraton of carbon, 1 trillion tons of fossil carbon
USG1	U.S. Government 1 (a designation for one of the five socioeconomic scenarios used in the IAMs)
USG2	U.S. Government 2 (a designation for one of the five socioeconomic scenarios used in the IAMs)
USG5	U.S. Government 5 (a designation for one of the five socioeconomic scenarios used in the IAMs)
W/m^2	Watts per square meter

Executive Summary

The social cost of carbon (SCC) for a given year is an estimate, in dollars, of the present discounted value of the damage caused by a 1-metric ton increase in carbon dioxide (CO_2) emissions into the atmosphere in that year or, equivalently, the benefits of reducing CO_2 emissions by the same amount in that year. The SCC is intended to provide a comprehensive measure of the monetized value of the net damages from global climate change that results from an additional unit of CO_2, including, but not limited to, changes in net agricultural productivity, energy use, human health effects, and property damages from increased flood risk. Federal agencies use the SCC to value the CO_2 emissions impacts of various regulations, including emission and fuel economy standards for vehicles; emission standards for industrial manufacturing, power plants, and solid waste incineration; and appliance energy efficiency standards.

The Interagency Working Group on the Social Cost of Carbon (IWG) developed a methodology for estimating the SCC and applied that methodology to produce estimates that government agencies use in regulatory impact analyses under Executive Order 12866. The IWG requested this Academies interim report to determine if a near-term update to the SCC is warranted, with specific questions pertaining to the representation of the equilibrium response of the climate system in the integrated assessment models used by the SCC modeling structure, as well as the presentation of uncertainty of the SCC estimates. This interim report is the first of two reports requested by the IWG: the second (Phase 2) report will examine potential approaches for a more comprehensive update to the SCC estimates.

The committee concludes that there would not be sufficient benefit of modifying the estimates to merit a near-term update that would be based on revising a specific parameter in the existing framework used by the IWG to reflect the most recent scientific consensus on how global mean temperature is, in equilibrium, affected by CO_2 emissions. Furthermore, the committee does not recommend changing the distributional form used to capture uncertainty in the equilibrium CO_2 emissions-temperature relationship. Rather than simply updating the distribution used for equilibrium climate sensitivity—the link that translates CO_2 emissions to global temperature change—in the current framework, the IWG could undertake efforts toward the adoption or development of a common representation of the relationship between CO_2 emissions and global mean surface temperature change, its uncertainty, and its profile over time. The committee outlines specific diagnostic criteria that can be used to assess whether such a module is consistent with the best available science.

Further, the committee recommends that the IWG provide guidance in their technical support documents about how SCC uncertainty should be represented and discussed in individual regulatory impact analyses that use the SCC. The committee recommends that each update of the SCC include a section in the technical support document that discusses the various types of uncertainty in the overall SCC estimation approach, addresses how different models used in SCC estimation capture uncertainty, and discusses uncertainty that is not captured in the estimates. In addition, the committee notes that it is important to separate the effects of the discount rate on the SCC from the effects of other sources of variability. Finally, the committee recommends that the IWG provide symmetric treatment of both low and high values from the frequency distribution of SCC estimates conditional on each discount rate.

The committee also reminds readers that it will be exploring these and other broader issues further in Phase 2 of this study; the committee may offer further discussion of these issues in its Phase 2 report including the modeling of the climate system and the representation of uncertainty in the estimation of the SCC.

1
Introduction

The social cost of carbon (SCC) for a given year is an estimate, in dollars, of the present discounted value of the damage caused by a 1-metric ton increase in CO_2 emissions into the atmosphere in that year or, equivalently, the benefits of reducing CO_2 emissions by the same amount in that given year.[1] The SCC is intended to provide a comprehensive measure of the monetized value of the net damages from global climate change from an additional unit of CO_2, including, but not limited to, changes in net agricultural productivity, energy use, human health effects, and property damages from increased flood risk.[2] Federal agencies use the SCC to value the CO_2 emissions impacts of various policies including emission and fuel economy standards for vehicles, regulations of industrial air pollutants from industrial manufacturing, emission standards for power plants and solid waste incineration, and appliance energy efficiency standards.

HISTORY AND DEVELOPMENT OF THE SCC

The effort to incorporate the SCC into regulatory decision making started during the latter part of the George W. Bush Administration. Prior to 2008, changes in CO_2 emissions were not valued in the cost-benefit analysis required when establishing federal rules and regulations (U.S. Government Accountability Office, 2014, p. 5). After a 2008 court ruling[3] that required incorporation of the benefits of CO_2 emissions reductions in every regulatory impact analysis, federal agencies began using a variety of methodologies for determining a dollar value for the SCC. In an effort to standardize SCC estimates across the federal government, in 2009 the Obama Administration assembled the Interagency Working Group on the Social Cost of Carbon (IWG) of technical experts from across the government to develop a single set of estimates.[4] Interim values for the SCC from the IWG were first used in a regulatory impact analysis for an August 2009 Department of Energy energy efficiency standard for beverage vending machines (74 *Federal Register* 44914). The SCC has since been used in dozens of regulatory actions (U.S. Government Accountability Office, 2014, App. I). For example, the March 2010 *Energy Conservation Program: Energy Conservation Standards for Small Electric Motors Final Rule*[5] used the SCC to monetize its global climate impacts.

Following the establishment of interim values for the SCC, the IWG undertook a more in-depth process that produced a February 2010 Technical Support Document with a more fully

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[1]In this report, we present all values of the SCC as the cost per metric ton of CO_2 emissions.

[2]Here, and throughout this report, "damage" is taken to represent the net effects of both negative and positive economic outcomes of climate change.

[3]*Center for Biological Diversity v. National Highway Traffic Safety Administration,* U.S. Court of Appeals, Ninth Circuit, 538 F.3d 1172 (9th Cir. 2008).

[4]The IWG, which operates under the U.S. Global Change Committee, is cochaired by the Council of Economic Advisors and the Office of Management and Budget; the other members are the Council on Environmental Quality, the Domestic Policy Council, the Department of Agriculture, the Department of Commerce, the Department of Energy, the Department of Transportation, the Environmental Protection Agency, the National Economic Council, the Office of Science and Technology Policy, and the Department of the Treasury.

[5]EERE–2007–BT–STD–0007, 75 *Federal Register* 10873.

developed methodology and a resulting set of four SCC estimates for use by government agencies. The estimates were developed employing the three most widely cited integrated assessment models (IAMs) that are capable of estimating the SCC, which this report refers to as "SCC-IAMs." Although the three SCC-IAMs were not developed solely to estimate the SCC, they are among the very few models that calculate net economic damages from CO_2 emissions. Since there are many IAMs in use in the climate change research community for multiple purposes, this report refers to these three models specifically as SCC-IAMs.[6]

The IWG retained most of the SCC-IAMs developers' default assumptions for the parameters and functional forms in the models, but with some important exceptions, and also a harmonized approach to discounting the results in future time periods across the models. The two exceptions are that the IWG used a single probability distribution for the equilibrium climate sensitivity (ECS)[7] parameter for all models, as well as a common set of five future socioeconomic and emissions scenarios. In addition, three constant discount rates were used for each SCC-IAM. The analysis resulted in 45 sets of estimates (three IAMs, five socioeconomic-emissions scenarios, one ECS distribution, and three discount rates) for the SCC for a given year, with each set comprising 10,000 estimates drawn on the basis of the uncertain variables in the models. The IWG summarized the results into an average value for each discount rate, plus a fourth value, selected at the 95th percentile for a 3 percent discount rate, intended to represent higher-than-expected impacts from temperature change farther out in the tail of the SCC estimates.

Motivation for the Study

There are significant challenges to estimating a dollar value that reflects all the physical, human, ecological, and economic impacts of climate change. Recognizing that the models and scientific data underlying the SCC estimates evolve and improve over time, the federal government made a commitment to provide regular updates to the estimates. For example, the IWG updated SCC estimates in May 2013 to take into account a variety of model-specific updates in each of the three SCC-IAMs.[8]

The IWG requested this National Academies of Sciences, Engineering, and Medicine study to assist future revisions of the SCC in two important ways. First, it requested that this study provide government agencies that are part of the IWG with an assessment of the merits and challenges of a limited near-term update to the SCC. Specifically, it requested that the committee consider whether there is sufficient benefit to conducting a limited near-term update to the SCC in light of ECS updates in the Fifth Assessment Report (AR5) of Working Group 1 of the Intergovernmental Panel on Climate Change (IPCC); whether a different distributional form should be used for the ECS; and whether the IWG should adopt changes in its approaches for

[6]There are many types of IAMs, which vary significantly in structure, resolution, computational algorithm, and application. In comparison with most other IAMs, the three SCC-IAMs used by the IWG, Dynamic Integrated Climate-Economy Model, Framework for Uncertainty, Negotiation and Distribution, and Policy Analysis of the Greenhouse Effect are specialized in their focus on modeling aggregate global climate damages and their highly aggregated economic and energy system representations, rather than being focused on potential economic, energy, and land system development and transformation. We note, however, that these models were not designed solely to estimate the SCC.

[7]ECS measures the long-term response of global mean temperature to a fixed forcing, conventionally taken as an instantaneous doubling of CO_2 concentrations from their preindustrial levels; see Chapter 3.

[8]In November 2013 and July 2015, the IWG also revised the estimates slightly to account for minor technical corrections.

enhancing the qualitative characterization of limitations and uncertainties in SCC estimates to increase their transparency for use in regulatory impact analyses.

Second, the IWG requested that the committee consider the merits and challenges of a comprehensive update of the SCC to ensure that the estimates reflect the best available science. Specifically, it requested that the committee review the available science to determine its applicability for the choice of IAMs and damage functions and examine issues related to climate science modeling assumptions, socioeconomic and emissions scenarios, the presentation of uncertainty, and discounting. The full statement of task is in Box 1-1.

Accordingly, the committee will recommend approaches that warrant consideration in future updates of the SCC estimates, as well as recommendations for research to advance the science in areas that are particularly useful for estimating the SCC. The committee will examine the merits and challenges of potential approaches for both a near-term limited update and longer-term comprehensive updates to ensure that the SCC estimates reflect the best available science and methods. As such, the study will be conducted in two phases and will result in two reports. This interim report focuses on near-term updates to the SCC estimates, Phase 1 of the study, and is narrowly scoped so that a consensus report could be produced in the short time line required (within 6 months). Phase 2 allows for broader consideration of the SCC.

BOX 1-1
Statement of Task

An ad hoc multidisciplinary committee will be appointed to inform future revisions to estimates of the social cost of carbon (SCC) developed and used by the federal government. The committee will examine the merits and challenges of potential approaches for both a near-term limited update and longer-term comprehensive updates to ensure that the SCC estimates continue to reflect the best available science and methods. The study will be conducted in two phases and will result in two reports.

Phase 1.

In Phase 1, the committee will assess the technical merits and challenges of a narrowly focused update to the SCC estimates and make a recommendation on whether to conduct an update of the SCC estimates prior to recommendations related to a more comprehensive update based on its review of the science related to the topics covered in the second phase. Specifically, the committee will consider whether an update is warranted based on the following:

1. Updating the probability distribution for the ECS to reflect the recent Intergovernmental Panel on Climate Change (IPCC) consensus statement in the Fifth Assessment Report of the IPCC, rather than the current calibration used in the SCC estimates, which were based on the most authoritative scientific consensus statement available at the time (the 2007 Fourth IPCC Assessment).
2. Recalibrating the distributional forms for the ECS by methods other than the currently used Roe and Baker (2007) distribution.
3. Enhancing the qualitative characterization of uncertainties associated with the current SCC estimates in the short term to increase the transparency associated with using these estimates in regulatory impact analyses. Noting that as part of a potential comprehensive update Part 2 of the charge requests information regarding the opportunity for a more comprehensive, and possibly more formal or quantitative, treatment of uncertainty.

The Phase 1 report will be an interim letter report to be completed in 6 months.

Phase 2.

In Phase 2, which represents the bulk of the statement of task, the committee will examine potential approaches, along with their relative merits and challenges, for a more comprehensive update to the SCC estimates to ensure the estimates continue to reflect the best available science. The committee will be asked to consider issues related to

1. an assessment of the available science and how it would impact the choice of integrated assessment models and damage functions,
2. climate science modeling assumptions,
3. socioeconomic and emissions scenarios,
4. presentation of uncertainty, and
5. discounting.

Within these areas, the committee will make recommendations on potential approaches that warrant consideration in future updates of the SCC estimates, as well as research recommendations based on their review that would advance the science in areas that are particularly useful for estimating the SCC.

Strategy to Address the Study Charge

This study was carried out by a committee of experts appointed by the president of the Academies. The committee consists of 13 members, with the assistance of a technical consultant and study staff. Committee expertise spans the issues relevant to the study task: environmental economics, climate science, energy economics, integrated assessment modeling, decision science, climate impacts, statistical modeling, and public policy and regulation. In composing the committee, care was taken to ensure that the membership possessed the necessary balance between research and practice by including academic scientists and other professionals, that members have the relevant disciplinary expertise, and to ensure there are no current connections that might constitute a conflict of interest with the Department of Energy, the Environmental Protection Agency, or other regulatory agency members of the IWG. The committee cochairs are experts in the fields of environmental and energy economics with demonstrated leadership capabilities. Biographical sketches of the committee members and staff are provided in Appendix A.

To address the Phase 1 task, the committee held one open meeting to receive information from federal agency staff to understand and explore its study charge; see Appendix B for the agenda. Closed sessions at the initial meeting and two subsequent meetings were held to refine and finalize the committee's findings and recommendations. The main body of the report addresses the Phase 1 charge questions.

CRITERIA AND CHALLENGES FOR A NEAR-TERM UPDATE

The committee considered a number of criteria for evaluating the merits and challenges of a near-term update to ECS assumptions within the framework for estimating the SCC. A "near-term update" was understood by the committee to be actions that government staff could undertake in less than 1 year. Specifically, the committee considered five main issues:

1. **Accuracy and characterization of uncertainty of climate system modeling.** If the ECS is updated within the existing SCC modeling framework to reflect the current scientific consensus as represented by the AR5, will it necessarily improve the representation of the response of temperature change to emissions, relative to more complete, state-of-the-art models of the climate system? Both the accuracy and characterization of uncertainty of the emissions-temperature relationship over time are important aspects of that representation.
2. **Overall SCC reliability.** Would a near-term improvement to the representation of ECS be likely to substantially improve the overall SCC estimate, given other elements of the IWG SCC framework that may also warrant improvement?
3. **Alternative options for climate system representation.** Are there near- to mid-term options—in addition to simply adjusting the ECS within the current framework—for altering the representation of the emission-temperature response in the SCC framework? Would these options enhance the ability of the IWG to undertake future updates in a manner that is well connected to developments in the climate science community?
4. **Opportunity cost of near-term efforts in terms of potential longer-term improvements.** Would the value of any near-term update, in terms of improvement in the SCC, justify the opportunity costs of engaging in the effort, rather than focusing instead on longer-term improvements to the SCC? Would such a change, if implemented, be likely to have a substantial effect on the SCC, thereby potentially warranting the near-term investment of resources related to the development of revised SCC estimates?
5. **Consistency of Phase 1 with possible Phase 2 conclusions and recommendations.** Would any actions taken in response to Phase 1 recommendations likely be consistent with actions taken in response to possible Phase 2 recommendations?

The committee also considered specific technical details in their analysis as described in later chapters.

STRUCTURE OF THE REPORT

The rest of the report covers the topics addressed in Phase 1. Chapter 2 describes how the IWG constructed the SCC estimates and is intended to be accessible to all readers. Chapters 3 and 4 present the technical details that underlie the committee's conclusions and recommendations. Chapter 3 describes the role of the ECS in determining temperature changes and discusses several additional relevant climate metrics that reflect the state of the climate literature. Chapter 4 highlights differences in the way the SCC-IAMs represent the climate system. Chapter 5 then summarizes the conclusions from the previous chapters and provides recommendations for whether a limited, short-term update to the ECS distribution is warranted and on how the qualitative characterization of uncertainty can be improved.

Consideration of broader updates to the SCC—including economic damages and damage functions, socioeconomic scenarios, and discounting—are not addressed in this report. These topics will be addressed in Phase 2 of the study, along with further assessment of climate system modeling the treatment of uncertainty (see Box 1-1, above).

2
Modeling the Climate System within the Broader SCC Modeling Structure

This chapter reviews the current methodology used to calculate the social cost of carbon (SCC) to provide the context for the committee's analysis, conclusions, and recommendations. We focus in particular on the assumptions that differ among the SCC integrated assessment models (SSC-IAMs) and uncertainties in the modeling framework.

STEPS IN CONSTRUCTING THE SCC: OVERVIEW

In order to estimate the SCC, one needs to project both the sequence of future annual incremental changes in the climate and the resulting economic damages from a marginal increase in CO_2 emissions, and then convert the stream of incremental economic damages into a present value equivalent (i.e., the total dollar value at the time of emissions of the discounted stream of future damages).[9] Since the atmospheric impacts of CO_2 emissions are global and vary over time, this calculation is complex, and it requires a global model with a long time horizon. The approach taken by the Interagency Working Group on the Social Cost of Carbon (IWG) was to utilize damage valuations from the three SCC-IAMs, described in more detail below. The SCC-IAMs use the causal chain of modeling steps to project incremental changes in climate change and resulting economic damages; see Figure 2-1.

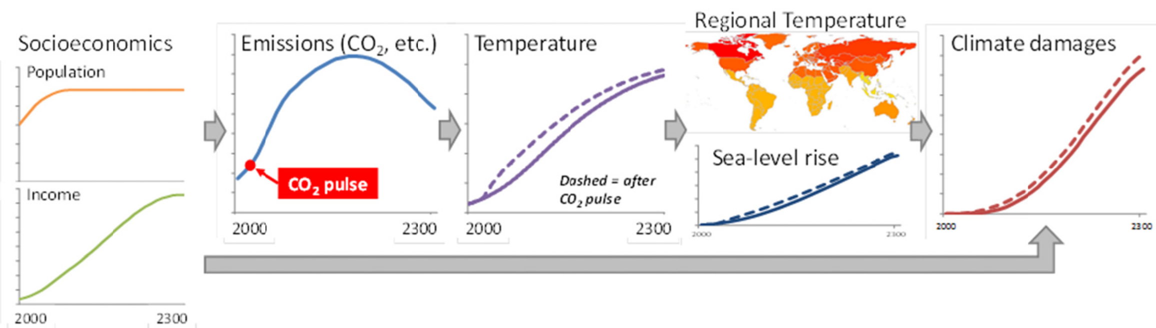

FIGURE 2-1 SCC modeling causal chain.
NOTE: Each figure in this chain represents a key element in the models used to produce estimates of the SCC with projections from one element flowing into the next element. Population and income projections are inputs to the derivation of projections for both emissions and climate damages.
SOURCE: Developed from Rose et al. (2014). Reprinted with permission.

[9]Damages from global climate change include, but are not limited to, changes in net agricultural productivity, energy use, human health effects, and property damages from increased flood risk.

Each model takes as inputs a projection of human population growth and of global or regional income, as well as emissions paths of global greenhouse gases.[10] A simple climate model component of each SCC-IAM translates the reference emissions trajectory into a reference global mean temperature trajectory and a reference trajectory of global mean sea level rise. In two of the models, regional average temperature trajectories are also derived from global mean temperature. Each model then uses one or multiple damage functions to translate temperature and sea level rise into economic damages or benefits. In the IWG analysis, global damages in the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) and Policy Analysis of the Greenhouse Effect (PAGE) are an equally weighted sum of regional damages (i.e., no equity weighting) (Interagency Working Group on the Social Cost of Carbon, 2010, p. 11).

In order to derive an SCC estimate, the impact of a CO_2 emissions pulse is calculated following the same causal chain: the CO_2 pulse is introduced in a particular year, creating a trajectory of temperature (global and regional), sea level rise, and climate damages. The difference between this damage trajectory (the dotted line in Figure 2-1, above) and the reference trajectory (the solid line) in each year is discounted to the present using annual discounting (a constant annual discount rate in the IWG application). The resulting value is an SCC estimate for the given set of assumptions used in the reference and perturbed scenarios.

There are several steps in the causal chain for each SCC-IAM that are worth highlighting because they are different across models and have notable implications for the ultimate calculation of an SCC estimate. We discuss these differences in more detail below, but flag them here:

- emissions can vary in terms of their coverage and time path;
- the reference and perturbed temperature trajectories depend on the way the climate system is modeled within each SCC-IAM; and
- there are significant observed differences in the global climate responses across SCC-IAMs and the regional temperatures derived by downscaling (i.e., by establishing geographically fine-scale information from changes in aggregate climate conditions).

Chapter 4 explores the relevant aspects of the climate systems of the SCC-IAMs in greater technical detail.

Another aspect in which the SCC-IAMs differ is in the handling of damages. The models differ in the spatial and sectoral resolution of damages, and they differ in which sectors are the most important sources of climate damages. For two of the models (Dynamic Integrated Climate-Economy Model [DICE], and PAGE), damages are functions of only temperature and income, while for the other (FUND) they are also functions of the rate of temperature increase, CO_2 concentrations, per capita income, population, and other drivers.

Overall, each SCC-IAM follows roughly the same causal chain in terms of the sequence of modeling information flow, yet differs in the model translations at each step. The IWG uses the following versions of three IAMs (IWG 2013, 2015):

[10] As designed, each of the three SCC-IAMs derives emissions from socioeconomic projections. However, in the IWG application of those models, socioeconomic and emissions projections were taken from an external source for two of the models, while the third derived its own fossil fuel combustion and industry CO_2 emissions.

- the 2010 version of DICE by William Nordhaus;
- version 3.8 of FUND by Richard Tol and David Anthoff; and
- the 2009 version of PAGE model by Chris Hope.

We note, however, that the IWG model version may be different from the modeler's original or most recent versions.

As mentioned above, the three models differ in the details of their implementation. Table 2-1 provides a broad summary of their dimensions. For a more comprehensive comparison of those differences, see Rose et al. (2014). Specific differences in socioeconomic and emissions modeling are described below, and, in Chapter 4, we discuss climate system modeling.

TABLE 2-1 SCC-IAM Coarse Feature Comparison

	DICE 2010	FUND v3.8	PAGE 09
Regions	1 region	16 regions	8 regions
Damage Sectors	2 sectors	14 sectors	4 sectors
Regional Temperature Downscaling	No	Yes	Yes
Damage Drivers	Temperature (level), income (total)	Temperature (level and growth), CO_2 concentration, income (total and per capita), population size/composition, other[a]	Temperature (level), income (total and per capita)
Sea Level Rise (SLR) Damage Specification	Quadratic function of global sea level rise (i.e., Damage = αSLR^2)	Additive functions for coastal protection costs, dryland loss, and wetland loss, based on an internal cost-benefit rule for optimal adaptation	Power function of global sea level rise (i.e., Damage = $\alpha SLR^{0.7}$)
Damage Specification (Excluding Sea Level Rise)	Quadratic function of global temperature (i.e., Damage = αT^2)	Uniquely formulated by sector	Power function of regional temperature (i.e., Damage = $\alpha T^{1.76}$)
Model-Specific Parametric Uncertainties	None	Yes (in climate and damage modeling)	Yes (in climate and damage modeling)
"Catastrophic" or "Discontinuity" Damages Included	Yes (as expected damages)	No	Yes (as uncertain threshold)

[a]"Other" includes: dryland value, wetland value, topography (elevation, coast length), protection cost, ocean temperature, and technological change.
SOURCE**:** Developed from Rose et al. (2014). Reprinted with permission.

As can be seen in the table above, there are several high-level structural differences among the SCC-IAMs. DICE is global (i.e., has only 1 region), while FUND and PAGE split the world into 16 and 8 regions, respectively. Each SCC-IAM covers multiple damage sectors, but only FUND disaggregates economic sectors in any detail. Since DICE is a global model, only FUND and PAGE downscale regional temperatures (with different methods).

The models also differ in the specific drivers of climate damages and their functional specification. DICE and PAGE use power functions—a quadratic or other polynomial function of temperature or sea level rise—for each of the represented sectors. FUND, on the other hand, disaggregates damage functions into a more detailed set of sectors. In addition, FUND and PAGE both consider model-specific climate and damage parametric uncertainty—each of those models allows for certain parameters to be drawn from probability distributions. Thus, FUND and PAGE reflect some uncertainty in their specifications; however, those characterizations and their implications vary between the two models (see Rose et al., 2014).

METHODOLOGY

The IWG methodology for constructing the official U.S. SCC estimates is discussed in detail in the IWG technical support documents (Interagency Working Group on the Social Cost of Carbon, 2010, 2013, 2015). The methodology results in 150,000 estimates of the SCC for each year and discount rate, yielding a frequency distribution of SCC results; see Figure 2-2. Percentiles and summary statistics of these estimates, also shown in Figure 2-2, are presented in the IWG technical support documents.[11]

In order to arrive at the 150,000 estimates for each discount rate, each of the three models was run 10,000 times with random draws from the equilibrium climate sensitivity (ECS) probability distribution (and other model-specific uncertain parameters), for each of the five socioeconomic scenarios (150,000 estimates = three models × five socioeconomic scenarios × 10,000 runs), for each of three discount rates (2.5 percent, 3 percent, and 5 percent).[12] Frequency distributions of results for 2020 estimates were summarized for each model, socioeconomic scenario, and discount rate.

To facilitate the use of the SCC in regulatory analysis, the values of the SCC are averaged across the three SCC-IAMs and the five emissions scenarios, implicitly defining a frequency distribution of SCC values conditional on each discount rate. In averaging the results across models and emissions scenarios, all models and all emissions scenarios are given equal weight. Figure 2-2 is an example of the resulting frequency distribution for 2020 SCC estimates as reported in the IWG's 2015 technical support documents.[13] The average value of the SCC is shown for each discount rate, using a vertical line, as is the 95th percentile of the frequency distribution of SCC results for the case of a 3 percent discount rate. The larger SCC estimates in Figure 2-2 arise, in part, from realizations in the positively skewed right tail of the ECS distribution used by the IWG.

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[11]The full set of estimates is available on request from the IWG.

[12]In terms of standardized uncertainties across all three models, five reference socioeconomic and emissions scenarios projected until 2300 were used, as well as one common probability distribution for the ECS parameter—the equilibrium temperature change that results from a doubling of CO_2 relative to preindustrial levels. For FUND and PAGE, the IWG methodology included model-specific parametric uncertainties for both the climate and damage components.

[13]Summary statistics of the distribution of results for each model, conditional on discount rate and socioeconomic scenario are reported in an appendix of the IWG's technical support document (Interagency Working Group on the Social Cost of Carbon, 2010, Appendix).

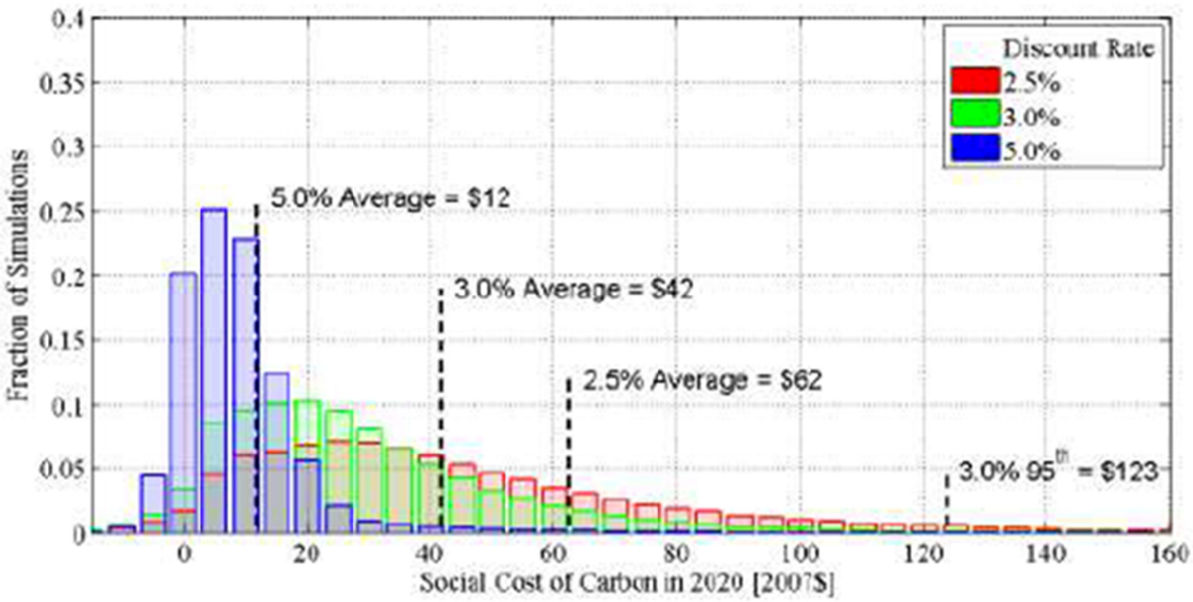


FIGURE 2-2 Frequency distributions of SCC estimates for 2020 (in 2007 dollars per metric ton CO_2).
NOTES: Each histogram (red, green, blue) represents model estimates, conditional on one of three discount rates, over five different socioeconomic-emissions scenarios, 10,000 random parameter draws, and the three SCC-IAMs (see text for discussion). The frequency distributions shown represent most of the 150,000 SCC estimates. However, they do not represent the entire distribution. Some estimates fall outside the range of the horizontal axis shown.
SOURCE: IWG Technical Support Document (Interagency Working Group on the Social Cost of Carbon, 2015, Figure 1).

In the appendix to each technical support document, the frequency distribution of results based on 10,000 runs is summarized for the year 2020 for each SCC-IAM, emissions scenario, and discount rate. Specifically, the average value of the SCC is reported, as well as the 1st, 5th, 10th, 25th, 50th, 75th, 90th, 95th, and 99th percentiles of the frequency distribution of SCC estimates. Table 2-2 illustrates this for a discount rate of 3 percent for each emissions scenario (i.e., 15 sets of results).

TABLE 2-2 2020 Global SCC Estimates at a 3 Percent Discount Rate (2007 dollars/metric ton CO_2).

Percentile	1st	5th	10th	25th	50th	Avg	75th	90th	95th	99th
Scenario					PAGE					
IMAGE	4	7	9	17	36	87	91	228	369	696
MERGE Optimistic	2	4	6	10	22	54	55	136	222	461
MESSAGE	3	5	7	13	28	72	71	188	316	614
MiniCAM Base	3	5	7	13	29	70	72	177	288	597
5th Scenario	1	3	4	7	16	55	46	130	252	632
Scenario					DICE					
IMAGE	16	21	24	32	43	48	60	79	90	102
MERGE Optimistic	10	13	15	19	25	28	35	44	50	58
MESSAGE	14	18	20	26	35	40	49	64	73	83
MiniCAM Base	13	17	20	26	35	39	49	65	73	85
5th Scenario	12	15	17	22	30	34	43	58	67	79
Scenario					FUND					
IMAGE	-13	-4	0	8	18	23	33	51	65	99
MERGE Optimistic	-7	-1	2	8	17	21	29	45	57	95
MESSAGE	-14	-6	-2	5	14	18	26	41	52	82
MiniCAM Base	-7	-1	3	9	19	23	33	50	63	101
5th Scenario	-22	-11	-6	1	8	11	18	31	40	62

SOURCE: IWG Technical Support Document (Interagency Working Group on the Social Cost of Carbon, 2015, Table A.3).

The official SCC estimates are reproduced in Table 2-3 below. For the given years of a CO_2 emission (2010, 2015, 2020, etc.), the four estimates are the average SCC values conditional on the three discount rates, plus the 95th percentile of SCC estimates using a 3 percent discount rate. As noted in the IWG technical support document 2015 update (p. 2):

> Three values are based on the average SCC from three integrated assessment models [SCC-IAMs], at discount rates of 2.5, 3, and 5 percent. The fourth value, which represents the 95th percentile SCC estimate across all three models at a 3 percent discount rate, is included to represent higher-than-expected impacts from temperature change further out in the tails of the SCC distribution.

SCC ESTIMATES

In summary, each single estimate of the 150,000 SCC estimates for each discount rate depends on the SCC-IAM used, the socioeconomic and emissions scenario, a draw from the assumed distribution of the ECS, and, for FUND and PAGE, a draw from the distributions of their particular uncertain parameters. The resulting four official SCC estimates for an emissions year are the mean of the 150,000 results for each discount rate, as well as the 95th percentile for the 3 percent discount rate (see Table 2-3).

TABLE 2-3 Revised Social Cost of CO_2, 2010 - 2050 (in 2007 dollars per metric ton of CO_2).

Discount Rate Year	5.0% Avg	3.0% Avg	2.5% Avg	3.0% 95th
2010	10	31	50	86
2015	11	36	56	105
2020	12	42	62	123
2025	14	46	68	138
2030	16	50	73	152
2035	18	55	78	168
2040	21	60	84	183
2045	23	64	89	197
2050	26	69	95	212

SOURCE: IWG Technical Support Document (Interagency Working Group on the Social Cost of Carbon, 2015, Table 2).

The most recent update of the official SCC estimates is shown in Table 2-3. SCC estimates are provided for different future years on the basis of modeling CO_2 pulses applied in each decade (half decade values are interpolations). The SCC estimates rise over time because, in the models, future emissions produce larger incremental damages as the economy grows and temperature rises.

3
Determining Temperature Changes in Response to CO_2 Emissions

This chapter introduces the technical details that underlie the committee's conclusions and recommendations. The role of the equilibrium climate sensitivity (ECS) in determining temperature changes is described. Several additional relevant climate metrics that reflect the state of the literature are discussed.

The first question in the committee's charge is to consider the merits and challenges associated with a near-term revision of the distribution of the ECS. A broad perspective on the relationship between emissions (a key input to the physical climate/carbon cycle model in the social cost of carbon integrated assessment models [SCC-IAMs]) and global mean temperature (the output) is considered in this chapter. Four metrics are of particular importance to the discussion: ECS, transient climate response (TCR), transient climate response to emissions (TCRE), and the initial pulse-adjustment time (IPT); see Box 3-1. In comparison with other metrics used to summarize the relationship between emissions and temperature change, researchers have noted that the ECS is not necessarily the most relevant physical parameter over the nearer-term timeframes particularly important to determining the SCC (e.g., Otto et al., 2013b).

BOX 3-1
Timescales and Key Metrics for Relating CO_2 Emissions to Temperature Change

The response of global mean temperature to climate forcing can be characterized by a number of different metrics, which represent different timescales.

Equilibrium climate sensitivity (ECS) measures the long-term response of global mean temperature to a fixed forcing, conventionally taken as an instantaneous doubling of CO_2 concentrations from their preindustrial levels. The "long-term" timeframe is set by the time it takes for the ocean as a whole to equilibrate with the change in forcing, typically on the order of many centuries to a couple of millennia. ECS is a measure of long-term planetary response, but it is not comprehensive. It includes the effects of atmospheric and ocean processes involving clouds, water vapor, snow, and sea ice. It does not, however, include other, mostly slower processes, that have not, at least until recently, been represented in coupled global climate models, such as those involving vegetation, land ice, or changes in the carbon cycle; see Figure 3-1.

Transient climate response (TCR) measures the transient response of global mean temperature to a gradually increasing forcing. The timeframe on which TCR is measured allows the shallow "mixed layer" of the ocean to approach equilibrium with the changed forcing, but it does not allow equilibration of the deep ocean. In models, TCR is assessed by increasing CO_2 concentrations at 1 percent per year until CO_2 concentrations double in year 70; TCR is the average temperature over the two decades around the time of doubling (years 61-80).

Transient climate response to emissions (TCRE) measures, on a similar timescale as TCR, the ratio of warming to cumulative CO_2 emissions. While the TCRE has become a widely used metric over the past decade, it has a shorter history in the scholarly literature than ECS or TCR, and thus the methods for assessing it are less established. In models, one way of assessing TCRE is from experiments similar to the 1 percent per year increase used to assess TCR, but using emissions rather than a prescribed change in concentrations to drive the experiment (see, e.g., Gillett et al., 2013). The TCRE is then estimated as the ratio of the TCR to the cumulative CO_2 emissions at the time of CO_2 doubling.

The initial pulse-adjustment timescale (IPT) has only recently been a focus of research and does not have a standard name or definition in the research community, but it may be of considerable importance for estimates of the SCC, which are driven by the injection of a pulse emission of CO_2. The IPT measures the initial adjustment timescale of the temperature response to a pulse emission of CO_2 (see. e.g., Joos et al., 2013; Herrington and Zickfeld, 2014; Ricke and Caldeira, 2014; Zickfeld and Herrington, 2015). For example, Joos et al. (2013) assessed the IPT by adding a 100 gigaton (Gt) carbon pulse to baseline emissions that stabilized CO_2 concentrations at a reference level of 389 ppm; the IPT from such an experiment is the time at which peak warming occurs in response to the pulse.

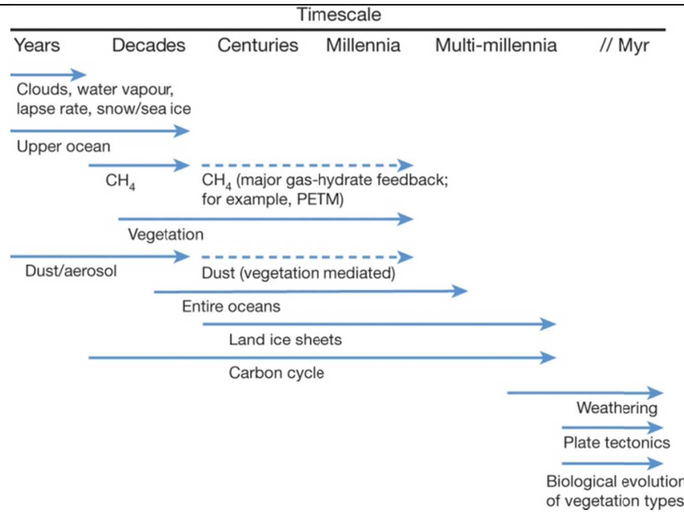


FIGURE 3-1 Different climate processes operate on different timescales.
NOTES: Atmospheric and oceanic processes operating on annual to decadal timescales affect the TCR; these include cloud formation, changes in water vapor, lapse rate, snow and sea ice, as well as heat exchange with the upper ocean. Heat exchange with the deep ocean also affects the ECS. Other processes that can contribute to the global mean surface temperature change caused by a forcing that have not, at least until recently, been included in coupled global climate models are not included in the definition of ECS and TCR. These include changes in vegetation, dust, ice sheets, and the carbon cycle. Some simple climate models do attempt to represent these additional processes.
SOURCE: PALAEOSENS Project (2012, Figure 1).

Modeling the effect of CO_2 emissions on global mean surface temperature entails estimating the effect of emissions on atmospheric CO_2 concentrations, the effect of CO_2 concentrations on radiative forcing, and the effect of forcing on temperature. Although this path is complex, the result appears to be a simpler relationship between temperature and cumulative emissions than between temperature and forcing. As described below ("The Carbon Cycle and TCRE"), the relationship between cumulative CO_2 emissions and global mean temperature change is approximately linear and can be summarized by a single parameter: the transient climate response to cumulative carbon emissions in the industrial era (TCRE). TCRE measures, on a time scale of decades, the ratio between CO_2-induced warming and cumulative emissions, expressed in units of °C/Tt C, where 1 Tt C is 1 trillion tons of fossil carbon or 3.67 trillion tons of CO_2. TCRE is, in turn, determined primarily by TCR (see Matthews et al., 2009; Gillett et al., 2013).

Calculating the SCC entails estimating a baseline temperature trajectory and the temperature response to a pulse of CO_2. The multidecade-to-century warming caused by a pulse of CO_2 can be approximated as the product of the TCRE and the total cumulative amount of carbon injected. The speed of this response, determined by the IPT, is also important for estimating the SCC; see discussion below ("Implications for Estimation of the SCC").

In Chapter 4, the committee details the implications of the discussion in this chapter for calculation of the SCC. The importance of ECS, relative to TCR, depends on the time pattern of damages associated with a time pattern of global temperature change. The higher the fraction of the present discounted value of damages that occur in the first century after emissions, the more important is the TCR relative to the ECS, since the TCR is a much better predictor of climate response on time scales of less than a century. In Chapter 4, the committee outlines tests that could be applied to the simple climate models used to generate the SCC to determine whether the central projections of these models agree with those of the class of Earth system models used by the Intergovernmental Panel on Climate Change (IPCC).[14]

EQUILIBRIUM CLIMATE SENSITIVITY AND TRANSIENT CLIMATE RESPONSE

The concepts of ECS and TCR arise, in their simplest form, from the conservation of energy. In equilibrium, the incoming solar radiation absorbed by Earth balances the outgoing longwave infrared radiation emitted by the planet to space. If either the absorbed solar radiation or the outgoing longwave radiation is perturbed from an equilibrium state, the heat content of the climate system will change at a rate set by the magnitude of the imbalance. The absorbed solar radiation is controlled by the amount of incoming solar radiation and by the Earth's albedo, which is the fraction of the incoming solar radiation reflected away by the atmosphere or the surface. The amount of outgoing longwave radiation is set primarily by the planet's radiative temperature—the temperature of the atmospheric level from which, on average, infrared radiation can be emitted through the "haze" of infrared-absorbing greenhouse gases and clouds to space. Because the radiative temperature increases as the climate system absorbs heat (thereby increasing outgoing longwave radiation) and declines as the climate system loses heat (thereby decreasing outgoing longwave radiation), the imbalance, and thus the rate of temperature change in response to a perturbation, declines over time until a new equilibrium is reached.

A climate forcing (measured in W/m^2 [watts per square meter]) refers to a decrease in net outgoing energy, relative to some initial state in which the planet was in equilibrium, driven by an exogenous factor, such as a change in greenhouse gas or aerosol concentrations. The change in temperature caused by a forcing triggers climate feedbacks: additional changes in the planet's albedo or emissivity that amplify or dampen the energy imbalance and thus cause additional changes in temperatures. Feedbacks involving greenhouse gases and clouds affect emissivity; those involving aerosols, clouds, and land surface characteristics affect albedo. For example, water vapor, which increases in concentration with temperature and thereby decreases emissivity, gives rise to one important amplifying feedback—sea ice—which decreases in surface area with temperature and thereby increases albedo, giving rise to another (amplifying) feedback.

To a good approximation, the equilibrium change in global mean temperature is proportional to the forcing applied. This magnitude is captured by ECS. However, the equilibrium response to a forcing may take centuries to be realized. Within the context of SCC estimates, it is therefore necessary to understand the *transient response* both to the range of human-caused forcings and to a pulse of CO_2, the marginal impact of which the SCC estimates. One common metric of the transient response is the TCR, which is defined as the global mean surface temperature change at the time of CO_2 doubling for a benchmark forcing scenario, specifically, an increase in CO_2 concentrations at a rate of 1 percent per year: see Figure 3-2. Under such a scenario, the time of CO_2 doubling occurs at year 70, and the TCR estimate is generally made by averaging global mean surface temperature over years 61-80. Just as ECS is a general measure of the equilibrium response to any indefinitely sustained radiative forcing, TCR is a general measure of the transient response to a gradually increasing radiative forcing. Because

[14]For formal definitions of IPCC-class Earth system models, see Randall et al. (2007).

the climate system does not instantaneously re-equilibrate in response to a forcing, TCR is always less than ECS.

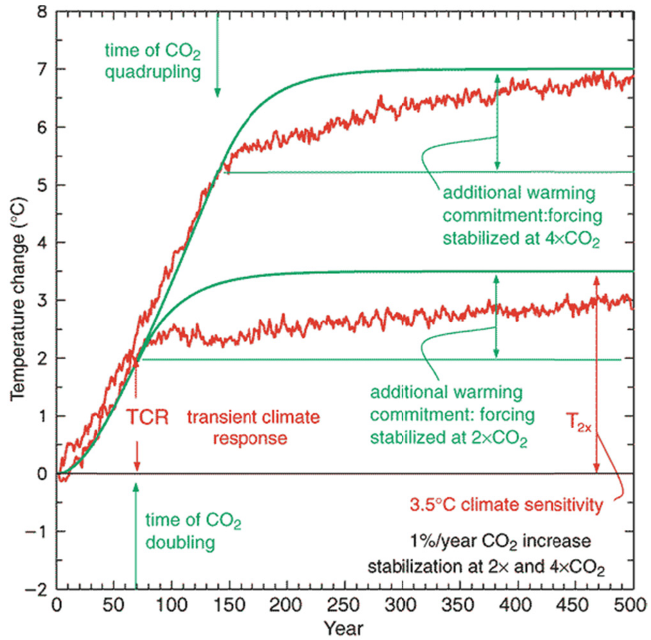


FIGURE 3-2 Global mean temperature response to selected scenarios.
NOTES: CO_2 concentrations increase at 1%/year and stabilize either at two times pre-Industrial CO_2 in year 70 or four times pre-Industrial CO_2 in year 140. Results from a coupled global climate model are shown in red; results from a one-box energy balance model are shown in green. TCR is measured as the average response of the system over years 61-80; ECS is measured after long-term equilibration at two-times CO_2.
SOURCE: Cubasch and Meehl (2001, Figure 9.1).

One source of the difference between ECS and TCR can be observed in a simple “one-box” energy balance model, in which all the heat taken up by the climate system as a result of a forcing is distributed evenly through the climate system as a whole. In such a simple model, the rate of increase in global mean temperature is directly proportional to the rate of heat uptake, with the proportionality set by the heat capacity of the climate system. In response to an instantaneous change in forcing, the temperature of a one-box climate will evolve toward its equilibrium response following an exponential decay with a single timescale. The timescale is directly proportional to both the heat capacity and ECS (see, e.g., Hansen et al., 1985). TCR therefore increases with ECS at a substantially less-than-linear rate: if the TCR is 2°C with an ECS of 3°C, then with the same heat capacity and an ECS of 6°C, TCR will be just 2.8°C.

In contrast to this simple one-box model, full-complexity climate models exhibit two dominant timescales of temperature change in response to a forcing: a fast timescale, associated with the response of the atmosphere and ocean mixed layer (the surface ~100 meters of the ocean), and a slow timescale, associated with the response of the deep ocean. The atmosphere and the mixed layer respond on a timescale of years to a change in forcing, while the deep ocean takes decades to centuries to warm, which slows down the overall response (see, e.g., Hansen et al., 1984; Held et al., 2010). In the scenario used to measure TCR, the mixed layer is nearly fully equilibrated with the applied forcing at the time TCR is assessed, but the deep ocean can be far from equilibrium. These two timescales can be adequately represented in a “two-box” simple climate model that distinguishes between the surface and the deep ocean (see, e.g., Gregory, 2000; Held et al., 2010).

The magnitude of ECS is uncertain due to a number of factors. First, the historical forcing, particularly the historical aerosol forcing, is uncertain (Myhre et al., 2013). Second, as noted, warming lags any radiative forcing, with the strong response implied by a high ECS that takes longer to realize than a weaker response associated with a low ECS. This lag makes it more challenging to distinguish values of ECS observationally. Third, the rate and magnitude of the heat flux from the mixed layer into the deep ocean are uncertain; accordingly, the same transient response can be produced either with a low ECS and faster ocean mixing, or a higher ECS and slower ocean mixing.

A fourth challenge has been identified in recent years: state-dependent feedbacks. Earth's outgoing longwave radiation depends not only on the average radiative temperature, but also on the spatial pattern of temperature, which changes as the planet warms. Accordingly, the rate of energy loss to space also depends on how far the system is from equilibrium (Held et al., 2010). As one example, cloud feedbacks can exhibit state dependence that is represented in atmosphere-ocean global circulation models and Earth system models but not in the simple climate models that specify a fixed ECS value.[15] State-dependent feedbacks can also be related to long-term changes in ocean circulations, land-surface conditions, ocean carbon uptake, and the cryosphere.

This state dependence gives rise to an *effective climate sensitivity*—not ECS, equilibrium climate sensitivity—that is constrained by observations of the recent energy budget constraint. Winton et al. (2010) found that, in 17 of the 22 global climate models participating in the Coupled Model Intercomparison Project Phase 3 (CMIP3),[16] the effective climate sensitivity at the time of CO_2 doubling was less than ECS. Estimates of ECS based on recent climate observations are actually estimates of effective climate sensitivity and may therefore significantly underestimate the true equilibrium response. Unfortunately, there are no clear observational constraints on the relationship between effective and equilibrium climate sensitivity, but this distinction does explain why different approaches to estimating ECS can provide very different ranges (depending on whether or not they assume, implicitly, a specific relationship between the two sensitivity parameters). Although paleoclimatic observations can provide additional constraints on ECS, they are hampered by uncertainties in past forcing and climate data.

Because of these four challenges and the associated uncertainties, the uncertainty in ECS is quite large, with a positively skewed tail of possible high values. A major source of this uncertainty can be seen from the simple treatment of Roe and Baker (2007), whose analysis gave rise to the form of the probability distribution for ECS currently used in the U.S. government's SCC analysis; see Figure 3-3. In the absence of any climate feedbacks other than the "Planck feedback" (by which changes in surface temperature stabilize radiative temperature), ECS would be about 1.2°C (e.g., Hansen et al., 1981). However, other feedbacks come into play. Using f to indicate the total magnitude of these feedbacks on temperature change and ECS_0 the value of ECS including only the Planck feedback gives $ECS = \frac{ECS_0}{1-f}$. The different processes contributing to f add linearly. The positive skewness of the ECS distribution arises from those values of f that approach 1. The Roe and Baker (2007) distributional form for ECS arises simply by assuming

[15]For formal definitions of atmospheric-ocean global circulation models, see Randall et al. (2007).

[16]CMIP provides a standard experimental protocol for IPCC-class global circulation models, and provides community-based support for climate model diagnosis, validation, intercomparison, documentation, and data access.

that *f* has a truncated normal distribution; the associated long right tail would also arise from many other symmetric distributions of *f*.

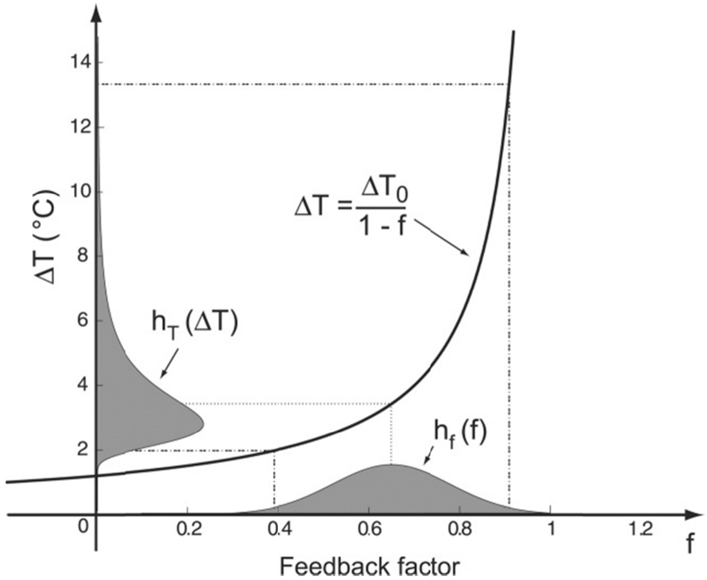


FIGURE 3-3 The relationship between ECS and a feedback factor.
NOTES: The feedback factor is given by $ECS = \frac{ECS_0}{1-f}$ (solid curve). The distributional form for ECS, plotted on the y axis, arises from a truncated normal distribution for the feedback factor, plotted on the x axis.
SOURCE: Roe and Baker (2007, Figure 1). Reprinted with permission from AAAS.

Because larger equilibrium responses caused by higher ECS take longer to realize, TCR is less skewed than ECS (Baker and Roe, 2009). Moreover, whereas ECS may take centuries of data to constrain, the transient response by definition plays out over timescales of less than a century; it can therefore be better constrained by observations (e.g., Gregory and Forster, 2008; Otto et al., 2013a). Box 3-2 describes how IPCC statements regarding the ECS and TCR have evolved from the Fourth to the Fifth Assessment Report (AR4 and AR5), as well as research since the AR5.

ECS and TCR by definition exclude feedbacks—such as those involving dust, vegetation, or land ice—that have not traditionally been represented in coupled climate models. If these other feedbacks are predominantly positive, for the timescales on which they are operative, measures such as ECS and TCR may understate the expected warming. Indeed, geological data suggest that omitted feedbacks may significantly amplify warming relative to that expected based on ECS alone (e.g., PALAEOSENS Project, 2012). Attempts to include relevant processes in Earth system models are a major area of active research. Some simple climate models also attempt to incorporate feedbacks traditionally absent from coupled climate models.

Because the experiments to assess ECS and TCR prescribe only CO_2 concentrations, these metrics also exclude carbon cycle feedbacks. The next section highlights the important role of land and ocean carbon cycle feedbacks in giving rise to CO_2 warming processes operating over millennia.

BOX 3-2
IPCC Estimates of ECS and TCR

The IPCC AR4 concluded

> [on the basis of] observed climate change and the strength of known feedbacks simulated in GCMs [global circulation models] … that the global mean equilibrium warming for doubling CO_2, or "equilibrium climate sensitivity," is likely to lie in the range 2°C to 4.5°C, with a most likely value of about 3°C. Equilibrium climate sensitivity is very likely larger than 1.5°C.

Following the standard interpretation of IPCC likelihood statements (see Table 3-1), the Interagency Working Group on the Social Cost of Carbon (IWG) (Interagency Working Group on the Social Cost of Carbon, 2010) calibrated a Roe and Baker (2007) distribution such that there was a 67 percent probability of a value between 2°C and 4.5°C. Although the IPCC does not detail a specific interpretation for the phrase "most likely," the IWG interpreted it as indicating the median of the calibrated distribution.

The IPCC AR5 revised this assessment of ECS:

> ECS is likely in the range 1.5°C to 4.5°C with high confidence. ECS is positive, extremely unlikely less than 1°C (high confidence), and very unlikely greater than 6°C (medium confidence).

Two changes between AR4 and AR5 are noteworthy. First, AR5 provided no "most likely" value. Second, AR5 reduced the lower bound of the likely range to 1.5 ºC, which was also the value used in the First, Second, and Third Assessment Reports, largely in response to a set of studies based on comparisons of climate observations, extended into the most recent decades, with simple climate models. Subsequent work (Andrews et al., 2012; Gregory et al., 2015; Knutti et al., 2015) has noted that many of these approaches neglected the difference between effective climate sensitivity and ECS, and so these values may underestimate ECS.

Regarding TCR, whereas AR4 concluded that TCR was "very likely above 1°C" and "very likely below 3°C" (i.e., an 80% probability of being between 1°C and 3°C),[a] the AR5 concluded

> with high confidence that the TCR is likely in the range 1°C to 2.5°C, close to the estimated 5 to 95% range of CMIP5 [Coupled Model Intercomparison Project Phase 5] (1.2°C to 2.4°C), is positive and extremely unlikely greater than 3°C.

The AR5 thus reduced the probability of TCR values greater than 3°C from 10 percent to 5 percent. The estimate was based on the good agreement between the range of estimates from observationally constrained simple climate models and the CMIP5 range. One major driver of this change in observational estimates was the downward revision of the negative aerosol forcing. This revision reduced the probability that the historically observed warming was a response to a very low total forcing, which thereby reduced the probability of a correspondingly high TCR.

The consensus on TCR appears to have been maintained since the publication of the AR5: for example, despite being critical of the IPCC's estimates of ECS, Lewis and

Curry (2014) arrive at a 5 to 95 percent confidence interval for TCR of 0.9°C-2.5°C, almost identical to the IPCC AR5 "likely" range. (IPCC statements on indirectly observable quantities are typically given at one level lower confidence than the formal evidence suggests, to account for unknown structural uncertainties). The only dissent is from Shindell (2014), who argues that TCR estimates based on recent observations may have been biased low by the assumption that spatially homogenous and inhomogenous forcings have identical efficacy. The attribution approach of Gillett et al. (2013), however, does not make this assumption of equal efficacies, and it arrives at a 5 to 95 percent range for TCR of 0.9°C-2.3°C. In contrast to TCR, ECS remains much more contested.

In summary, the change in the ECS distribution between AR4 and AR5 is small relative to the remaining uncertainties in this and other parameters that determine the SCC. This change arose primarily from assumptions about the multicentury adjustment of the climate system to a constant forcing that remain contested in the literature since the AR5. Neglected processes primarily affect the upper bound on ECS, continuing to support a positively skewed distributional form for this parameter such as that used by Roe and Baker (2007). The AR4 did not give a likely range for TCR that is directly comparable to that in the AR5, but the AR5 did reduce the probability of TCR values greater than 3°C from 10 to 5 percent, reflecting greater confidence and consensus on the upper bound for this parameter.

TABLE 3-1 AR5: Likelihood Scale

Term*	**Likelihood of the Outcome**
Virtually certain	99-100% probability
Very likely	90-100% probability
Likely	66-100% probability
About as likely as not	33-66% probability
Unlikely	0-33% probability
Very unlikely	0-10% probability
Exceptionally unlikely	0-1% probability

*Additional terms that were used in limited circumstances in the AR4 (*extremely likely,* 95-100% probability; *more likely that not*, >50-100% probability; and *extremely unlikely,* 0-5% probability) may also be used in the AR5 when appropriate.
SOURCE: Mastrandrea et al. (2010, Table 1). Reprinted with permission from Macmillan Publishers Ltd.

[a]The terms "most likely value," "likely," "very likely," and "zero probability" are the keys to translating the uncertainty information into probability distributions representing the IPCC assessments; see Table 3-1 for more details.

THE CARBON CYCLE AND TCRE

The discussion so far has focused on the response of global mean surface temperature to a particular level or time path of greenhouse gas concentrations in the atmosphere. To fully understand the response of temperature to CO_2 emissions, one must also understand how CO_2 emissions translate into atmospheric concentrations, how atmospheric CO_2 concentrations translate into forcing, and how forcing translates into temperature change.

For CO_2, the relationship between concentrations and forcing is fairly straightforward. To a good approximation, the radiative forcing of CO_2 is logarithmic in concentration (Arrhenius, 1896). This logarithmic relationship means that, for higher CO_2 concentrations, further incremental increases in the CO_2 concentration yields a diminishing increase in the CO_2 forcing.

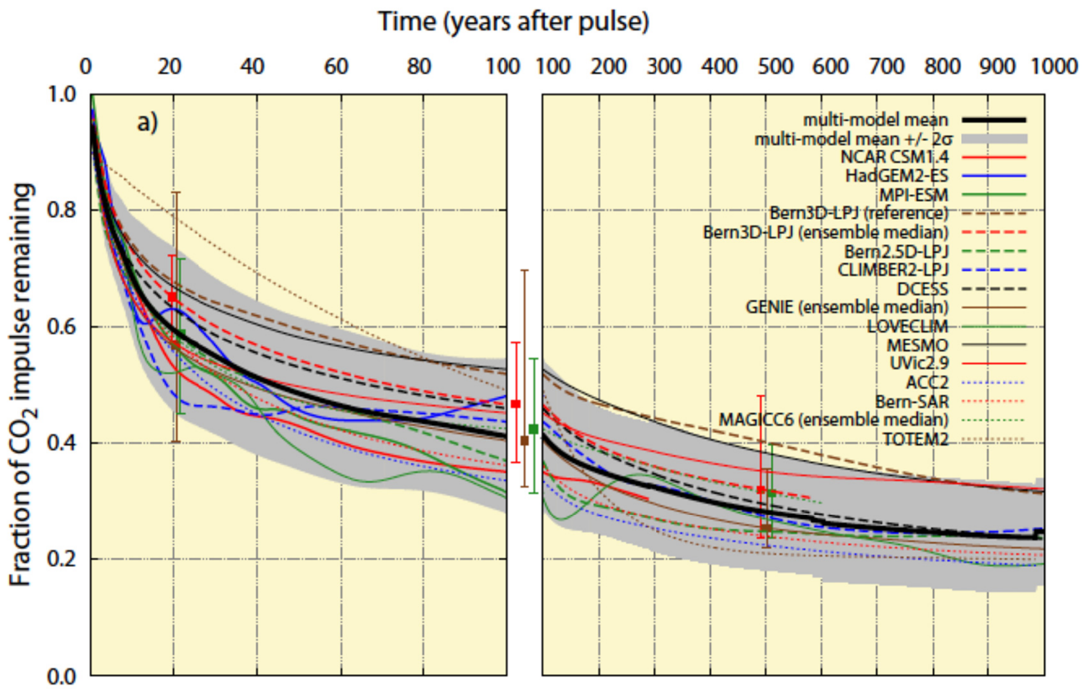


FIGURE 3-4 The perturbation to atmospheric CO_2 concentrations in response to an emission pulse.

NOTES: The figure uses an emission pulse of 100 billion tons of carbon (367 Gt CO_2) added to an atmospheric background concentration of 389 ppm, expressed as the fraction of the initial pulse remaining in the atmosphere for a range of Earth system models (thick solid lines), intermediate complexity (dashed and thin solid lines), and simple climate models (dotted lines). A value of 1.0 corresponds to an increase in CO_2 concentrations of 47.2 ppm. The multimodel mean, computed by giving each available model equal weight, and the corresponding ± two standard deviation range is shown by the black solid line and the grey shading.

SOURCE: Joos et al. (2013, Figure 1a). with caption reproduced, slightly edited for clarity.

The relationship between emissions and concentrations is more complicated, as it involves the full carbon cycle, including some crucial feedbacks between concentrations, temperatures, and fluxes. When a ton of CO_2 is emitted into the atmosphere, a small fraction, about 20 percent, is removed within the first 5 years by the land biosphere and by the ocean, so that about 80 percent is still airborne; see Figure 3-4. After 20 years, about 40 percent of the emitted ton has been thus taken up, and about 60 percent is still airborne; after 100 years, about 60 percent has been removed from the atmosphere and about 40 percent is still airborne. Over the course of the following centuries, the oceans become the major repository of the added carbon.

There are two major bottlenecks in the ocean uptake of CO_2. The first is across the air-sea interface: the CO_2 partial pressure in the surface oceans, i.e., the pressure pushing CO_2 back into the atmosphere, increases with carbon uptake and the accompanying decrease in pH. The second is below the mixed layer, where carbon is mixed into the deeper ocean on multicentennial timescales. Yet even on multicentennial timescales, the carbonate chemistry and the ocean volume dictate that oceans cannot absorb 100 percent of the added carbon, and about 20 percent will remain in the atmosphere after a millennium (Broecker et al., 1979). The ultimate carbon sink occurs through weathering reactions and sedimentation on the ocean floor, which takes place on time scales of hundreds of thousands of years (Archer et al., 2009; Ciais et al., 2013).

The effect of climate change on the carbon cycle gives rise to an amplifying feedback between atmospheric CO_2 and temperature. Warming accelerates decomposition on land faster than CO_2 fertilization increases the rate of photosynthesis, weakening the land-carbon sink (Friedlingstein et al., 2006). Warming also further stratifies the oceans, slowing the penetration of heat and carbon to the deep ocean. The decreasing pH and the warmer temperatures (decreasing solubility) also shift the equilibrium of the carbonic acid/bicarbonate buffer and reduce the ocean absorption of CO_2 from the atmosphere (Archer and Brokin, 2008).

The weakening of the land and ocean carbon sinks as a result of warming increases the atmospheric residence time of CO_2 (Jones et al., 2013), giving rise to a convex relationship between cumulative carbon emissions and atmospheric CO_2 concentrations. When the convex relationship between emissions and concentrations is combined with the concave relationship between concentrations and forcing, the result is a coincidental cancellation that results in a nearly linear relationship between cumulative CO_2 emissions and radiative forcing.

The global mean surface temperature also responds approximately linearly to a continually increasing effective radiative forcing (Flato et al., 2013). Hence, provided the forcing is increasing slowly relative to the response time of the ocean mixed layer (Held et al., 2010), there is a linear relationship between the forcing at any given time and the resulting warming at that time. (Note that this warming is generally not in equilibrium with the forcing.) When the nearly linear relationship between cumulative CO_2 emissions and forcing is combined with the linear relationship between forcing and temperature, the result is a simple, nearly linear relationship between cumulative carbon emissions and the resulting warming (Goodwin et al., 2015).

Another cancellation, between the gradual decline of atmospheric CO_2 and the slow approach of the ocean to thermal equilibrium, causes temperatures to remain nearly constant for centuries following a complete cessation of CO_2 emissions (Matthews and Caldeira, 2008; Solomon et al., 2009). This cancellation arises because both of these processes operate on similar timescales set by the mixing of carbon and heat into the deep ocean; see Figure 3-5.

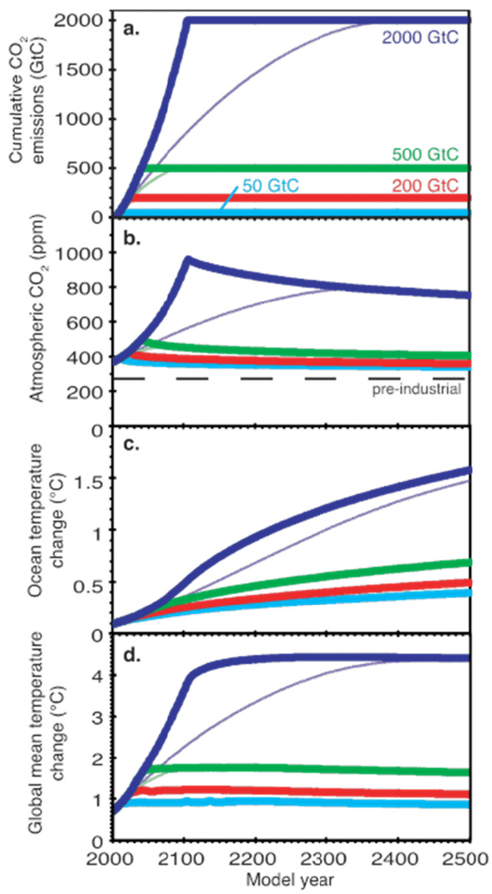


FIGURE 3-5 The response of an Earth system model of intermediate complexity to different levels of cumulative emissions

NOTES: The four responses reveal the long-lived nature of the CO_2-forced warming: (a) scenarios of cumulative CO_2 emissions, (b) resulting atmospheric CO_2 concentrations, (c) associated change in mean ocean temperature, and (d) associated change in global mean surface temperature. The combination of declining atmospheric CO_2 and increasing mean ocean temperature give rise to a nearly stable global mean surface temperature after the cessation of emissions.

SOURCE: Matthews and Caldeira (2008, Figure 2). Reprinted with permission.

A series of papers published in the late 2000s (e.g., Allen et al., 2009; Matthews et al., 2009; Meinshausen et al., 2009; Zickfeld et al., 2009) pointed out that, as a consequence of the longevity of the warming associated with CO_2 emissions, temperatures in any given year were largely determined by cumulative CO_2 emissions up to that time. Gillett et al. (2013) updated the carbon budget estimates in these early papers to take into account updated estimates of the strength of anthropogenic forcing and the evolution of global temperatures since 2000; see Figure 3-6. In the AR5, Collins et al. (2013, p. 1033) concluded that “the principal driver of long-term warming is total emissions of CO_2 and the two quantities are approximately linearly related.”

The approximately linear relationship between cumulative CO_2 emissions and the warming it causes simplifies the estimation of the climate response to CO_2 emissions. It means that the global mean temperature change induced by CO_2 can be largely summarized by a single parameter, the TCRE.

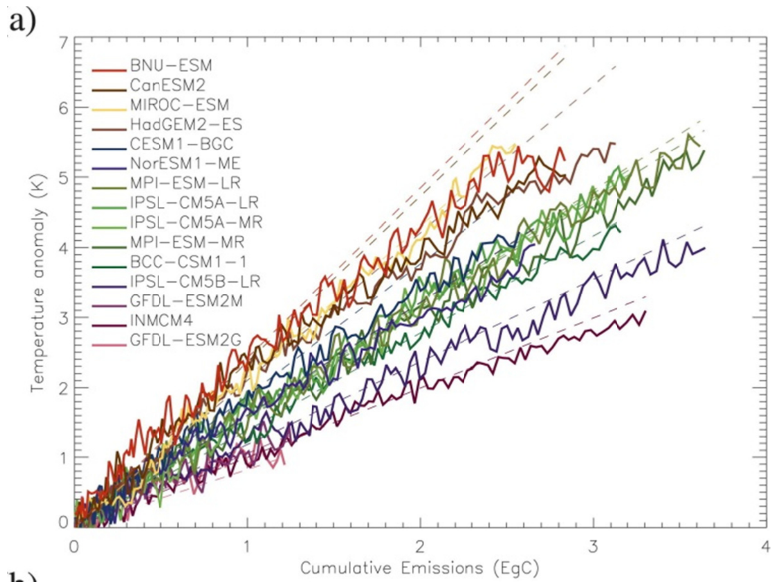


FIGURE 3-6 Temperature anomaly plotted against cumulative CO_2 emissions.
NOTES: The data are from the 1 percent/year CO_2 increase experiment for Earth system models participating in CMIP5. Dashed curves are lines with constant slope. The data show approximate linearity of warming in cumulative CO_2 emissions up to 1.5-2.0 exagrams of carbon (EgC) cumulative carbon emissions.
SOURCE: Gillett et al. (2013, Figure 1a). ©American Meteorological Society. Used with permission.

Herrington and Zickfeld (2014) show that the TCRE is a robust measure of the climate response, regardless of the timescale of injection for realistic emission scenarios, although the response takes up to a century to stabilize for very large instantaneous CO_2 pulses. The AR5 (Collins et al., 2013) suggested the TCRE was approximately constant for cumulative injections up to 2 teratons of carbon (Tt C), although Herrington and Zickfeld (2014), consistent with Allen et al. (2009), suggest it declines slightly for cumulative emissions in excess of 1.5 Tt C. Gillett et al. (2013), with a broader range of models, find evidence for a smaller decline, with any departure from linearity being small relative to uncertainty in the response (Figure 3-6).

TCRE is determined by two quantities. First, TCRE depends on the cumulative airborne fraction at the time of CO_2 doubling (or, approximately equivalently, after a cumulative release of 1 Tt C in the form of CO_2) following a gradual increase in concentrations over a multidecade period. This fraction is between 0.47 and 0.67 in current climate models (Gillett et al., 2013). Second, TCRE depends on the warming at the time of CO_2 doubling following a gradual increase in concentrations, or the TCR. Most of the uncertainty in TCRE arises from the uncertainty in TCR, leading to an AR5 consensus "likely" range, accounting for both model and observational lines of evidence, of 0.8°C-2.5°C/Tt C, which is equivalent to 0.2°C-0.7°C/1000 Gt CO_2 (Collins et al., 2013).

While uncertainty in ECS gives rise to uncertainty in the additional warming that would occur over centuries if atmospheric CO_2 concentrations were stabilized, current comprehensive Earth system models indicate that uncertainty in ECS is largely irrelevant to TCRE and hence to the temperature response to a pulse injection of CO_2. This irrelevancy occurs because, after a cessation of emissions, atmospheric CO_2 concentrations do not stabilize, but rather fall just fast enough that the "recalcitrant" warming reflected by ECS (Held et al., 2010) never materializes (Matthews and Caldeira, 2008; Solomon et al., 2009).

TEMPERATURE EFFECT OF A CO_2 PULSE AND THE INITIAL PULSE-ADJUSTMENT TIME

The constancy of the TCRE indicates that the multidecade-to-century-timescale climate response to any CO_2 injection can be accurately approximated by a constant temperature increase set by the total cumulative amount of carbon injected and the TCRE. A key remaining aspect of the response that is relevant to the SCC is the form and speed of the adjustment immediately following a pulse injection of carbon. The most comprehensive study to date to address this question was the multimodel comparison of Joos et al. (2013). They examined the impact of a 100 Gt C pulse injection of CO_2, relative to a baseline scenario in which CO_2 concentrations were held constant at 389 ppm following a historical transition to that point in a range of simple climate models and Earth system models of both intermediate and full complexity.

Results are shown in Figure 3-7, with solid lines corresponding to full-complexity models, dashed lines to intermediate-complexity models, and dotted lines to simple models. The full-complexity models display large fluctuations that can be understood entirely as random internal variability, given the small size of the temperature response even to a pulse of this magnitude (comparable to about a decade of CO_2 emissions at 2015 levels). Strikingly, all models, including the most complex, adjust relatively rapidly, with temperatures rising to about 0.2°C within 10 to 20 years of the pulse and then remaining constant for the remainder of a century. A slight decline is observed over the millennium (right panel).

In modeling the carbon cycle response to this pulse injection, Joos et al. (2013) find a very rapid IPT of only a few years and very slow subsequent adjustments on multidecade and multicentury timescales. The short IPT in Figure 3-7 is primarily set by the ocean mixed-layer thermal response time, which is known, on physical grounds, to be of the order of a decade or less (Held et al., 2010). The adjustment to a pulse injection of CO_2 can thus be adequately characterized by an initial adjustment within a timeframe of 4 years to a decade, followed by stable temperatures for a century and slow decline thereafter.

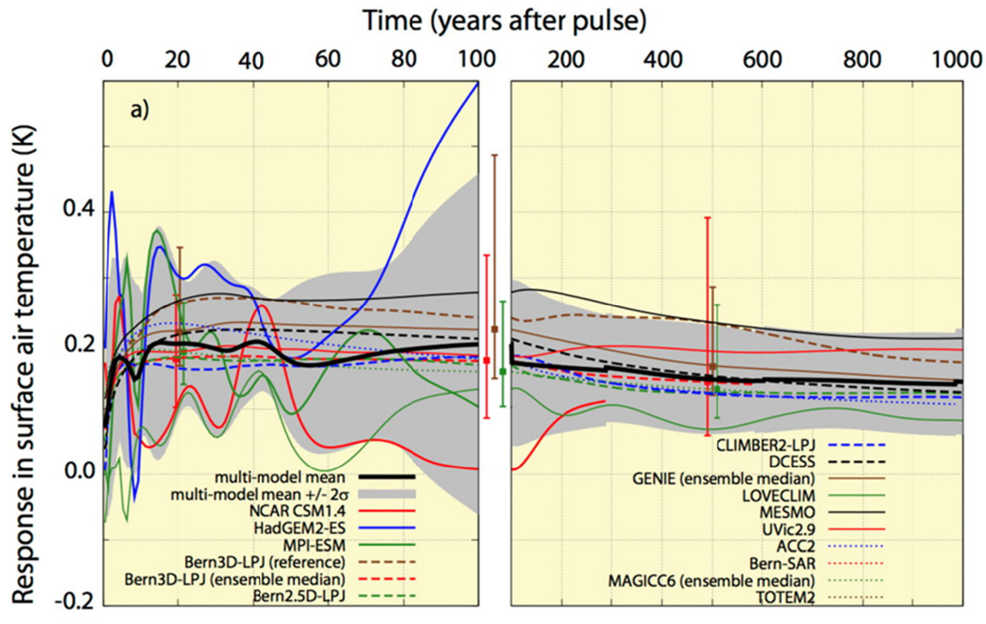


FIGURE 3-7 Response of global mean temperature to a 100 GtC pulse emission of CO_2.
NOTES: The data are from the same experiments shown in Figure 3-4 (above), with temperature change expressed relative to a stable baseline CO_2 concentration of 389 ppm. Participating full-complexity Earth system models (solid curves) have a high degree of variability. The Earth system models of intermediate complexity and simple climate models are shown with dashed and dotted lines, respectively.
SOURCE: Joos et al. (2013, Figure 2a).

Ricke and Caldeira (2014) use a simple climate model that combines a carbon cycle model fit to the results of Joos et al. (2013) with a simple model of the thermal response (similar to that of Held et al. [2010]) to obtain the temperature response to a pulse CO_2 emission. They find that temperature peaks between 7 and 31 years after the emissions (90% probability range, median of 10 years). While their simple climate model suggests a modest decline in temperatures after the peak, this finding arises from the lack of explicit climate carbon cycle feedback in their composite model, and it is not evident in the more complex models on which their composite model is based (Joos et al., 2013). In order for a simple climate model to generate the near linearity of warming in cumulative carbon emissions, as well as the longevity of the associated warming, it is necessary to use either a carbon cycle model that includes the effects of pH and warming on CO_2 solubility (e.g., Glotter et al., 2014), the impact of warming on land carbon sinks (e.g., Friedlingstein et al., 2006; Allen et al., 2009), or a direct approximation of the linearity in cumulative carbon emissions (e.g., Kopp and Mignone, 2013).

On the basis of the current evidence, the committee concludes that the likely approximation for characterizing the response over annual-to-centennial timescales of the climate system to a pulse of emissions of CO_2 is a simple rapid adjustment (4 years to one decade) to the level of warming indicated by the TCRE, with modest decline for at least a century thereafter.[17] As noted in Chapter 4, experiments like those of Joos et al. (2013) can be used to evaluate the SCC-IAM climate modeling.

IMPLICATIONS FOR ESTIMATION OF THE SCC

To estimate the SCC, it is necessary to project both the physical climate changes associated with a baseline emissions trajectory and the effect of a small, additional pulse of CO_2 emitted on top of that baseline trajectory.[18]

While the TCRE and IPT are relevant for capturing the response to cumulative or pulse emissions of CO_2, other measures are relevant for computing a baseline climate, which may be influenced by CO_2 emissions high enough (greater than approximately 1.5 Tt C) that the TCRE is not constant and is also affected by non-CO_2 forcers. The relative importance of TCR and ECS in characterizing the SCC depends on the relative proportion of net present value damages that occur in roughly the first century of emissions. By construction, TCR is a much better predictor than ECS of the climate response on timescales of less than a century.[19] As a result, Otto et al. (2013b) found that in their simple model for estimating the SCC, for a moderate emissions trajectory[20] and a quadratic damage function, reducing uncertainty in TCR leads to a greater reduction in SCC uncertainty than reducing uncertainty in ECS, provided that the discount rate is at least about 1 percent higher than the growth rate of consumption; see Figure 3-8. For highly convex damage functions and discount rates sufficiently close to the consumption growth rate, Otto et al. (2013b) found that learning about ECS leads to a greater reduction in SCC uncertainty than learning about TCR.

Factors that increase the fraction of the SCC due to damages after the first century, and thus increase the importance of ECS in comparison with TCR, include an increase in baseline temperatures as well as economic factors. In climate damage functions, such as those used in the SCC-IAMs, faster economic growth for a given discount rate or a lower discount rate for given economic growth will both tend to increase the importance of the more distant future and thus the ECS. In this context, it is worth noting that the IWG analysis holds the discount rate constant but assumes a decrease in growth rates after 2100, thereby increasing the importance of TCR over ECS relative to a constant growth-rate scenario or one in which the discount rate declines when the growth rate declines. In the 21st century, the average economic growth rate in the IWG scenarios ranges between 2.0 and 2.4 percent per year, while over 2100-2300 it ranges between

[17]Joos et al. (2013) found that the magnitude of the temperature response to a pulse injection (0.20 ± 0.12°C/100 Gt C) is comparable to—though slightly higher than—the AR5 range for TCRE, although their analysis was based on a subset of the models used by the AR5 for its statement on TCRE. In single-model studies, Herrington and Zickfeld (2014) and Zickfeld and Herrington (2015) found that TCRE falls with both the speed and magnitude of a pulse injection, while Krasting et al. (2014) found that TCRE is larger for both small (~2 Gt C/yr) and large (~20 Gt C/yr) rates of emissions than for current rates of emission (~10 Gt C/yr).

[18]This requirement can be seen in a simple, typical model: If damages are equal to economic output times a power function of temperature, $D(T) = aT^b$, then the change in damages associated with an emission pulse that shifts temperature from T to $T + \Delta T$ at time t is proportional to $T(t)^{b-1}\,\Delta T(t)$. Thus, the physical climate model underlying the SCC calculation must provide reasonable projections for both $T(t)$ and $\Delta T(t)$; that is, both the baseline temperature response and the long-term temperature changes due to an emissions pulse. The economic valuation also depends on the relative sizes of the growth rate of consumption and the rate at which damages are discounted.

[19]This finding can be seen from the 1 percent/year CO_2 concentration growth scenario used to define TCR, in which ECS provides no additional information about the temperature response until after year 70.

[20]Otto et al. used representative concentration pathway (RCP) 4.5. RCPs are greenhouse gas concentration trajectories used by the IPCC in AR5 (van Vuuren et al., 2011).

0.5 and 0.9 percent per year.[21] In the context of the Otto et al. (2013b) results, the low growth rates after 2100 suggest that TCR will be a more important determinant than ECS of the SCC calculated using the IWG methodology, even at the lowest discount rate used (2.5% per year).

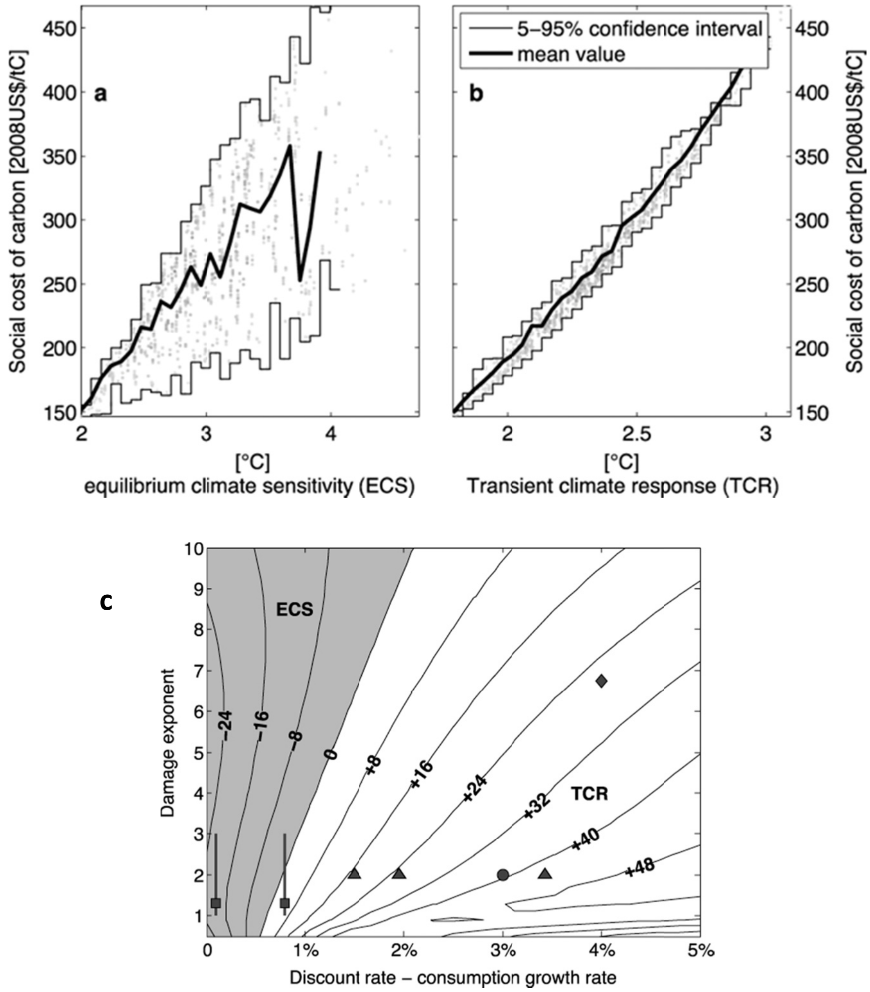


FIGURE 3-8 Impact of information on climate system properties for the SCC.
NOTES: Panel (a) shows the Otto et al. estimates of the SCC allowing for uncertainty in climate and carbon cycle properties plotted as a function of ECS, with the black line showing mean estimate and the shaded region showing 5 to 95 percent range and dots showing individual estimates, all assuming a discount rate minus consumption growth rate of 3 percent and a quadratic damage function [the round dot in panel (c)]. The broad vertical range indicates that learning the value of the ECS does not substantially reduce uncertainty in SCC except at very low values of ECS. Panel (b) shows the Otto et al. estimates of the SCC similarly plotted as a function of TCR. The narrow vertical range indicates that learning the value of TCR substantially reduces uncertainty in SCC. Panel (c) shows the relative benefits of learning the value of ECS or TCR as a function of the discount rate and curvature of the damage function, with high values of the damage exponent corresponding to strongly convex damage functions.

[21]The IWG used aggregate output (GDP) as a socioeconomic input, not macroeconomic aggregate consumption, which is a component of aggregate output. For this purpose, it is reasonable to think of consumption growth as proportional to output growth.

White/grey regions indicate parameter combinations for which learning TCR is more or less informative than learning ECS.
SOURCE: Adapted from Otto et al. (2013b, Figures 2 and 3). Reprinted with permission.

TCRE is the crucial parameter determining the contribution of the physical climate system response to the SCC, since it determines the magnitude of multidecade-to-century timescale warming resulting from a pulse injection of CO_2. TCRE is primarily determined by TCR, not ECS. Revisions to ECS are therefore relevant to SCC estimation, principally through their possible implications for baseline warming after a century or more. TCR and IPT determine temperature changes over shorter time periods, including the response to a small pulse emission of CO_2. Hence, the revision of the "likely" range of ECS from 2.0°C to 4.5°C in the AR4 to 1.5°C to 4.5°C in the AR5 should have a minimal impact on estimates of the SCC.

4
Climate System Modeling in the SCC-IAMs and the Role of ECS

This chapter provides information on how the social cost of carbon integrated assessment models (SCC-IAMs) currently model the climate system and how equilibrium climate sensitivity (ECS) is incorporated into each SCC-IAM. In addition, the committee outlines tests that could be applied to the simple climate models used to generate the SCC, to determine whether the central projections of these models agree with those of more comprehensive Earth system models.

REPRESENTATION OF THE CLIMATE SYSTEM IN THE SCC-IAMS

The three SCC-IAMs used by the Interagency Working Group on the Social Cost of Carbon (IWG) are the Dynamic Integrated Climate-Economy Model (DICE), the Policy Analysis of the Greenhouse Effect (PAGE) model, and the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) model. The climate system in each of them consists of three major elements: calculation of the path of atmospheric concentrations of CO_2 from greenhouse gas emissions, translation of concentrations to radiative forcing, and the response of global mean surface temperature to changes in radiative forcing. However, the specification (structural and parametric) of each element varies across the models; see Table 4-1.[22] Significant differences exist in the structure of the carbon cycle, radiative forcing per doubling of CO_2 concentrations, the derivation of global mean temperature from forcing, the coverage of and interactions with non-CO_2 concentrations and forcing, and climate feedback representation. Differences in model time steps are also meaningful, as they have an impact on the climate system dynamics in the models.

[22]For additional discussion and details, see Rose et al. (2014). This is one of the few systematic reviews and comparisons of the SCC-IAMs; it is used in this chapter to introduce the differences between the three IAMs.

TABLE 4-1 Climate Modeling Structural Characteristics for the SCC-IAMs.

Characteristic	DICE	FUND	PAGE
Atmospheric Concentrations			
CO_2	3-box carbon cycle	5-box carbon cycle	1-box carbon cycle
Non-CO_2 Kyoto	Not modeled	CH_4, N_2O, SF_6	Not modeled
Non-CO_2 non-Kyoto	Not modeled	SO_2	SO_2
Radiative forcing			
CO_2 (per doubling)	3.80 W/m^2	3.71 W/m^2	3.81 W/m^2
Non-CO_2 Kyoto	Exogenous	CH_4, N_2O, SF_6	Exogenous
Non-CO_2 non-Kyoto	Exogenous	SO_2	SO_2, non-SO_2 exogenous
Global Mean Surface Temperature	Rate temperature moves toward equilibrium is a function of climate sensitivity & surface temperature modulated by ocean heat uptake	Rate temperature moves towards equilibrium is a function of climate sensitivity	Function of global mean land and ocean temperatures
Ocean Temperatures	2-box (upper and deep ocean)	1-box	1-box
Regional Temperatures	n/a	Implicit with regional damage parameters calibrated to regional temperatures downscaled based on a linear pattern-scale average of 14 global circulation models	Explicit with regional temperatures downscaled according to latitude and landmass adjustment
Global Mean Sea Level Rise	Components (thermal expansion, glacier and small ice cap melt, GIS melt, WAIS melt) computed as functions of temperature and lagged temperature	Computed as a function of temperature and lagged temperature	Computed as a function of temperature and lagged temperature
Time Steps	10-year	1-year	Variable (10-year 2000-2060, 20-year 2060-2100, 100-year 2100-2300)
Implementation of CO_2 Pulse in Year t	Pulse spread equally over the decade straddling year t	Pulse spread equally over the decade from year t forward	Pulse distributed evenly over the two decades preceding and subsequent to year t
Model-Specific Uncertainties Other than ECS (number of parameters; distribution types)	None	11 – normal, truncated normal, triangular, and gamma distributions	10 – triangular distributions

NOTE: See text for discussion.
SOURCE: Modified from Rose et al. (2014, Table 5-1).

We note that the IWG has modified the SCC climate modeling components of each model. In DICE, the IWG changed the time steps and averaged CO_2 concentrations across time periods. In PAGE, the IWG modified the time-step scheme, the modeling of non-CO_2 emissions and forcing, and the ECD modeling approach.[23] The IWG also standardized the distribution of the ECS used in each model.

[23]Non-CO_2 forcing is also captured in the models in significantly different ways, with FUND deriving non-CO_2 concentrations and forcing, and DICE and PAGE using forcing assumptions developed from sources outside the models. Also, the models vary in their coverage of non-CO_2 forcing, with all three different in total forcing coverage: FUND covers the fewest of the broad set of non-CO_2 forcing constituents, including long-lived and short-lived gases and aerosols.

Differences in the derivation of temperature from forcing are also noteworthy with regard to the IWG's standardization of the ECS distribution. In DICE and FUND, the rate at which temperature moves toward equilibrium is affected by ECS. In these two models, a higher ECS corresponds to a slower convergence toward the equilibrium temperature (i.e., a longer period of time, or lag, before reaching the equilibrium temperature). Varying the adjustment speed (or lag) with the climate sensitivity parameter ensures some consistency with historical observations. Importantly, it also moderates the effect of changing the ECS parameter, in particular on transient climate response (TCR). The temperature response in PAGE, which does not include this temperature lag adjustment, is more sensitive to alternative ECS values. DICE, which uses a two-box ocean model, also includes a moderating feedback from the ocean, with deep ocean temperatures moderating the rate at which surface temperature increases. Finally, FUND and PAGE include an explicit climate carbon cycle feedback that accelerates global warming at higher temperatures. The feedback represents global physical mechanisms (e.g., terrestrial drying and vegetation dieback) that release additional emissions into the atmosphere as the planet warms and in so doing increase the rate of global warming.

Global mean surface temperature is the primary climate variable driving the climate damage estimates in all three of the models. In addition, the rate of temperature change and CO_2 concentrations are also used in some FUND damage categories. Other climate variables such as precipitation, weather variability, and extreme weather events are not modeled explicitly, although these effects may be captured implicitly in the calibration of damage response to global mean temperature change.

Global mean surface temperature drives projected global average mean sea level rise in all three models and projected regional average temperatures in FUND and PAGE, which in turn drive damages. However, differences in the downscaling approach lead to differences in projected regional temperatures across FUND and PAGE for the same global mean surface temperature, with PAGE projecting greater warming for many regions. The sea level rise calculations also vary across models, with projected sea level rise in 2100 varying by a factor of two across models for the same projected levels of warming (Rose et al., 2014).

It is worth noting that in the IWG's SCC methodology, climate system parametric uncertainty is accounted for in all three models, but to different degrees. All models consider ECS parameter uncertainty through a probability distribution for ECS calibrated to the likelihoods of the Intergovernmental Panel on Climate Change (IPCC, 2007), with a distributional form adopted from Roe and Baker (2007). In addition, FUND and PAGE incorporate additional climate-model-specific parametric uncertainties.

In the DICE model, the climate model component is represented using a two-layer ocean (see Chapter 3, "Determining Temperature Changes in Response to CO_2 Emissions"). In FUND and PAGE, the temperature response is characterized by a single exponential decay. In DICE and FUND, the timescale of the temperature response varies with the ECS.[24]

Figure 4-1 shows that the models used in the IWG analysis vary by decades in the time taken to reach peak warming associated with a pulse emission. This contrasts with the time of about one decade indicated by the models participating in the Joos et al. (2013) intercomparison (see Figure 3-7 in Chapter 3). However, direct comparison between the two sets of results is complicated by differences in their experimental design and baselines.

[24] In the standard version of the 2009 PAGE model, the timescale and TCR are parameters, and ECS is a function of them. In the IWG version of PAGE, timescale is invariant to the ECS parameter, and TCR is not an explicit parameter.

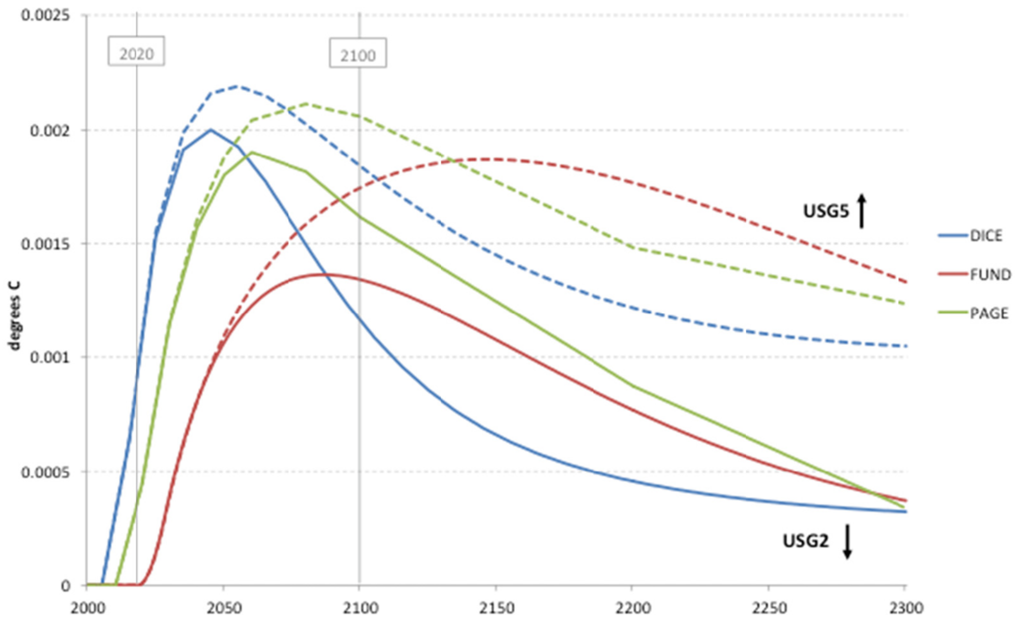


FIGURE 4-1 Incremental annual global mean temperature responses to 2300 from the climate components of the SCC-IAMs.
NOTES: The responses are for a 1 GtC emissions pulse in 2020 with higher (USG2, solid) and lower (USG5, dashed) reference emissions. USG2 and USG5 are the socioeconomic scenarios that produce the highest and lowest fossil fuel and industrial CO_2 emission projections respectively in the IWG methodology. The lower baseline USG5 results (dashed) are more comparable to those from the Joos et al. (2013) experiment shown in Figure 3-7 (in Chapter 3), which performed a pulse experiment on top of a 389 ppm CO_2 baseline. Note that the Joos et al. (2013) experiment is not fully comparable.
SOURCE: Developed from Rose et al. (2014). Reprinted with permission.

Harmonization of Emissions Inputs and the ECS by the IWG

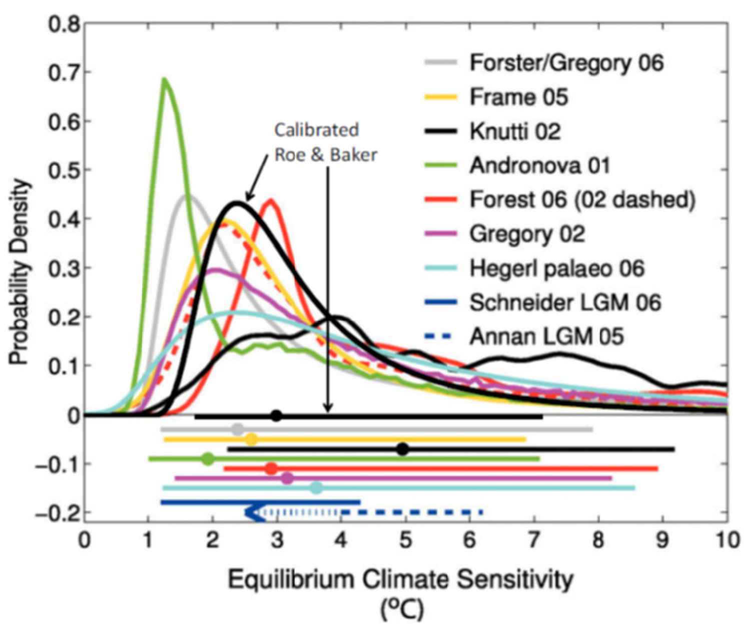
The IWG methodology harmonizes assumptions across the three models along three dimensions: socioeconomic and emissions projections (five cases), ECS uncertainty (using a common assumed ECS probability distribution), and discount rates (three alternative constant values). Given their climate modeling and projection implications, this section discusses the socioeconomic/emissions and ECS harmonizations. Note that the IWG socioeconomic and emissions and ECS modeling approaches were developed for the IWG's 2010 SCC estimates (Interagency Working Group on the Social Cost of Carbon, 2010) and retained for the 2013 and 2015 estimates (Interagency Working Group on the Social Cost of Carbon, 2013, 2015). The IWG methodology regarding socioeconomic and emissions modeling differs to different degrees from each model's standard structure.

Socioeconomic and emissions variability are considered in the IWG SCC calculations through the five alternative scenarios (USG1 through USG5). Four of the scenarios are described as "baseline" futures assuming negligible greenhouse gas mitigation, and one is described as a "policy" future that stabilizes atmospheric concentrations by 2100 at 550 ppm CO_2-equivalent. Each scenario consists of a set of projections for gross domestic product, population, fossil and industrial CO_2 emissions, land use CO_2 emissions, and non-CO_2 emissions and forcing.

In the IWG methodology, the baseline socioeconomic, emissions, and forcing projections to the year 2100 are drawn from scenario data from the Energy Modeling Forum's 22nd study, EMF 22 (Clarke et al., 2009), which was a multimodel scenario exercise of 10 global IAMs with detailed energy sectors to explore the cost and energy transformation implications of climate targets and international cooperation. The four baseline scenarios are reference "no climate policy" futures associated with 4 of the 10 models participating in the EMF 22 study. The "policy" scenario was derived by the IWG by averaging the 550 ppm CO_2-equivalent scenario results from the same four models, with each variable averaged separately. In the IWG exercise, the SCC estimates resulting from each socioeconomic/emission scenario are given equal weight in the averaging used to derive the overall SCC estimates.

Implementation of these inputs varied somewhat across the three models (see Rose et al., 2014): FUND and PAGE require translation of the projections into model-specific regional population and income; PAGE and DICE use level values, and FUND uses growth rates; and FUND requires derivation of its own fossil and industrial CO_2 emissions in lieu of the standardized projections. In addition, only FUND uses explicit emissions for a subset of non-CO_2 Kyoto greenhouse gases (CH_4, N_2O, SF_6); and DICE and PAGE include non-CO_2 forcing exogenously. To estimate climate damages beyond 2100, the IWG extrapolated the EMF 22-based socioeconomic and emissions inputs from 2100 to 2300.

The IWG approach standardized one climate system modeling assumption, the distribution of the ECS parameter. The IWG calibrated a Roe and Baker (2007) distributional form (see discussion in Chapter 3) to match statements regarding the likelihood of the ECS value made in the IPCC Fourth Assessment Report. Figure 4-2 depicts the chosen calibrated Roe and Baker distribution.[25]



[25]For a detailed discussion, see IWG (2010); also see Box 3-2 in Chapter 3.

FIGURE 4-2 IWG calibrated Roe and Baker ECS distribution.
NOTES: The black line is based on the Roe and Baker (2007) functional form. Additional probability distributions adopted from Figure 9.20 in the source for this figure. The circles below the distributions reflect the median ECS estimate; the ends of the horizontal bars represent the 5th and 95th percentiles of the ECS distributions.
SOURCE: Interagency Working Group on the Social Cost of Carbon (2010, Figure 2).

Role of ECS and Other Assumptions in Determining the Emissions-to-Temperature Link

Projecting global mean surface temperature change from projected emissions in the SCC-IAMs requires sequentially translating emissions trajectories into concentrations, concentrations into radiative forcing, and radiative forcing trajectories into temperature. In the IWG analysis, the ECS parameter is one of several critical parameters governing the last translation from forcing to temperature.

The ECS is a long-standing metric for climate system responsiveness (e.g., Arrhenius, 1896) and is used as an input parameter to most simple climate models, such as those used by the IWG. However, the ECS is not an input parameter to more complex climate models. Rather, it emerges from the behavior of each complex model and is derived as an output based on each model's global mean surface temperature response to a doubling of CO_2 concentrations. The ECS is therefore unique to each model's structure, parameterization, and settings.

The ECS is recognized as an influential parameter in the three IAMs used to calculate the SCC, with studies finding SCC estimates to be relatively sensitive to the assumed ECS (Anthoff and Tol, 2013a, 2013b; Hope, 2013; Butler et al., 2014). This reflects in part the way the ECS is incorporated into these models. Direct comparison of the SCC-IAMs' climate responses has also found that the sensitivity of projected temperature (level and incremental) to the ECS assumptions varies significantly across the three models, with PAGE being the most sensitive and FUND the least sensitive (see Figure 4-3).

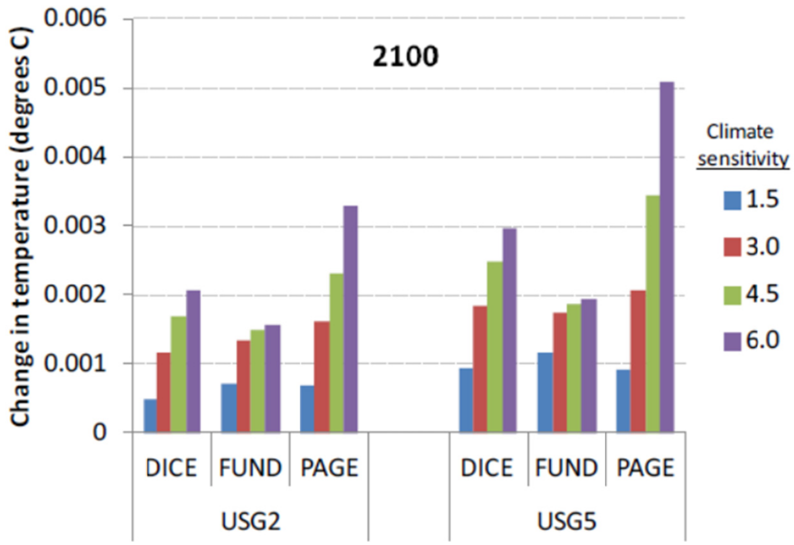


FIGURE 4-3 Projected incremental global mean temperature increase in 2100 of the SCC-IAMs varying the ECS assumption.
NOTES: In DICE, FUND, and PAGE, the increase is in response to a 2020 1 GtC pulse varying the ECS parameter and reference emissions scenario. USG2 and USG5 represent the IWG's highest and lowest emission scenarios, respectively.
SOURCE: Rose et al. (2014, Figure 5-13). Reprinted with permission.

Other climate modeling elements of the three SCC-IAMs, in addition to the ECS, play a significant role in translating emissions into projected global mean temperatures. These include the specifications for the carbon cycle, the ocean response to forcing, non-CO_2 forcing, climate feedbacks, and non-ECS parametric uncertainties. As a result of variations in these specifications across the models, PAGE has slower CO_2 concentration accumulation but higher projected temperatures, FUND has faster accumulation of CO_2 concentrations and higher non-CO_2 forcing but lower projected temperatures, and DICE has CO_2 concentrations and temperature that are the most sensitive to projected emissions. Non-ECS uncertainty also plays a role in FUND and PAGE in defining the distribution of projected temperature.

SENSITIVITY OF THE SCC TO OTHER MODELING ASSUMPTIONS

The committee's charge emphasizes the role of the ECS in estimating the SCC, but the ECS is one of many assumptions that can influence an SCC estimate. Other assumptions include the projected size of the economy and population, emissions levels, discount rate, non-ECS climate parameters, regional temperature downscaling, the assumed sea level rise response rate, and the functional forms and parameterizations for the various climate damages (Anthoff and Tol, 2013a, 2013b; Hope, 2013; Butler et al., 2014; Rose et al., 2014). Some assumptions are potentially more influential than the ECS, as well as interacting with the ECS.

Looking specifically at damages, Anthoff and Tol (2013a, 2013b) identified key sensitivities for FUND SCC estimates in parameters associated with cooling damages, agricultural damages, migration, and energy efficiency improvement. Looking more broadly across the overall PAGE modeling framework, Hope (2013) finds key sensitivities in the model's discounting parameters, climate feedback response, sulfate aerosol effects, and noneconomic damage function exponent and weight parameters. In addition, Butler et al. (2014) illustrate with a modified version of the DICE model the potential importance of interactions between uncertain parameters.

Direct comparison of the model damage components of the three IWG SCC models illustrates the differences in sensitivity of damage estimates to assumed warming levels and the size of the economy. Such comparison finds that PAGE damages are the most sensitive to changes in the level of warming, and FUND damages are the least sensitive. At low levels of warming, DICE and PAGE damages are the most sensitive to changes in the size of the economy, but at high levels of warming, FUND damages are the most sensitive. In both contexts there are warming and income ranges for which there are even differences in the sign of estimated damages, as well as the responsiveness.

These insights suggest that it is important to look beyond the ECS when evaluating current methods and identifying opportunities for improvement. Those opportunities include not only other climatic factors, but also sensitivity to changes in other model inputs and assumptions in other components of the causal chain. There are also uncertainties, and potential sensitivities, associated with elements not currently modeled, including other factors that will drive the physical impacts of global climate change, such as changes in the regional and temporal distribution of precipitation, humidity, changing aerosol and cloud patterns, sea level rise, and potential extreme events.

ASSESSMENT OF SIMPLE CLIMATE MODEL PERFORMANCE

The climate modeling community assesses the performance of its models in two ways: (1) intermodel comparison diagnostics and (2) comparison of projections to historical data. With the exception of some limited intermodel comparison exercises (e.g., Warren et al., 2010; van Vuuren et al., 2011; Rose et al., 2014), similar diagnostics and historical comparisons have not been applied to the simple climate models that serve as inputs to SCC-IAMs calculations.

Simple climate models, such as the ones used in SCC-IAMs, can be assessed through a set of diagnostic experiments described below. The key point of comparison is whether the central projections and ranges of the simple climate models agree with those of more comprehensive Earth system models. These diagnostics should not necessarily disqualify models based on broader responses than the Earth system models, however, as the latter models are known to cluster near central estimates (e.g., Huybers, 2010; Roe and Armour, 2011). Similarly, it is not inappropriate for simple climate models to include feedbacks not represented in Earth system models; but the diagnostics should be run with these additional feedbacks disabled so as to facilitate comparison with more complex models that, because of computational limits, do not include such feedbacks.

Four key properties of any simple climate model can be assessed:

- Transient climate response to emissions (TCRE) can be assessed using extended release experiments along the lines of those conducted by Matthews and Caldeira (2008) or Herrington and Zickfeld (2014). In these experiments, CO_2 is emitted at a constant rate of 20 Gt C/year until such time that cumulative emissions reached 50, 200, 500 or 2000 Gt C, at which point emissions are ceased. The TCRE is given by the ratio of warming to cumulative emissions at the end of the emission period. The TCRE experiments assess the combined response of the climate and the carbon cycle to CO_2 emissions.
- TCR can be assessed with an experiment in which CO_2 concentrations are increased at 1 percent/year from a preindustrial initial value, with the mean warming over years

60-80 defining the TCR. This assesses the multidecade response of climate to CO_2 concentrations, removing from the equation the effects of the carbon cycle and the multicentury adjustments that contribute to ECS.

- The initial pulse-adjustment timescale (IPT) can be assessed with experiments such as that of Joos et al. (2013), in which the temperature response over time to a pulse emission of 100 GtC was assessed relative to a steady-state baseline CO_2 concentration of 389 ppm. Such experiments provide information on both the IPT and the TCRE, but extended release experiments are more relevant to TCRE.
- Finally, the overall baseline response to forcing can be assessed using the representative concentration pathway/extended concentration pathway (RCP/ECP)[26] experiments driven by total forcing (Collins et al., 2013). Specifically, a range of possible forcings can be examined by using the high-emissions 6 RCP/ECP 8.5 and low-emissions RCP/ECP 2.6 pathways. By driving the model directly with climate forcing, these experiments isolate the energy balance portion of the simple climate model.

Although these experiments and this report focus on the climate effect of CO_2 emissions, similar diagnostics can be applied to the simple climate models used in the calculation of the social cost of other climate forcers.

[26]Extended concentration pathways are an extension of representative concentration pathway emissions scenarios from 2100 through 2300 (van Vuuren et al., 2011).

5
Discussions, Conclusions, and Recommendations

The first part of this chapter summarizes the committee's conclusions and presents its recommendation on the first two questions covered in this first phase of the study. The second part of this chapter introduces concepts relevant to the committee's third question and provides conclusions and recommendations on that question.

NEAR-TERM UPDATES TO CLIMATE SYSTEM MODELING IN SCC ESTIMATION

The first two charge questions direct the committee to consider near-term updates to the social cost of carbon (SCC). Specifically, the committee considered whether a near-term update is warranted on the basis of recent evidence regarding the sensitivity of temperature change to carbon emissions. The basic issues are the technical merits and challenges of a narrowly focused update to the SCC estimates and whether the Interagency Working Group on the Social Cost of Carbon (IWG) should conduct a near-term update of the SCC prior to receiving recommendations related to a more comprehensive update (Phase 2 of the committee's study).

In its analysis, the committee considered the criteria outlined in Chapter 1, including

- the accuracy and characterization of uncertainty of climate system modeling (e.g., assessing whether a near-term update would necessarily improve the representation of the response of temperature change to emissions relative to more complete, state-of-the-art models of the climate system);
- overall SCC reliability;
- alternative options for climate system representation; and
- whether there is sufficient benefit to warrant investing limited available resources in conducting a near-term update to the SCC estimates, relative to investing those resources in lasting improvements to the methods and science underlying the SCC.

CONCLUSION 1 The equilibrium climate sensitivity (ECS) is only one parameter affecting the social cost of carbon (SCC). Each of the three SCC integrated assessment models also embodies a different representation of the climate system and its underlying uncertainties, including relationships and parameters beyond the ECS. Therefore, updating the ECS alone within the current SCC framework may not significantly improve the estimates.

CONCLUSION 2 The relationship between CO_2 emissions and global mean surface temperature can be summarized by four metrics: equilibrium climate sensitivity (ECS), transient climate response, transient climate response to emissions, and the initial pulse-adjustment timescale. ECS is less relevant than the other three metrics in characterizing the climate system response on timescales of less than a century. As a long-term, equilibrium metric, ECS alone does not provide an adequate summary of the relationship between CO_2 emissions and global mean surface temperature for calculating the social cost of carbon (SCC). Therefore, simply

updating the distribution of ECS without assessing the impact on these other metrics may not result in an improved estimate of the SCC.

RECOMMENDATION 1 The committee recommends against a near-term update to the social cost of carbon based simply on a recalibration of the probability distribution of the equilibrium climate sensitivity (ECS) to reflect the recent consensus statement in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Consequently, the committee also recommends against a near-term change in the distributional form of the ECS.

Rather than updating the ECS in the current framework, the IWG could undertake efforts to adopt or develop a common "module" that represents the relationship between CO_2 emissions and global mean surface temperature change, its uncertainty, and its profile over time. If the IWG pursues such an effort, the following criteria would provide a more robust alternative to assessing the link between CO_2 emissions to temperature change than ECS alone:

1. The module's behavior should be consistent with the best available scientific understanding of the relationship between emissions and temperature change, its pattern over time, and its uncertainty. Specifically, the module should be assessed on the basis of both its response to a pulse of emissions and its response to long-term forcing trajectories (specifically, trajectories designed to assess transient climate response and transient climate response to emissions, as well as high- and low-emissions baseline trajectories). Given the degree of assessment they face, including consistency with observational data, the IPCC-class Earth system models provide a reference for evaluating the central projections of a climate module.
2. The proposed module should strive for simplicity and transparency so that the central tendency and range of uncertainty in its behavior are readily understood, are reproducible, and are amenable to continuous improvement over time through the incorporation of evolving scientific evidence.
3. The possible implications of the choice of a common climate module for the assessment of impacts of other, non-CO_2 greenhouse gases should also be considered.

NEAR-TERM ENHANCEMENT OF THE QUALITATIVE CHARACTERIZATION OF SCC UNCERTAINTY TO INCREASE TRANSPARENCY

The third charge question directs the committee to consider ways to enhance the qualitative characterization of uncertainties associated with the current SCC estimates in the near term to increase the transparency associated with using these estimates in regulatory impact analyses.

To be well defined, the SCC must be conditioned on certain variables, for example, the year in which the change in emissions is assumed to occur. Parameters that may require policy or value judgments must also be specified: these may concern how effects across people are aggregated, including across time, across different income levels, and over political jurisdictions. The SCC may be presented on the basis of different assumed values for such parameters, but it is generally inappropriate to take averages across such values because the variation does not reflect—or does not *only* reflect—uncertainty. For practical regulatory purposes, for example, it is necessary to present SCC estimates conditional on alternative discount rates in order to allow those SCC estimates to be combined with other cost and benefit estimates that use different discount rates.

The SCC depends on a number of inputs that are uncertain. Some are aspects of the natural world, such as the sensitivity of temperature change to emissions and how it evolves over time. Others are consequences of current and future human behavior, such as population growth, economic growth, and the trajectory of global greenhouse gas emissions. For regulatory decision making, it is at least conceptually possible to describe the uncertainty of these inputs in SCC calculations using probability distributions. Ideally, joint probability distributions could be defined for all of the uncertain inputs to an SCC-IAM, and the impact of uncertainty on the SCC could be evaluated using Monte Carlo analysis or a related approach.

One reason for modeling uncertainty is related to nonlinearities. If the SCC calculation involves nonlinearities over the range of uncertain parameters, the average value of the SCC computed from random draws of these uncertain inputs may not be the same as the single SCC computed from the average parameter values. The implications of such nonlinearities may be difficult to know a priori, suggesting it is best to compute the SCC from random draws of uncertain inputs.

It is also important to model uncertainty in order to provide a range of plausible estimates for cost-benefit analysis. The U.S. Office of Budget and Management (OMB) Circular A-4 requests a formal quantitative analysis of uncertain costs and benefits for major rules with effects of $1 billion or more. Given the consequences of the presence of CO_2 emissions across many government rulemakings, it is important to address this need.

Handling of Uncertainty in IWG Analysis

In constructing the SCC, the IWG treated some parameters of the climate system and damage functions as uncertain and random and represented these parameters using probability distributions. A common distribution, using a distributional form developed by Roe and Baker (2007), was used to represent the ECS in each of the three SCC-IAMs: the Dynamic Integrated Climate-Economy Model (DICE), the Policy Analysis of the Greenhouse Effect (PAGE), and the Climate Framework for Uncertainty, Negotiation and Distribution (FUND). In addition, 11 climate system parameters in FUND and 10 in PAGE were also represented by probability distributions, as were 50 parameters in FUND's damage model and 46 in PAGE's damage model (see Chapter 2 for an overview of these models). Socioeconomic and emissions uncertainty was also considered through five alternative scenarios. In calculating the SCC, each SCC-IAM was run by taking 10,000 draws from the relevant probability distributions and calculating the SCC for each draw, conditional on a socioeconomic and emissions scenario and discount rate.

CONCLUSION 3 The Interagency Working Group on the Social Cost of Carbon (SCC) technical support document explicitly describes the factors on which the SCC is conditioned, such as the year emissions occur and the discount rate and also makes explicit the sources of distributions for various inputs. However, it does not detail all sources of model-specific uncertainty in the social cost of carbon integrated assessment models.

RECOMMENDATION 2 When presenting the social cost of carbon (SCC) estimates, the Interagency Working Group (IWG) on the SCC should continue to make explicit the sources of uncertainty. The IWG should also enhance its efforts to describe uncertainty by adding an appendix to the technical support document that

describes the uncertain parameters in the Climate Framework for Uncertainty, Negotiation and Distribution and Policy Analysis of the Greenhouse Effect models.

CONCLUSION 4 Multiple runs from three models provide a frequency distribution of the social cost of carbon (SCC) estimates based on five socioeconomic-emissions scenarios, three discount rates, draws from the equilibrium climate sensitivity distribution, and other model-specific uncertain parameters. This set of estimates does not yield a probability distribution that fully characterizes uncertainty about the SCC.

Sources of Uncertainty Omitted from the IWG Analysis

The committee notes that none of the three SCC-IAMs (nor any others of which the committee is aware) are sufficiently comprehensive to include all of the uncertainties in the inputs that are likely to be important in calculating the SCC. Moreover, explicit distributions for some important inputs (e.g., emission scenarios, economic growth, and population) have not been developed by the IWG for use in estimating the SCC. Factors omitted or not adequately captured by the analysis need to be better characterized. In addition, a single unifying discussion of captured and omitted uncertainty is needed. There is, however, no section of the IWG's technical support documents that contain a unified discussion of this topic.

RECOMMENDATION 3 The Interagency Working Group on the Social Cost of Carbon (IWG) should expand its discussion of the sources of uncertainty in inputs used to estimate the social cost of carbon (SCC), when presenting uncertainty in the SCC estimates. The IWG should include a section entitled "Treatment of Uncertainty" in each technical support document updating the SCC. This section should discuss various types of uncertainty and how they were handled in estimating the SCC, as well as sources of uncertainty that are not captured in current SCC estimates.

The uncertainties discussed in this section would include the uncertain parameters unique to each of the models, uncertainty about climate change impacts and their valuation, and the risk of potential catastrophic outcomes. The section would also discuss the implicit, equal weight placed on the three IAMs and five socioeconomic scenarios in computing an average SCC, the possible alternatives of unequal weights or alternative models and scenarios, and the motivation for the chosen approach. The executive summary of the technical support document and individual regulatory impact analyses that use the SCC might usefully provide a summary of this discussion.

Reporting of Results

In the executive summaries of the IWG's technical support documents, the presentation of SCC estimates and the description of the uncertainty underlying them are brief. For each year of interest, four summary estimates of the SCC are shown (see Table 2-3, in Chapter 2): the average SCC for 2.5, 3, and 5 percent discount rates, as well as the 95th percentile for a 3 percent discount rate.[27] Thus, the only range of SCC estimates presented in the executive summary of the technical support documents is the range based on discount rates, together with the 95th percentile of the SCC based on a 3 percent discount rate. A more complete characterization of uncertainty would include other sources of variability in the SCC, for each discount rate, and would include both high and low values. These values could be used in sensitivity analyses in regulatory impact analyses.

CONCLUSION 5 It is important to continue to separate the impact of the discount rate on the social cost of carbon from the impact of other sources of variability. A balanced presentation of uncertainty includes both low and high values conditioned on each discount rate.

RECOMMENDATION 4 The executive summary of each technical support document should provide guidance concerning interpretation of reported social cost of carbon (SCC) estimates for cost-benefit analysis. In particular, the guidance should indicate that SCC estimates conditioned on a particular discount rate should be combined with other cost and benefit estimates conditioned on consistent discount rates, when they are used together in a particular analysis.

The guidance should also indicate that when uncertainty ranges are presented in an analysis, those ranges should include uncertainty derived from the frequency distribution of SCC estimates. To facilitate such inclusion, the executive summary of the technical support document should present symmetric high and low values from the frequency distribution of SCC estimates with equal prominence, conditional on each assumed discount rate.

One approach to the implementation of this recommendation would be to present in the executive summary a table similar to Table 5-1 below which would show high and low estimates of the SCC, as well as the average estimate, for each discount rate. The executive summary could also display the frequency distribution of SCC estimates as in Figure 5-1, with separate graphs for each discount rate. Separating the presentation of frequency distributions will encourage careful attention to the special role of discount rates on the basis of the regulatory context and the need to combine the SCC with other cost and benefit estimates. Also, the IWG could identify a high percentile (e.g., 90th, 95th) and corresponding low percentile (e.g., 10th, 5th) of the SCC frequency distributions on each graph. This approach would define a usable uncertainty range for the regulatory impact analysis for each discount rate.

[27] The most recent IWG technical support document states (Interagency Working Group on the Social Cost of Carbon, 2015, p. 2): "Three values are based on the average SCC from three integrated assessment models (SCC-IAMs), at discount rates of 2.5, 3, and 5 percent. The fourth value, which represents the 95th percentile SCC estimate across all three models at a 3 percent discount rate, is included to represent higher-than-expected impacts from temperature change further out in the tails of the SCC distribution."

TABLE 5-1: An Example of a Table of SCC Estimates

	Discount Rate								
Year	5.00%			3.00%			2.50%		
	Low	Avg.	High	Low	Avg.	High	Low	Avg.	High
2020	--	--	--	--	--	--	--	--	--
2025	--	--	--	--	--	--	--	--	--
…									
2050	--	--	--	--	--	--	--	--	--

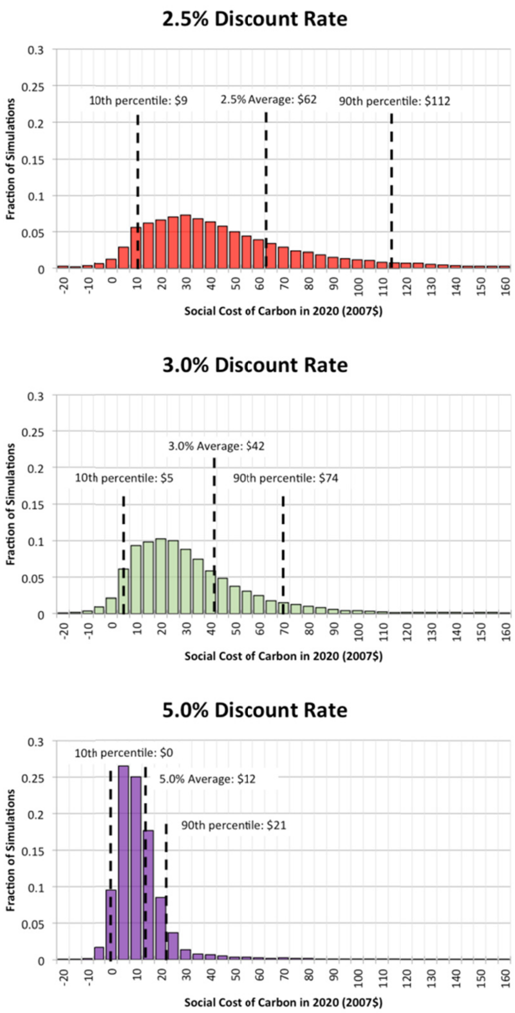


FIGURE 5-1 Examples of the frequency distribution of SCC estimates for 2020 (in 2007 dollars per metric ton of CO_2).
NOTES: The 10th and 90th percentiles of the SCC estimates are identified only as an example for presentation. The frequency distributions shown represent most of the 150,000 SCC estimates. However, they do not represent the entire distribution. Some estimates fall outside the range of the horizontal axis shown.
SOURCE: Developed from IWG SCC estimates provided to the committee by the U.S. Environmental Protection Agency.

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Appendix A
Biographical Sketches of Committee Members and Staff

MAUREEN L. CROPPER (*Cochair*) is a distinguished university professor and chair of the Department of Economics at the University of Maryland. She is also a senior fellow at Resources for the Future and a research associate of the National Bureau of Economic Research. Previously, she was a lead economist at the World Bank. Her research has focused on valuing environmental amenities (especially environmental health effects), on the discounting of future health benefits, and on the tradeoffs implicit in environmental regulations. Her current research focuses on energy efficiency in India, on the impact of climate change on migration, and on the benefits of collective action in pandemic flu control. She has served as chair of the Economics Advisory Committee of the Science Advisory Board of the U.S. Environmental Protection Agency and as past president of the Association of Environmental and Resource Economists. She is a member of the National Academy of Sciences. She has a B.A. in economics from Bryn Mawr College and a Ph.D. in economics from Cornell University.

RICHARD G. NEWELL (*Cochair*) is the Gendell professor of energy and environmental economics at Duke University's Nicholas School of the Environment and director of the Duke University Energy Initiative. Previously, he served as the administrator of the U.S. Energy Information Administration and as the senior economist for energy and environment on the President's Council of Economic Advisers. He is on the board of directors of Resources for the Future, a research associate of the National Bureau of Economic Research, and a member of the North Carolina Energy Policy Council. His work has covered the economics of markets and policies for energy, the environment, and related technologies, including energy systems forecasting, market-based policy, energy efficiency, discounting, and incentives for technological innovation and adoption. He has a B.S. and a B.A. from Rutgers, an M.P.A. from the Woodrow Wilson School of Public and International Affairs at Princeton University, and a Ph.D. from Harvard University.

MYLES ALLEN is professor of geosystem science in the Environmental Change Institute in the School of Geography and the Environment and in the Department of Physics, both at the University of Oxford. His research focuses on how human and natural influences on climate contribute to observed climate change and extreme weather events. He founded climateprediction.net and weatherathome.org experiments, using volunteer computing for weather and climate research. His recent work has dealt with quantifying the cumulative impact of carbon dioxide emissions on global temperatures and on the implications of reframing climate change as a carbon stock problem. He has served on several working groups on the physical science assessments of the Intergovernmental Panel on Climate Change and on the core writing team of the synthesis report in 2014. He was awarded the Appleton Medal from the Institute of Physics in 2010. He has a doctorate in physics from the University of Oxford.

MAXIMILIAN AUFFHAMMER is the George Pardee Jr. professor of international sustainable development and associate dean of interdisciplinary studies at the University of California at Berkeley. His research focuses on environmental and resource economics, energy economics, and applied econometrics. He is a research associate at the National Bureau of Economic Research in the Energy and Environmental Economics group, a Humboldt Fellow, and a lead author for the Intergovernmental Panel on Climate Change (IPCC). He is a recipient of the Cozzarelli Prize awarded by the *Proceedings of the National Academy of Sciences* and of the

Campus Distinguished Teaching Award and the Sarlo Distinguished Mentoring Award from the University of California at Berkeley. He has a B.S. in environmental science and an M.S. in environmental and resource economics from the University of Massachusetts at Amherst and a Ph.D. in economics from the University of California at San Diego.

CHRIS E. FOREST is associate professor of climate dynamics in the Departments of Meteorology and Geosciences, an associate in the Earth and Environmental Systems Institute, and associate director for the Network for Sustainable Climate Risk Management, all at Pennsylvania State University. He studies how to characterize uncertainties in climate projections from global to regional scales and understanding how these uncertainties should be included in climate change decision analyses. He served as a lead author on the Intergovernmental Panel on Climate Change chapter on the evaluation of climate models and as a lead author on a Climate Change Science Program synthesis and assessment report examining atmospheric and surface temperature trends. He serves on the leadership team for the Atmospheric and Hydrospheric Sciences Section of the American Association for the Advancement of Science. He has a B.S. in applied math, engineering, and physics from the University of Wisconsin-Madison and a Ph.D. in meteorology from the Massachusetts Institute of Technology.

INEZ Y. FUNG is a professor of atmospheric sciences at the University of California at Berkeley. She is also a member of the science team for NASA's Orbiting Carbon Observatory. She studies the interactions between climate change and biogeochemical cycles, particularly the processes that maintain and alter the composition of the atmosphere. Her research emphasis is on using atmospheric transport models and a coupled carbon-climate model to examine how CO_2 sources and sinks are changing. She is a recipient of the American Geophysical Union's Roger Revelle Medal. She is a member of the National Academy of Sciences, and a fellow of the American Meteorological Society, the American Geophysical Union, the American Academy of Arts and Sciences, and the American Philosophical Society. She has a S.B. in applied mathematics and a Sc.D. in meteorology from the Massachusetts Institute of Technology.

JAMES K. HAMMITT is professor of economics and decision sciences at the T.H. Chan School of Public Health and director of the Center for Risk Analysis, both at Harvard University, and an affiliate of the Toulouse School of Economics. His research concerns the development and application of quantitative methods—including benefit-cost, decision, and risk analysis—to health and environmental policy. Topics include management of long-term environmental issues with important scientific uncertainties, such as global climate change and stratospheric-ozone depletion, evaluation of ancillary benefits and countervailing risks associated with risk-control measures, and characterization of social preferences over health and environmental risks using revealed-preference, stated-preference, and health-utility methods. He has a Ph.D. in public policy from Harvard University.

HENRY D. JACOBY is the William F. Pounds professor of management (emeritus) in the Sloan School of Management and former codirector of the Joint Program on the Science and Policy of Global Change, both at the Massachusetts Institute of Technology (MIT). His work has focused on the integration of the natural and social sciences and policy analysis in application to the threat of global climate change. Previously, he served on the faculties of the Department of Economics and the Kennedy School of Government, both at Harvard University. He has also served as director of the Harvard Environmental Systems Program, director of the

MIT Center for Energy and Environmental Policy Research, associate director of the MIT Energy Laboratory, and chair of the MIT faculty. He has an undergraduate degree in mechanical engineering from the University of Texas at Austin and a Ph.D. in economics from Harvard University.

JENNIFER A. HEIMBERG (*Study Director*) is a senior program officer in the Division of Earth and Life Sciences (DELS) and the Division of Behavioral and Social Sciences and Education. In her work for the Nuclear and Radiation Studies Board in DELS, she has focused on nuclear security, nuclear detection capabilities, and environmental management issues, and she has directed studies and workshops related to nuclear proliferation, nuclear terrorism, and the management of nuclear wastes. Previously, she worked as a program manager at the Johns Hopkins University Applied Physics Laboratory, where she established its nuclear security program with the Department of Homeland Security's Domestic Nuclear Detection Office. She has a B.S. in physics from Georgetown University, a B.S.E.E. from Catholic University, and a Ph.D. in physics from Northwestern University.

ROBERT KOPP is associate director of Rutgers Energy Institute and an associate professor in the Rutgers University Department of Earth & Planetary Sciences. His research focuses on understanding uncertainty in past and future climate change, with major emphases on sea level change and on the interactions between physical climate change and the economy. He is a contributing author to the working groups on physical science and on impacts, adaptation, and vulnerability of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. He is a Leopold Leadership fellow and a recipient of the Sir Nicholas Shackleton Medal of the International Union for Quaternary Research and the William Gilbert Medal of the American Geophysical Union. He has an undergraduate degree from the University of Chicago and a Ph.D. in geobiology from the California Institute of Technology.

WILLIAM PIZER is a professor in the Sanford School of Public Policy and faculty fellow at the Nicholas Institute for Environmental Policy Solutions at Duke University. His current research examines how public policies to promote clean energy can effectively leverage private-sector investments, how environmental regulation and climate policy can affect production costs and competitiveness, and how the design of market-based environmental policies can be improved. Previously, he was Deputy Assistant Secretary for Environment and Energy at the U.S. Department of the Treasury, overseeing the department's role in the domestic and international environment and energy agenda of the United States. He was also a researcher at Resources for the Future in Washington, D.C. He has a bachelor's degree in physics from the University of North Caroling at Chapel Hill and a master's degree and a Ph.D. in economics from Harvard University.

STEVEN ROSE is a senior research economist in the Energy and Environmental Research Group at the Electric Power Research Institute. His research focuses on long-term modeling of energy systems and climate change drivers, mitigation, and potential climate risks and responses, as well as the economics of land use and bioenergy as they relate to climate change and energy policy. He serves on the U.S. government's Carbon Cycle Scientific Steering Group and Environmental Protection Agency's Science Advisory Board panel on biogenic carbon dioxide emissions accounting. He was also a lead author for the Fifth and Fourth Assessment Reports of the Intergovernmental Panel on Climate Change and for the U.S. National Climate Assessment.

He has a B.A. in economics from the University of Wisconsin-Madison and a Ph.D. in economics from Cornell University.

RICHARD SCHMALENSEE is the Howard W. Johnson professor of management (emeritus) and professor of economics (emeritus) at MIT. Previously, at MIT, he was the John C. Head III dean of the Sloan School of Management, director of the Center for Energy and Environmental Policy Research, and a member of the Energy Council. He also previously served as a member of the President's Council of Economic Advisers. His research and teaching have focused on industrial organization economics and its applications to business decision making and public policy. He is a fellow of the Econometric Society and of the American Academy of Arts and Sciences. He has served on the executive committee of the American Economic Association and as a director of several corporations, and he is currently chair of the board of Resources for the Future. He was a distinguished fellow of the Industrial Organization Society. He has an S.B. and a Ph.D. in economics from the Massachusetts Institute of Technology.

JOHN P. WEYANT is professor of management science and engineering, director of the Energy Modeling Forum, and deputy director of the Precourt Institute for Energy Efficiency, all at Stanford University. His current research focuses on analysis of global climate change policy options, energy efficiency analysis, energy technology assessment, and models for strategic planning. He has been a convening lead author or lead author for several chapters of the IPCC reports, and, most recently, as a review editor for the climate change mitigation working group of the IPCC's Fourth and Fifth Assessment Reports. He was also a founder and serves as chair of the Scientific Steering Committee of the Integrated Assessment Modeling Consortium, a collaboration of 53 member institutions from around the world. He is a recipient of the Adelmann-Frankel award from the U.S. Association for Energy Economics for unique and innovative contributions to the field of energy economics. He has a B.S./M.S. in aeronautical engineering and astronautics and M.S. degrees in engineering management and in operations research and statistics from Rensselaer Polytechnic Institute and a Ph.D. in management science with minors in economics, operations research, and organization theory from the University of California at Berkeley.

CASEY J. WICHMAN (*Technical Consultant*) is a fellow at Resources for the Future in Washington, D.C. His research is concentrated at the intersection of environmental and public economics, with an emphasis on examining the ways individuals make decisions in response to environmental policies using quasi-experimental techniques. In particular, his work analyzes the effectiveness of price and nonprice interventions for water conservation, the role of information in the design of environmental policy, and the effect of water scarcity in the energy sector. He has a B.A. in economics from Ithaca College, an M.S. from North Carolina State University, and an M.S. and a Ph.D. in agricultural and resource economics from the University of Maryland at College Park.

Appendix B

Open Meeting Agenda

First Meeting
Committee on Assessing Approaches to Updating the Social Cost of Carbon

Room 208
Keck Center
500 5th St., NW
Washington, DC 20001

Wednesday, September 2, 2015
OPEN SESSION (open to the public)

9:30 Welcome Introductions
MaryEllen O'Connell, Interim Director, Board on Environmental Change and Society
Maureen Cropper and Richard Newell, Cochairs
Marisa Gerstein Pineau, Program Officer

9:45 Presentation: Sponsors' Interests and Goals for the Study
Ken Gillingham, Council of Economic Advisers
Q&A: **Richard Newell and Maureen Cropper**, Moderators

10:45 *Break*

11:15 Presentation: Methodology for the Social Cost of Carbon Estimates
Elizabeth Kopits, U.S. Environmental Protection Agency
Q&A: **Richard Newell and Maureen Cropper**, Moderators

12:45 Closing Remarks
Maureen Cropper and Richard Newell, Co-Chairs

1:00 Adjourn Open Session

Exhibit G

Institute *for* Policy Integrity
NEW YORK UNIVERSITY SCHOOL OF LAW

April 29, 2016
National Academies of Sciences

Subject: Recommendations for Changes to the Final Phase 1 Report on the Social Cost of Carbon, and Recommendations in Anticipation of the Phase 2 Report on the Social Cost of Carbon

The Institute for Policy Integrity at New York University School of Law[1] respectfully submits these comments to the National Academies of Sciences (NAS) on its review of the social cost of carbon (SCC). Policy Integrity is a non-partisan think tank dedicated to improving government decision-making through scholarship and advocacy in administrative law, economics, and public policy. Policy Integrity and its staff have produced significant scholarship on the social cost of carbon, including running the Cost of Carbon Project.[2]

These comments both recommend changes to the draft Phase 1 report that the NAS should make before finalizing that document, as well as suggest directions for the NAS to take or avoid during Phase 2.

The bulk of the conclusions in the NAS's draft Phase 1 report are appropriate. In particular, the Interagency Working Group (IWG) should not undertake a near-term update of the equilibrium climate sensitivity parameter, but instead should work toward longer-term refinements to its application of the integrated assessment models (IAMs). However, <u>when finalizing the Phase 1 report, the NAS should:</u>

- **Rescind its proposed expansion of the range of SCC estimates** by giving equal weight to low, central, and high estimates at each discount rate, resulting in 9 (or possibly 27) different SCC estimates, including some at or near the improbable value of $0. There is no economic justification for including low percentile estimates; the multiplicity of estimates will confuse agencies, lead to inconsistent cherry-picking of estimates, undermine transparency, and erode public confidence in the SCC methodology; and the inclusion of $0 values raises significant policy and legal difficulties. (See our Recommendation 2.1 below.)
- **Define "consistent" discount rates as "compatible," not "identical," rates.** The NAS's draft proposal for "consistent" discounting is vague, but possibly supports applying different yet theoretically consistent rates. For example, a 3% rate may be appropriate for most short-run benefits and costs in an economic analysis, while a 2.5% or lower rate may be simultaneously appropriate for the SCC, reflecting greater uncertainty. (See Recommendation 3.1.)

<u>In the Phase 2 report, the NAS should:</u>

- **Endorse a focus on the global SCC**, as justified by the economics of international reciprocity and consistent with legal mandates. Focus on a domestic-only SCC would undermine strategic goals and would be misleading, by overlooking significant spillover effects and U.S. willingness to pay to prevent climate damages occurring outside U.S. borders. (See Recommendation 1.)
- **Adopt a certainty-equivalent SCC** as the central estimate for use in decision-making. (See Recommendation 2.2.)
- **Urge the use of declining discount rates**, as consistent with the latest theory and evidence. (See Recommendation 3.2.) The NAS should also call for a normative approach to discounting (see Recommendation 3.4), or minimally for the IWG to include lower constant rates, below 2.5%, to reflect the true range of consumption discount rates (see Recommendation 3.3.).

[1] No part of this document purports to present the views, if any, of New York University.
[2] http://www.costofcarbon.org.

- **Expand the module system, first to include a damage function module**, and later to explore adaptation, structural, and tipping point modules. Current IAMs omit significant damage categories, including growth effects; they fail to incorporate the latest economic and scientific data; and they lack direct damage estimates for high temperatures. The IWG should use bottom-up and top-down estimation approaches, including meta-analysis and expert elicitations. (See Recommendations 4.1-4.3.) The NAS should develop criteria for when, if ever, modules should move beyond sensitivity analysis to replace IAM components. (See Recommendation 4.4.)
- **Develop transparent criteria for IAM selection.** There are many more peer-reviewed models besides the three IAMs chosen by the IWG; some models are inter-related, sharing data or structures. The IWG should both expand the range of models it incorporates into its methodology and disclose the relationships between the models chosen. (See Recommendations 5.1-5.2.)
- **Call for the IWG to update its socio-economic assumptions.** (See Recommendations 6.1-6.2.)
- **Call for the federal government to support future research**, including increased funding for a broad set of interdisciplinary researchers. The NAS should highlight key areas for future research, such as monetizing omitted damages and testing climate models' predictive powers. (See Recommendations 7.1-7.2.)

Finally, in adopting any recommendations, the NAS should consider that there is value to maintaining relatively stable SCC estimates over time. Even as the NAS helps guide and push the IWG toward improved estimates based on the best available economics and science, overly frequent—and especially contradictory—fluctuations from one year to the next could create problems. The IWG was convened in 2009 to ensure consistent use of SCC estimates across federal agencies; a degree of consistency over time is likewise valuable. Erratic changes could confuse agencies and erode confidence in the methodology. The NAS should help guide the IWG toward a steady path of constant but careful refinements.

1. A Global SCC Value Is Most Appropriate; a Domestic-Only Calculation Is Misleading

The NAS has received comments signed by a few economists and policy scholars encouraging the NAS to recommend "refocus[ing]" the SCC on domestic impacts, with the global SCC relegated to a "separate reporting" (Fraas et al., 2016). Those comments are misguided on multiple counts. First, they wrongly dismiss the role of strategic motivations in justifying a focus on the global SCC, as well as how the U.S. directly benefits from reciprocal foreign actions. Second, it is a domestic-only, not a global SCC, that is "misleading," because a domestic-only SCC overlooks spillovers and U.S. willingness to pay to prevent climate damages occurring outside U.S. borders. In fact, both methodological limitations and the realities of global economic, atmospheric, ecological, and political systems may make it impossible to accurately calculate a reliable, consistent domestic-only range. Third, they overlook the most recent White House guidance on regulatory policy, which encourages international harmonization. Fourth, they mischaracterize the "current approach" of agencies: in fact, the vast majority of regulatory impact analyses already include both domestic and global calculations, and even the "global" estimates discount foreign welfare to some degree. Finally, these comments are out of the mainstream, with dozens of economists and policy experts supporting a global SCC.

Recommendation 1: The NAS Should Endorse a Focus on the Global SCC, as Justified by the Economics of International Reciprocity, Spillovers, and Willingness to Pay to Prevent Foreign Damages

A. Strategic Motivations, Grounded in Economic Theory, Justify a Global SCC; a Domestic-Only SCC Undermines U.S. Strategic Goals in International Climate Negotiations

Fraas et al. (2016) concede that using the global SCC in U.S. regulatory analysis "might . . . make sense if such actions would help persuade foreign governments that the U.S. had done its part to reduce [greenhouse gas] emissions and therefore other governments ought to do more." Indeed, such strategic motivations are a fundamental justification for a global focus. The United States has specifically chosen a tit-for-tat strategy of harmonizing with other countries on use of the global SCC, and the United States has directly and immensely benefited from foreign actions and commitments on carbon reductions. Highlighting instead a domestic-only SCC would risk undermining long-term U.S. interests in securing reciprocal foreign actions on climate change.

To avoid a global "tragedy of the commons" that could irreparably damage all countries, every nation should set policy according to a global SCC value. "[E]ach pursuing [only its] own best interest . . . in a commons brings ruin to all" (Hardin, 1968). If all countries set their carbon emission levels based on only domestic costs and benefits, ignoring the large global externalities, the aggregate result would be substantially sub-optimal climate protections and significantly increased risks of severe harms to all nations, including the United States. Thus, basic economic principles demonstrate that the United States stands to benefit greatly if all countries apply a global SCC value in their regulatory decisions. In a recent Policy Integrity report, we estimate that foreign climate actions have already directly benefited the United States by upwards of $200 billion, with trillions of dollars more at stake in securing future foreign commitments to reduce more carbon pollution (Howard & Schwartz, 2015).

A rational tactical option in the effort to secure ongoing international cooperation is for the United States to continue using a global SCC value itself. Game theory models have long been applied to climate negotiations (DeCanio & Fremstad, 2013). Under a number of scenarios and assumptions, a strategy of leading by example with unilateral action or continuing a tit-for-tat dynamic could successfully induce ongoing international cooperation on climate change. For instance, in the "coordination" strategic model, all parties realize mutual welfare gains if they all choose mutually consistent strategies. A classic version is when two drivers meet on a narrow road: only when both swerve in the same direction (e.g., both to their right) can they avoid collision. In a coordination model of climate negotiations, unilateral abatement by one major emitting country or bloc of countries can increase the incentive for other governments to also abate. In this strategy, good faith signals can build credibility and trust with other nations, which can increase those countries' perceptions of whether a broadly cooperative outcome is probable, which in turn actually induces cooperation. Trust-building exercises and signals can be especially useful when players are risk adverse (Stewart et al., 2013). Calculating the global costs of U.S. emissions could provide a good faith signal that the United States cares about the welfare of other countries, and finalizing U.S. regulations that use the global SCC value can further increase the incentives for other governments to follow suit.

In a number of additional negotiation structures, a "tit-for-tat" strategy can prove successful in inducing cooperation, once the model reflects more realistic assumptions allowing repeat negotiations over time. For instance, when the "prisoner's dilemma" model assumes that two decision-makers will each have only a single opportunity to choose a strategy, both actors unfortunately perceive that defection is their best personal option, which ultimately leaves both worse off. The classic version involves two criminal co-conspirators being questioned by police in separate rooms, where each end up confessing on the other since their physical separation prevents them from collaboratively making a mutually beneficial agreement to both stay silent. Yet when the model is extended over multiple rounds of decision-making instead, a tit-for-tat strategy allows the actors to punish in future rounds those who fail to cooperate (Wood, 2011). Experiments suggest that tit-for-tat is a very robust strategy in most negotiating environments (Axelrod, 1984). Assumptions that nations will defect or try to free ride in climate negotiations are often based on simple Nash equilibria models that do not capture the real-world conditions that make cooperation more likely. In real negotiations among repeat, sophisticated players, negotiators may have even greater foresight with respect to counter-moves than classic models of strategic behavior may predict. One recent article concludes that, applying more realistic assumptions about foresight with respect to counter-moves, every one of the 25 possible basic game structures that may describe climate negotiations has at least one cooperative solution (Madani, 2013).

Multiple other countries, including the United Kingdom, Sweden, Germany, France, Norway, and Canada, have either adopted a global SCC value or otherwise priced carbon at a global value (Howard & Schwartz, 2016). By matching these global SCC values already in use by other countries, the United States could be seen as continuing a tit-for-tat dynamic designed to reinforce those countries' existing commitments and to encourage reciprocal action from additional countries. In fact, for the United States to now depart from this collaborative dynamic by reverting to a domestic-only SCC estimate could undermine long-term U.S. interests in future climate negotiations and could jeopardize emissions reductions underway in other countries, which are already benefiting the United States by upwards of $200 billion (Howard & Schwartz, 2015). A domestic-only SCC value could be construed as a signal that the United States does not recognize or care about the effects of its policy choices on other countries, and could signal that it would be acceptable for other countries to ignore the harms they cause the United States. Further, a sudden about-face could undermine the United States' credibility in negotiations. If the United States sees the climate negotiations as a repeated dynamic of tit-for-tat, using the global SCC value is a rational strategy.

Universal adoption of the global SCC is not required for use by the United States to be rational. Building a small, stable coalitions of key actors is another viable strategy for securing broader international cooperation over time. Coalitions can lead by example through joint initial commitments to act. Coalitions also foster communication and trust among nations, and they allow member nations to learn by doing and to apply those lessons in future negotiations with other countries (Grasso & Roberts, 2014; Ostrom, 2014; Stewart et al., 2013; Finus, 2008). Some evidence exists that the small coalition strategy is more likely to be successful in climate negotiations if nations' initial commitments are close to their actual optimal emissions reductions and are not mere half-measures (Smead et al., 2014). By joining other nations in using global SCC values and adopting meaningful greenhouse gas limitations, the United States may be employing a coalition-building strategy. Thus, the United States need not hold out for the promise of immediately inducing complete reciprocity among all countries before it is justified in using the global SCC; using the global SCC now can help build a small coalition of key actors, which will both benefit the United States in the short term and help build toward global agreement. (Similarly, after factoring in reasonable predictions on how climate change damages will unfold in the future, even partial reciprocity can justify using a global SCC estimate (Kopp & Mignone, 2013)).

Experiments also show that negotiators balance fairness considerations against pure self-interest. In the classic "ultimatum game" experiment, one player is offered a sum of money to split with another player; only if the second player accepts the split will either get any money. Economic theory would predict that a purely rational first player would offer just one cent to the second player, and a purely rational second player would accept the single penny rather than get nothing. In fact, real first players rarely offer anything less than 30% of the money, and real second players rarely accept any split perceived as unfair. Multiple studies find that, irrespective of the amount at stake in the ultimatum game, first players from industrialized countries typically offer around a 50% split, and second players frequently reject anything less than a 20% share (Sanfey et al., 2003; Oosterbeek et al., 2004). This experimental result "provides evidence that an international environmental agreement is more likely to be stable if it is perceived by its parties to be fair" (Wood, 2011, citing Barrett, 2003). By counting the full global damages of its emissions, the United States may be able to improve its reputation for fairness, building the trust and credibility essential to secure reciprocal actions from other countries.

Quotes from high-ranking officials in the Obama administration suggest that the United States has consciously adopted a tit-for-tat or coalition-building strategy in selecting to emphasize the global SCC value in U.S. regulatory policy. For example, Office of Information and Regulatory Affairs administrator Howard Shelanski (2013) has said "[Climate change] is a global problem, and it seems much easier to exercise global leadership and to get other countries around the world to recognize the social costs of carbon if we are doing so ourselves." Chair of the Council of Economic Advisors Jason Furman has said:

> It is entirely appropriate to include those [global benefits] because we're trying to motivate a range of countries all to act together. . . . If everyone did a social cost of carbon for their own country, everyone would have too low a number and everyone would act too little. And it would make everyone, including the U.S., worse off. . . . [The global SCC is] in effect like a proxy for not only looking at the domestic [benefits], taking into account that we'll get benefits not just from the reduced emissions in the U.S. from our rule, but that it will lead to policy changes . . . from other countries (quoted in Hendrixson, 2014).

The IWG itself explained that a global SCC value was justified in part because "Emphasizing the need for a global solution to a global problem, the United States has been actively involved in seeking international agreements to reduce emissions and in encouraging other nations, including emerging major economies, to take significant steps to reduce emissions" (IWG, 2010). And as President Obama (2015) explained in announcing the Clean Power Plan, "[I]f we don't do it, nobody will. The only reason that China is now looking at getting serious about its emissions is because they saw that we were going to do it, too."

Indeed, the U.S. strategy of encouraging international reciprocity through the use of the global SCC is already working. Most recently, Canada—which already based its SCC estimates on the IWG's 2010 global SCC estimates—agreed to continue aligning its SCC with the U.S. SCC in evaluating and setting regulatory policies. As explained by a Joint Statement released by the White House (2016):

> Given the integrated nature of many aspects of the U.S. and Canadian economies, alignment of analytical methods for assessing and communicating the impact of direct and indirect [greenhouse gas] emissions of major projects, and of measures to reduce those emissions, can be mutually beneficial. Canada and the U.S. will align approaches, reflecting the best available science for accounting for the broad costs to society of the GHG emissions that will be avoided by mitigation measures, including using similar values for the social cost of carbon and other [greenhouse gases] for assessing the benefits of regulatory measures.

The United States has good reason to expect additional countries to adopt policies based on the global SCC so long as the United States continues using the global SCC itself; reverting to emphasize a domestic-only SCC would undermine this strategy.

B. A Domestic-Only SCC Would Misleadingly Ignore Spillover Effects and U.S. Willingness to Pay to Prevent Climate Damages Occurring Outside U.S. Borders

Even after conceding that strategic factors can justify the use of a global SCC, Fraas et al. (2016) argue that using the global SCC in U.S. regulatory analysis is "misleading." To the contrary, because a domestic-only SCC ignores spillover effects and U.S. willingness to pay to prevent climate damages occurring outside U.S. borders, a domestic-only SCC would be misleading. Moreover, a domestic-only range may be impossible to calculate accurately.

The United States is not an island. Due to its unique place among countries—both as the largest economy with trade- and investment-dependent links throughout the world, and as a military superpower—the United States is particularly vulnerable to effects that will spill over from other regions of the world. Spillover scenarios could entail a variety of serious costs to the United States as unchecked climate change devastates other countries. Correspondingly, mitigation or adaptation efforts that avoid climate damages to foreign countries will radiate benefits back to the United States as well (Freeman & Guzman, 2009).

As climate change disrupts the economies of other countries, decreased availability of imported inputs, intermediary goods, and consumption goods may cause supply shocks to the U.S. economy. Shocks to the supply of energy, technological, and agricultural goods could be especially damaging. For example, when Thailand—the world's second-largest producer of hard-drives—experienced flooding in 2011, U.S.

consumers faced higher prices for many electronic goods, from computers to cameras (Arthur, 2011). Similarly, the U.S. economy could experience demand shocks as climate-affected countries decrease their demand for U.S. goods. Financial markets may also suffer, as foreign countries become less able to loan money to the United States and as the value of U.S. firms declines with shrinking foreign profits. As seen historically, economic disruptions in one country can cause financial crises that reverberate globally at a breakneck pace (Schwarz, 2008).

The human dimension of climate spillovers includes migration and health effects. Water and food scarcity, flooding or extreme weather events, violent conflicts, economic collapses, and a number of other climate damages could precipitate mass migration to the United States from regions worldwide, perhaps especially from Latin America. For example, a 10% decline in crop yields could trigger the emigration of 2% of the entire Mexican population to other regions, mostly to the United States (Feng, Krueger & Oppenheimer, 2010). Such an influx could strain the U.S. economy and will likely lead to increased U.S. expenditures on migration prevention. Infectious disease could also spill across the U.S. borders, exacerbated by ecological collapses, the breakdown of public infrastructure in poorer nations, declining resources available for prevention, shifting habitats for disease vectors, and mass migration.

Finally, climate change is predicted to exacerbate security threats—and possibly catalyze new security threats—to the United States (CNA, 2014). Besides threats to U.S. military installations and operations abroad from flooding, storms, extreme heat, and wildfires, President Obama (2014) has explained how climate change is "a creeping national security crisis, . . . as [the U.S. military will be] called on to respond to refugee flows and natural disasters, and conflicts over water and food." The Department of Defense's 2014 Defense Review declared that climate effects "are threat multipliers that will aggravate stressors abroad such as poverty, environmental degradation, political instability, and social tensions—conditions that can enable terrorist activity and other forms of violence," and as a result "climate change may increase the frequency, scale, and complexity of future missions, including defense support to civil authorities, while at the same time undermining the capacity of our domestic installations to support training activities" (DOD, 2014). As an example of the climate-security-migration nexus, prolonged drought in Syria likely exacerbated the social and political tensions that erupted into an ongoing civil war, which has triggered an international migration and humanitarian crisis (CAP, 2013; Kelley et al., 2014; Gleick, 2014).

In short, the direct and spillover effects of climate change to the United States are considerable, and carving out any precise, quantified portion of the global SCC that does not apply to the United States is very difficult and controversial. Trying to calculate a domestic-only SCC as either based on geographic boundaries or the U.S. share of global GDP arbitrarily and wrongly assumes that climate damages stop at borders, and ignores the world's deeply interconnected economic, political, and planetary systems. In fact, IAMs currently omit most inter-regional spill overs and socially contingent damages: as a result, calculating any range of domestic SCC estimates is highly inaccurate if not outright impossible.

Additionally, U.S. willingness to pay to prevent climate damages extends beyond strict geographic borders. U.S. citizens have economic and other interests abroad that are not fully reflected in the U.S. share of global GDP. Ownership interests in foreign businesses, properties, and other assets, as well as consumption abroad including tourism and eco-tourism, counsel against a rigid split based on U.S. GDP (EPA, 2008). U.S. citizens have some willingness to pay to protect purely foreign welfare (Rowell, 2015). The United States also has some willingness to pay—as well as perhaps a legal obligation—to protect the global commons of the oceans and Antarctica from climate damages (Madrid Protocol, 1991). Thus, a domestic-only SCC would fail to "provide to the public and to OMB a careful and transparent analysis of the anticipated consequences of economically significant regulatory actions" (OMB, 2011).

C. A Global SCC Is Consistent with the Most Recent White House Guidance and Legal Authorities

Fraas et al. (2016) are wrong that a focus on the global SCC value is inconsistent with Executive Orders and the Office of Management and Budget's guidance for regulatory analysis; in fact, the most recent Executive Order on regulatory policy encourages international harmonization. Fraas et al. focus on two executive orders on regulatory policy and claim that Executive Order 12,866 and 13,563 require an exclusively domestic perspective. Executive Order 12,866 in fact requires agencies to consider "all costs and benefits of available regulatory alternatives" (Clinton, 1993); Executive Order 13,563 expands that, when appropriate, agencies may consider "equity, human dignity, fairness, and distributive concerns" (Obama, 2011). The Office of Management and Budget's guidance on implementing these orders does assume that most regulatory impact analyses would focus on domestic costs and benefits (since most non-climate regulations do have predominantly or exclusively domestic effects), but the guidance ultimately defers to the discretion of individual agencies on whether to evaluate "effects beyond the borders of the United States" (OMB, 2003). To the extent either Executive Order 12,866 or 13,563 implies that agencies should focus on American welfare alone, as explored above, using a global SCC value directly benefits American welfare by stimulating reciprocal foreign actions on climate change that positively affect the United States. But more importantly, these two orders were followed by Executive Order 13609, on "promoting international regulatory cooperation." This 2012 order explicitly recognizes that significant regulations can have "significant international impacts," and it calls on federal agencies to work toward "best practices for international regulatory cooperation with respect to regulatory development" (Obama, 2012). A Regulatory Working Group on Executive Order 13,609 has clarified that cost-benefit analysis ("comparison of costs and benefits") is a "prerequisite[ ] for effective international regulatory cooperation" (RWG, 2015). In fact, the recently announced Canada-U.S. agreement to continue aligning their global SCC estimates represents the very kind of international cooperation envisioned by Executive Order 13,609.

Use of a global SCC value is also consistent with the relevant statutory authorities under which U.S. climate regulations have been promulgated and analyzed. In fact, some legal authorities may require a global perspective. For example, Section 115 of the Clean Air Act requires the control of "international air pollution" (42 U.S.C. § 7415), and the National Environmental Policy Act instructs that "all agencies of the Federal Government *shall* . . . recognize the worldwide and long-range character of environmental problems" (42 U.S.C. § 4332(2)(f)). Similarly, the United Nations Framework Convention on Climate Change (1992) requires that member nations' "policies and measures to deal with climate change should be cost-effective so as to *ensure global benefits* at the lowest possible cost." Policy Integrity's forthcoming report *Think Global: International Reciprocity as Justification for a Global Social Cost of Carbon* (Howard & Schwartz 2016) will further detail such legal requirements. The NAS should generally defer to agencies' interpretations of their statutory authorities, as well as to White House policy on matters touching on international negotiations.

D. The Vast Majority of Regulatory Impact Analyses to Date Discuss Domestic Calculations, though Properly Emphasize the Global SCC, and Even "Global" Estimates Reflect Domestic Biases

Fraas et al. (2016) wrongly state that the "current approach" of regulatory impact analyses is "reporting only the global benefits." In fact, the vast majority of regulatory impact analyses that apply the SCC have included both domestic and global calculations. The Government Accountability Office catalogued all regulatory actions (both proposed and final rules) that used a SCC value through June 2014. Of the 68 regulatory actions catalogued, 42 actions were by the Department of Energy (GAO, 2014), and the Department of Energy has always included domestic calculations in its regulatory impact analyses, even while emphasizing the global value. Most recently, in the agency's March 2016 analysis of its proposed energy efficiency standards for commercial boilers, table 14.4.1 shows "estimates of global present value of CO_2 emissions reductions," and table 14.4.2 shows "estimates of domestic present value of CO_2 emissions reductions" (DOE, 2016). Other agencies, including the Environmental Protection Agency, have also at times included in their regulatory proposals a discussion or calculation of the domestic SCC. For example, EPA's 2011 proposed air quality performance standards for the oil and gas sector first estimated the global value of the rule's climate co-benefits, but also discussed the "provisional and highly speculative" domestic range developed by the IWG (EPA, 2011). Moreover, even when EPA has appropriately chosen to emphasize the global SCC in its rules, the rulemaking dockets still contain EPA's thorough response to any public comments that argue for a domestic-only calculation,[3] as well as copies of the IWG's Technical Support Documents that explain the reason for emphasizing the global SCC and give the provisional range for the domestic-only calculation.[4] Thus, even while agencies routinely provide the public with information on the speculative estimates of the domestic-only SCC, they also correctly emphasize the global SCC value, for the preceding reasons.

Notably, even the "global" calculations of the SCC currently discount foreign welfare to some extent, and thus are arguably already somewhat biased toward a U.S.-centered perspective. Given decreasing marginal utility of consumption and heterogeneity in regional wealth, a dollar loss has heterogeneous welfare effects across regions. Therefore, some modelers have proposed applying equity weights (i.e., weighting the dollar loss in each region by the expect welfare impact it will have in this region) in the calculation of the SCC to accurately measure the change in the "expected value of social welfare" from emissions. Nevertheless, the IWG (2010) rejected equity weighting.[5] Consequently, the IWG's current calculation of the SCC already places relatively greater weight on domestic climate impacts, because it fails to apply equity weights to impacts experienced by foreign countries with lower GDP per capita. Any further weighting or emphasis of domestic impacts would therefore be theoretically and morally questionable.

E. Dozens of Economists and Climate Policy Experts Support the Global SCC

Fraas et al. (2016) are far out of the mainstream with their focus on a domestic-only SCC. The following is a selection of statements from economists and climate policy experts on why a global SCC is the appropriate value:

- "The moral, ethical, and security issues . . . [and the] strategic foreign relations question . . . are compelling reasons to focus on a global SCC" (William Pizer, Matthew Adler, Joseph Aldy, David Anthoff, Maureen Cropper, Kenneth Gillingham, Michael Greenstone, Brian Murray, Richard Newell, Richard Richels, Arden Rowell, Stephanie Waldhoff, Jonathan Wiener, 2014).
- "Another important issue in estimating the SCC was whether to include damages that are projected to occur outside the United States. . . . The interagency group concluded that a global measure of the benefits from reducing US emissions is preferable to a domestic measure because

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[3] See, e.g., EPA's Response to Comments document for the Clean Power Plan, https://www.regulations.gov/#!documentDetail;D=EPA-HQ-OAR-2013-0602-37106, at Section 8.7.2, discussing the 7-23% range and why it was not chosen.

[4] See, e.g., the rulemaking docket for the Clean Power Plan, which includes the 2010 TSD, posted on June 18, 2014, the same day the proposed rule was published for public comments. https://www.regulations.gov/#!documentDetail;D=EPA-HQ-OAR-2013-0602-0398.

[5] The IWG (2010) states that "When quantifying the damages associated with a change in emissions, a number of analysts (e.g., Anthoff, et al. 2009a) employ "equity weighting" to aggregate changes in consumption across regions. This weighting takes into account the relative reductions in wealth in different regions of the world. A per-capita loss of $500 in GDP, for instance, is weighted more heavily in a country with a per-capita GDP of $2,000 than in one with a per-capita GDP of $40,000. The main argument for this approach is that a loss of $500 in a poor country causes a greater reduction in utility or welfare than does the same loss in a wealthy nation. Notwithstanding the theoretical claims on behalf of equity weighting, the interagency group concluded that this approach would not be appropriate for estimating a SCC value used in domestic regulatory analysis. For this reason, the group concluded that using the global (rather than domestic) value, without equity weighting, is the appropriate approach."

the climate change issue is highly unusual in at least two respects" (Michael Greenstone, Elizabeth Kopits & Ann Wolverton, 2013).

- "The analysis by the federal Interagency Working Group is significant . . . for its recognition that policy should be based on global, rather than domestic, impacts" (Frank Ackerman & Elizabeth A. Stanton, 2012).
- "Empirical, theoretical, and ethical arguments strongly support the use of a global value" (Laurie Johnson & Chris Hope, 2012).
- "The domestically optimal price approaches the global cooperative optimum linearly with increasing circumspection and reciprocity" (Robert Kopp & Bryan Mignone, 2013).

2. In Recommending a Range of SCC Estimates for Agency Decision-making, More Is Not Always Better

The bulk of conclusions and recommendations in the NAS's first report are appropriate. In particular, the IWG should not undertake a near-term update of the equilibrium climate sensitivity (ECS) parameter or its corresponding distribution to reflect the minor change in the ECS from the 4th to the 5th IPCC reports, given the high opportunity cost of this potential update; instead, the IWG should develop a common climate module to more accurately model warming over the timespan relevant to IAMs. Furthermore, the NAS's call for increased transparency on the uncertainty underlying the IWG's SCC estimates is admirable.

The exception is the NAS's vague fourth recommendation in the draft of its first report. This recommendation jointly addresses the presentation of uncertainty and discount rates. The NAS should clarify and fix the two components of this recommendation in the finalized version of the first report. With respect to the uncertainty, the NAS should rescind its recommendation of the presentation of low and high (e.g., 5th and 95th percentile) SCC estimates conditioned on each discount rate, to avoid the draft recommendation's likely unintended consequences in the application of the SCC in benefit-cost analysis by agencies. If the NAS decides not to make these changes in the finalized version of its first report, the NAS should specify a central SCC estimate for decision making: ideally, a certainty-equivalent SCC.

Recommendation 2.1: In the Final Version of Its First Report, the NAS Should Eliminate Its Current Recommendation that the IWG Include Nine Different SCC Estimates and Should Give Each Equal Weight

The IWG (2010; 2013) recommends four SCC estimates. To calculate these SCC estimates, the IWG (2010; 2013) conducts Monte Carlo simulations of 10,000 random draws for each of the three IAMs (DICE, FUND and PAGE), five socio-economic scenarios (four business as usual scenarios and one mitigation scenario), and three discount rates (2.5%, 3%, and 5%). The resulting output is 45 distributions—one for each IAM, socio-economic scenario, and discount rate combination—made up of 45,000 SCC estimates. By averaging these SCC estimates (applying equal weights) across the various IAMs and scenarios for each discount rate, the IWG produces three final SCC distributions corresponding to each discount rate assumption. Using these distributions, the IWG selects four formal SCC estimates: the mean values of the final SCC distributions for each of the three discount rates, and the 95th percentile of the SCC distribution corresponding to the 3% discount rate. Of these estimates, the mean value of the SCC distribution corresponding to the 3% discount rate is understood as the "central value," and the 95th percentile estimate is understood as a means to address the systematic underestimation of the SCC due to the omission of a risk premium, catastrophic risks, and key negative climate impacts.[6]

[6] The IWG (2015b), in response to comments on the 2013 Technical Support Update, stated the following: (1) "We agree with the commenters who suggested the IAMs do not fully capture the impacts associated with changes

Currently, the NAS draft report (2016) recommends that the Technical Support Document (TSD) "present symmetric high and low values . . . with equal prominence . . . [for] each assumed discount rate." It is unclear if NAS intends just for the TSD to include such values (i.e., present these values for transparency purposes), or if it intends agencies to use those values (i.e., replace the four official SCC estimates currently used by the IWG with these nine estimates). If the former is its intention, the NAS should clarify this intention in the final version of its first report. If the latter is its intention, the NAS should drop this portion of its fourth recommendation given its potential to undermine current objectives of the IWG analysis.

Specifically, the NAS has not justified why 5th percentile estimates would be appropriate or useful, and the NAS has ignored how their introduction undermines the usefulness of the 95th percentile estimate. Currently, the IWG uses the 95th percentile SCC estimate (corresponding to the 3% discount rate) to address the systematic underestimation of the SCC (IWG, 2015b). By requiring equal weighting of the 5th percentile estimates, the NAS is undermining the legitimate role of the 95th percentile, despite the fact that the "IWG is not aware of systematic upward biases in the estimates comparable to the downward biases" (IWG, 2015b). The 95th percentile estimate is intended to account for lower-probability, high-damage, irreversible outcomes as well as risk aversion and other uncertainties and omitted factors. The same kinds of assumptions do not exist to support a 5th percentile estimate: there is no reason to believe the public or the government should be systematically risk seeking with respect to climate change; the consequences of overestimating the risk of climate damages (i.e., spending more than we need to on mitigation) are likely not nearly as irreversible as the consequences of underestimating the risk of climate damages (i.e., catastrophic outcomes); on balance, uncertainties point toward higher, not lower, SCC estimates; and there is no empirical basis for any "long tail" of potential benefits from climate change, unlike the long tail of potential extreme harms. Thus, giving the 5th percentile estimates equal weight as the 95th percentile estimates essentially undermines the current justification of the 95th percentile estimates, and in

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in climate variability and weather extremes… Similarly, we agree that the models' functional forms may not adequately capture potential discontinuous "tipping point" behavior in Earth system… In fact, large-scale earth system feedback effects (e.g., Arctic sea ice loss, melting permafrost, large scale forest dieback, changing ocean circulation patterns) are not modeled at all in one IAM, and are imperfectly captured in the others. This limitation of the three IAMs is discussed extensively in the 2010 TSD, and again in the 2013 update. The SCC estimate associated with the 95th percentile of the distribution based on the 3 percent discount rate is included in the recommended range partly to address this concern;" (2) "To the extent that [climate catastrophes] may not be adequately represented in the IAMs, the central tendency estimates from these models may not capture the full range of potential damages from CO2 emissions. For this reason, in addition to the three mean SCC estimates using discount rates of 2.5, 3 and 5 percent, the IWG recommended including a rate based on the 95th percentile damage estimate (with a 3 percent discount rate) for the upper end of the range of plausible SCC estimates;" (3) "As the 2010 TSD discusses, the SCC estimates derived from the three integrated assessment models have several significant limitations that could lead to a substantial underestimation of the SCC. These limitations include the incomplete treatment and monetization of non-catastrophic damages, the incomplete treatment of potential catastrophic damages, and uncertainty in extrapolation of damages to high temperatures… The 95th percentile estimate was included in the recommended range for regulatory impact analysis to address these concerns;" (4) "the SCC estimates derived from the three IAMs did not take into consideration the possibility of risk aversion. That is, individuals may have a higher willingness-to-pay to reduce the likelihood of low-probability, high-impact damages than they do to reduce the likelihood of higher-probability, lower-impact damages with the same expected cost. The inclusion of the 95th percentile estimate in the SCC values was also motivated by this concern;" and (5) "the IWG is not aware of systematic upward biases in the estimates comparable to the downward biases discussed above. For this reason, while the IWG has been fully transparent regarding the entire range of uncertainty reflected in the probability distributions, we did not include a 5th percentile estimate in the selected range for regulatory impact analysis… The recommended range represents the central tendency of SCC estimates across three reasonable discount rates, plus a high-end estimate to account for missing damage categories and catastrophic outcomes."

turn would necessitate that the IWG explicitly and separately address risk aversion, catastrophic impacts, and omitted damages.

Assuming that the primary goal of the NAS's fourth recommendation is transparency, requiring the presentation and equal weighting of the 5th percentile SCC estimates may also be counter to this goal. Specifically, the presentation of *nine* SCC estimates in each regulation's benefit-cost analysis may obfuscate analysis conducted by agencies, particularly if insufficient reasoning is provided for the agency's choice of a "central" SCC estimate for decision-making. This is likely to occur if a regulation or proposal is cost-benefit justified under only a subset of (i.e., some, but not all) SCC estimates, and if agencies must use their discretion to determine which set of SCC estimates are valid for decision-making.

For example, a recent proposed rule from the U.S. Forest Service to allow the construction of roads through national forests to enable the operation of new coal mines could not be economically justified under the IWG's four recommended SCC estimates. Therefore, the Forest Service departed from the IWG's recommendations and instead justified its proposal by focusing on a 10th percentile estimate of global SCC values at a 3% discount rate, as well as domestic-only SCC values (Forest Service 2015; Policy Integrity et al., 2016). The fundamental purpose of the IWG's creation in 2009 was to develop a single harmonized range of estimates for all agencies to use, to correct the inconsistent practices up to that time of agencies developing estimates that suited their own goals (GAO, 2014). Should the NAS and the IWG sanction a range of nine SCC estimates, some agencies would see it as license to emphasize for decision-making and public disclosure whichever estimate best fit their objectives. Consistency would erode, and with it the confidence of the public in the SCC estimates overall. Note that these problems would be compounded if coupled with a misguided recommendation to focus equal weight on the domestic and global SCC values. Given that the speculative domestic range itself has a high (e.g., 23% of the global SCC) and low (e.g., 7% of the global SCC) value, the result would be 27 separate estimates (low, central, and high values for each discount rate at the global level, the low domestic level, and the high domestic level). Such an overwhelming number of estimates, with such an enormous range of values, would actually undermine the goal of transparency and create confusion.

Indeed, an overly broad range of SCC estimates could lead agencies and the public to dismiss the entire SCC methodology as meaningless. For example, a Department of Interior field office has cautioned against giving SCC estimates too much consideration because "there is no consensus for the quantitative value of greenhouse gas emissions, and estimates for an incremental ton of carbon dioxide vary widely" (OSMRE, 2015). A sudden expansion to nine (or 27) estimates, including near-$0 estimates at the low end of the 5% rate distribution, would open the entire SCC methodology to challenges. Note also that the U.S. Court of Appeals for the Ninth Circuit (2008) has ruled that "while . . . there is a range of values, the value of carbon emissions reduction is certainly not zero." It is therefore troubling that, in table 5-1 and figure 5-1, the NAS's draft report (2016) suggests that the IWG and agencies should give equal weight to a low estimate of the 5% rate distribution which, at the 10th percentile level, includes $0 estimates.

Though fully transparent presentation of uncertainty is an admirable goal, as the Office of Management and Budget's guidance reminds, "the goal [of regulatory analysis] is not to characterize the full range of *possible* outcomes . . . but rather the range of *plausible* outcomes" (OMB, 2011). The NAS should consider the real world implications, including the likely application of SCC estimates by agencies, before making recommendations.

Recommendation 2.2: The NAS Should Recommend a Central SCC Estimate for Use in Benefit-Cost Analysis by Agencies, and Should Choose the Certainty-Equivalent SCC

If the NAS moves forward with its fourth recommendation as currently drafted, the NAS should recommend in its second report a central (preferably a certainty equivalent) estimate for use in decision-making; this is necessary to address the above problems with the real world application of the SCC in benefit-cost analysis. The certainty-equivalent SCC estimate is the theoretically correct measurement of social costs. Furthermore, given that the introduction of the 5th percentile SCC estimate would undermine the salutary goal served by the 95th percentiles (i.e., the systematic underestimation of the SCC due to the omission of lower-probability, high-damage, irreversible outcomes as well as risk aversion and other uncertainties and omitted factors, as discussed in the previous sub-section), a certainty-equivalent SCC would help address one of these omitted factors: specifically, the omission of a risk premium to account for societal risk aversion. In terms of the criteria that this NAS committee laid out in its first draft report, this recommendation is consistent with the Phase 1 conclusions and recommendations and would significantly change the SCC (NAS, 2016).

The NAS should recommend that the IWG clearly indicate a central estimate for use in the decision criteria of benefit-cost analysis. While providing sensitivity analysis over a range of SCC values can advance transparency goals, if a central estimate is not specified, it can also force regulators—who potentially lack a sophisticated knowledge about the SCC and discount rates—to make a choice of which SCC estimate to use in the decision-making process. This is particularly problematic when a benefit-cost analysis finds that a regulation is justified at some, but not all, of the SCC estimates. By specifying a central SCC for decision-making, the IWG can ensure that the SCC is being uniformly used across all agencies—an essential goal of the IWG (2010).[7] A discussion of the central estimate and how to use it in benefit-cost analysis should be included in the "guidance [section] concerning interpretation of reported SCC estimates for cost-benefit analysis" discussed in the NAS's fourth recommendation.

In a stochastic world, the certainty-equivalent SCC is the ideal central estimate of the SCC (Newbold et al., 2013; Kopp et al., 2012). Under uncertainty, "the 'social cost of carbon' in a particular year is the decrease in aggregate consumption in that year that would change the current *expected value of social welfare* by the same amount as a one unit increase in carbon emissions in that year" (Newbold et al., 2013) (emphasis added). Instead of the unweighted average SCC estimates currently calculated by the IWG (i.e., the expected value), the certainty equivalent SCC is the weighted average of the deterministic SCC where the marginal welfare of consumption is the appropriate weight (Gerlagh, 2014). Thus, only when the marginal utility of consumption is known with certainty (Kopp et al., 2012) does the SCC under uncertainty equal the expected value of the deterministic SCC.[8] Given that this assumption does not hold when the consumption or population path is uncertain—as is assumed by the IWG in its decision to use five socio-economic scenarios—the IWG does not solve for the theoretically correct specification of the SCC.

The certainty equivalent SCC can be calculated (see Kopp et al., 2012). Using the theory developed for discounting the benefits of risky projects (Gollier & Hammitt, 2014), the present value of benefits of a risky project is calculated by determining the certainty-equivalent benefits of the project over time, discounting these benefits using the risk-free discount rate (potentially a declining discount rate), and then summing across time periods. Thus, there is a simple series of steps for calculating the certainty equivalent SCC: (1) calculate change in certainty-equivalent consumption over time due to climate change for the base scenario and the perturbation scenario (e.g., the base emission scenario plus a gigaton of CO_2 emissions in the period of interest), (2) take the difference, and (3) calculate the present value of the change in certainty equivalent consumption (potentially using a declining discount rate). However, to

[7] The IWG (2010) states that "The main objective of this process was to develop a range of SCC values using a defensible set of input assumptions grounded in the existing scientific and economic literatures. In this way, key uncertainties and model differences transparently and consistently inform the range of SCC estimates used in the rulemaking process…To ensure consistency in how benefits are evaluated across agencies, the Administration sought to develop a transparent and defensible method, specifically designed for the rulemaking process, to quantify avoided climate change damages from reduced CO2 emissions."

[8] Given the isoelastic utility function commonly assumed by IAMs, the weight is a function of the population, the level of consumption, the pure rate of time preference, and the elasticity of the marginal utility of consumption. However, it is common to assume an exogenous utility function, and great care should be taken if modelers assume that the preference parameters are unknown (Gerlagh, 2014).

make calculations tractable, it is necessary to make the common assumption that the utility function is exogenous such that the pure rate of time preference and the elasticity of marginal utility of consumption are known (Gerlagh, 2014; Newbold et al., 2014).

Using a certainty-equivalence SCC could significantly increase the IWG's current SCC estimates. Using DICE, Kopp et al. (2012) finds a significant difference between the certainty-equivalent SCC and the 50th percentile SCC that increases with relative risk aversion. While the IWG assumes a risk-neutral central planner—thus minimizing this difference—this assumption does not correspond with the literature (i.e., current IAM assumptions) nor with the IWG's own discussion (2010) of the possible values of the elasticity of the marginal utility of consumption. This is an issue that needs to be simultaneously addressed by the NAS. (See our recommendation 3.4 below). However, even with a risk-neutral central planner, the certainty-equivalent SCC does not necessarily collapse to the expected value of the deterministic SCC due to an uncertain population level.[9]

Calculating the certainty equivalent SCC also addresses the IWG's omission of the risk premium corresponding to economic and climate change uncertainty that arises when the central planner is risk averse.

3. The NAS Should Recommend Declining Discount Rates; Otherwise, It Should Recommend an Expansion in the Range of Constant Discount Rates Considered

The fourth recommendation in the interim version of the NAS's first report recommends the use of "consistent" discount rates between the SCC and the benefit-cost analysis in which the SCC is used. Since the NAS did not define "consistency," the NAS should clarify its meaning to avoid confusion by agencies and to ensure the appropriate use of the SCC in benefit-cost analysis. Partially to address this issue and to ensure the choice of discount rates that corresponds with economic theory, the NAS should recommend that the IWG adopt declining discount rates, or at least expand its current choice of discount rates to include a larger range of possibilities.

Recommendation 3.1: The NAS Should Make Clear that "Consistent" Discount Rates With Respect to SCC Estimates and the Benefit-Cost Analysis in Which They Are Applied Does Not Mean Identical Discount Rates, but Instead that the Two Potentially Differing Rates Should Be "Theoretically Consistent"

It is unclear what the NAS means by "consistent" discount rates in the fourth recommendation of its first draft report on the SCC. On the one hand, "consistent" could be interpreted to mean "identical," such that the same discount rate would apply both to the SCC and to all other costs and benefits in the cost-benefit analysis. On the other hand, "consistent" could be interpreted to mean "compatible" and based on the same theoretically-sound methodology (i.e., theoretically consistent): for example, applying a higher discount rate (say 3%) to other costs and benefits may be "consistent" with a lower discount rate (say 2.5%) for the SCC, to account for the greater uncertainty with respect to climate change relative to more short-run benefits and costs. Given that the latter approach is appropriate when climate uncertainty exceeds the short-run uncertainty captured by most benefit-cost analysis in which the SCC is applied, the NAS should clarify in its final Phase 1 report if it intended the second meaning.

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[9] The weight in state k is $p_k = L_k B C_k^{-\eta}$ where L_k and C_k are the population and consumption per capita in state *k,* respectively, B is the discount factor, and η is the elasticity of the marginal utility of consumption. Assuming a risk neutral central planner ($\eta = 0$), the weight simplifies to $p_k = L_k B$. Because the certainty-equivalent SCC in period *t* equals $SCC_t = \left(\sum_k L_{t,k} * B_t * SCC_{t,k}\right)/\left(\sum_k L_{t,k} * B_t\right) = \sum_k L_{t,k} * SCC_{t,k}/\sum_k L_{t,k}$ where $SCC_{t,k}$ is the deterministic SCC in period *t* and state *k*, it is easy to see that the certainty-equivalent SCC does not collapse to the expected value of the deterministic SCC if population is uncertain across states, even when the central planner is risk neutral. Instead, it collapses to the population weighted SCC.

Recommendation 3.2: The NAS Should Recommend that the IWG Directly Implement a Declining Discount Rate[10]

To correct for potential problems with real-world applications of the NAS's fourth recommendation in its first report, the NAS should recommend the use of a declining discount rate. In doing so, the NAS will better achieve its stated goal of using the theoretically correct methodologies. Specifically, using one constant discount rate treats inter-generational and intra-generational benefits and costs in the same manner, violating recently developed economic theory (Arrow et al., 2013; Arrow et al., 2014; Gollier & Hammitt, 2014; Cropper et al., 2014). Adopting a declining discount rate addresses these benefits and costs differently, while ensuring "consistency in decision making" (i.e., applying the same discount rates to benefits and costs in the same time period) (Arrow et al., 2013). Not only are declining discount rates theoretically correct, they are actionable (i.e., doable given our current knowledge), consistent with current IWG assumptions, and solve the practical problems raised by the NAS's fourth draft recommendation as discussed in the above sub-section.

Since the IWG undertook its initial analysis, a consensus (Arrow et al., 2013) has emerged among leading climate economists that a declining discount rate should be used for climate damages to reflect long-term uncertainty in interest rates. This consensus view is held whether economists favor descriptive or prescriptive approaches to discounting (Freeman et al., 2015). Several key papers (Arrow et al., 2013; Arrow et al., 2014; Gollier & Hammitt, 2014; Cropper et al., 2014) presents arguments that strongly support the use of declining discount rates for long-term benefit-cost analysis in both the normative and positive contexts. Finally, in a recent survey of experts on the economics of climate change, Howard and Sylvan (2015) found that experts support using a declining discount rate relative to a constant discount rate at a ratio of approximately 2 to 1.

Perhaps the best reason to adopt a declining discount rate schedule is the simple fact that there is considerable uncertainty around which interest rate to use: uncertainty in the rate points directly to the need to use a declining rate, as the impact of the uncertainty grows exponentially over time. The uncertainty about future discount rates could stem from a number of reasons particularly salient to climate damages, including uncertainties in future economic growth, consumption, and the interest rate reaped by investments.

In the descriptive setting adopted by the IWG (2010), economists have demonstrated that the expected net present value rule implies a declining certainty equivalent discount rate when (1) discount rates are uncertain, and (2) discount rates are positively correlated (Arrow et al., 2014). Real consumption interest rates are uncertain given that there are no multi-generation assets to reflect long-term discount rates and the real returns to all assets—including government bonds—are risky due to inflation and default risk (Gollier & Hammitt, 2014). Furthermore, recent empirical work analyzing U.S. government bonds demonstrates that they are positively correlated over time; this empirical work has estimated several declining discount rate schedules that the IWG can use (Cropper et al., 2014; Freeman et al., 2014; Arrow et al., 2013).

The current IWG approach (2010; 2013) is internally inconsistent (i.e., the assumptions of constant discount rates and discount rate uncertainty cannot simultaneously hold given the empirical evidence). Applying the descriptive approach, the IWG adopts three constant discount rates, presumably reflecting uncertainty over the true consumption discount rate. While the recent consensus supports the IWG selecting a discount rate based upon declining discount rates, a constant certainty-equivalent discount rate is only appropriate when discount rates are independent and identically distributed (Cropper et al., 2014). Given the above empirical evidence with respect to U.S. government bond yields and the IWG's current uncertainty over the consumption discount rate, this assumption is likely invalid and, according to the

[10] The arguments here are primarily based on: Arrow et al. (2013); Arrow et al. (2014); Cropper et al. (2014); Gollier & Hammitt (2014); and Newell & Pizer (2003).

latest economic theory, the IWG should adopt a declining discount rate schedule. While the IWG (2010) argues for a constant discount rate adjustment based on potential "time inconsistency" when using a declining rate (i.e., that formerly cost-benefit justified policies are no longer justified if the discount rate schedule changes), this can be avoided by regularly updating the discount rate schedule to reflect new information (Arrow et al, 2014). Such updates could be scheduled every two to three years when the IWG meets to update its SCC estimates.

If the IWG were to adopt the normative perspective in the future, economists have demonstrated that an extended Ramsey rule implies a declining discount rate when (1) the growth rate of per capita consumption is stochastic,[11] and (2) consumption shocks are positively correlated over time (or their mean or variances are uncertain) (Arrow et al., 2013; Arrow et al., 2014; Gollier & Hammitt, 2014; Cropper et al., 2014). While a constant adjustment downwards (known as the precautionary effect[12]) can be theoretically correct when growth rates are independent and identically distributed (Cropper et al., 2014), empirical evidence supports the two above assumptions for the United States, thus implying a declining discount rate (Cropper et al., 2014; Arrow et al., 2014; IPCC, 2014).[13] Several papers have estimated declining discount rate schedules for specific values of the pure rate of time preference and elasticity of marginal utility of consumption (e.g., Arrow et al., 2014), though recent work demonstrates that the precautionary effect increases and discount rates decrease further when catastrophic economic risks (such as the Great Depression and the 2008 housing crisis) are modeled (Gollier & Hammitt, 2014; Arrow et al., 2014). It should be noted that this decline in discount rates due to uncertainty in the global growth path is in addition to that resulting from a declining central growth path over time (Nordhaus, 2014; Marten, 2014).

Another possible declining interest rate schedule for consideration by the IWG is the one proposed by Weitzman (2001).[14] It is derived from a broad survey of top economists in context of climate change, and explicitly incorporates arguments around interest rate uncertainty.[15]

Many leading economists support the United States government adopting a declining discount rate schedule (Arrow et al., 2014; Cropper et al., 2014). Moreover, the United States would not be alone in using a declining discount rate. It is standard practice for the United Kingdom and French governments, among others (Gollier & Hammitt, 2014; Cropper et al., 2014). The U.K. schedule explicitly subtracts out an estimated time preference.[16] France's schedule is roughly similar to the United Kingdom's. Importantly, all of these discount rate schedules yield lower present values than the constant 2.5%

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[11] The IWG assumption of five possible socio-economic scenarios implies an uncertain growth path.

[12] The precautionary effect measures aversion to future "wiggles" in consumption (i.e., preference for consumption smoothing) (Traeger, 2014).

[13] Essentially, the precautionary effect increases over time when shocks to the growth rate are positively correlated, implying that future societies require higher returns to face the additional uncertainty (Cropper et al., 2014; Arrow et al., 2014; IPCC, 2014).

[14] Weitzman (2001)'s schedule is as follows:

1-5 years	6-25 years	26-75 years	76-300 years	300+ years
4%	3%	2%	1%	0%

[15] Freeman and Groom (2014) demonstrate that this schedule only holds if the heterogeneous responses to the survey were due to differing ethical interpretations of the corresponding discount rate question.

[16] The U.K. declining discount rate schedule that subtracts out a time preference value is as follows (Lowe, 2008):

0-30 years	31-75 years	76-125 years	126- 200 years	201- 300 years	301+ years
3.00%	2.57%	2.14%	1.71%	1.29%	0.86%

Newell-Pizer rate, suggesting that even the lowest discount rate evaluated by the IWG is too high.[17] The consensus of leading economists is that a declining discount rate schedule should be used, harmonious with the approach of other countries like the United Kingdom. Adopting such a schedule would likely increase the SCC substantially from the administration's central estimate, potentially up to two to three fold (Arrow et al., 2013; Arrow et al., 2014; Freeman et al., 2015).

Recommendation 3.3: If the IWG Decides to Continue Using the Descriptive Approach to Calibrate Constant Discount Rates, the NAS Should Recommend that It Include a Lower Constant Discount Rate than 2.5% to Reflect the True Range of Consumption Discount Rates

The IWG appropriately used consumption discount rates rather than returns on capital. With respect to the discount rate, the IWG conducted sensitivity analysis of the results to three constant consumption discount rates: 2.5%, 3%, and 5%; for each of the discount rates, the TSDs reported the various moments and percentiles of the SCC estimates.

In doing so, the IWG correctly excluded a 7% discount rate, a typical private sector rate of return on capital, for several reasons. First, typical financial decisions, such as how much to save in a bank account or invest in stocks, focus on private decisions and use private rates of return. Private market participants typically have short time horizons. However, in the context of climate change, analysts are concerned with social discount rates because emissions mitigation is a public good, where individual emissions choices affect public well-being broadly. Rather than evaluating an optimal outcome from the narrow perspective of investors alone, economic theory would require that analysts make the optimal choices based on societal preferences (and discount rates). Second, climate change is expected to affect primarily consumption, not traditional capital investments.[18] OMB (2003) guidelines note that in this circumstance, consumption discount rates are appropriate. Furthermore, it corresponds with current IAM modeling structure in which climate change directly affects consumption, and not the return on investment. Third, 7% is considered much too high for reasons of discount rate uncertainty and intergenerational concerns; see our Recommendation 3.2 above. As discussed further below, recent surveys find that the average expert economist (experts on either discounting or climate change) supports a social discount rate of approximately 2% (Drupp et al., 2015; Howard & Sylvan, 2015).

The current range of constant consumption discount rates—2.5% to 5%—may still be too high. According to economic theory, depending on the link between climate risk and economic growth risk, even a rate of 1% may be too high.[19] Furthermore, several expert elicitations on the appropriate discount

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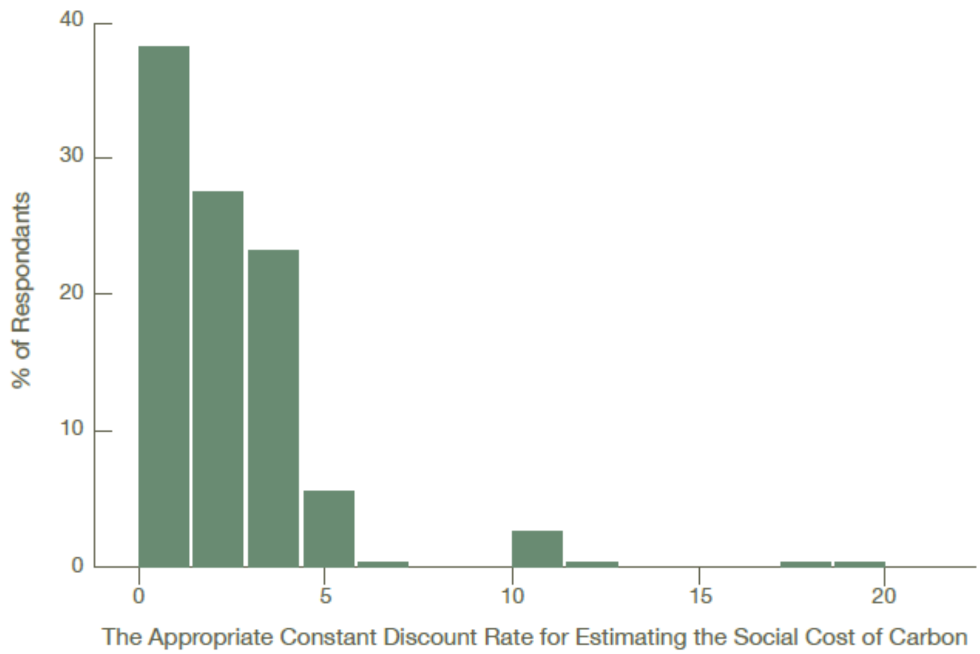
[17] Using the IWG's 2010 SCC model, Johnson and Hope (2012) find that the U.K. and Weitzman schedules yield SCCs of $55 and $175 per ton of CO_2, respectively, compared to $35 at a 2.5% discount rate.

[18] "There are two rationales for discounting future benefits—one based on consumption and the other on investment. The consumption rate of discount reflects the rate at which society is willing to trade consumption in the future for consumption today. Basically, we discount the consumption of future generations because we assume future generations will be wealthier than we are and that the utility people receive from consumption declines as their level of consumption increases. . . .The investment approach says that, as long as the rate of return to investment is positive, we need to invest less than a dollar today to obtain a dollar of benefits in the future. Under the investment approach, the discount rate is the rate of return on investment. If there were no distortions or inefficiencies in markets, the consumption rate of discount would equal the rate of return on investment. There are, however, many reasons why the two may differ. As a result, using a consumption rather than investment approach will often lead to very different discount rates" (Cropper, 2012).

[19] "If climate risk dominates economic growth risk because there are enough potential scenarios with catastrophic damages, then the appropriate discount rate for emissions investments is lower than the risk-free rate and the current price of carbon dioxide emissions should be higher. In those scenarios, the 'beta' of climate risk is a large negative value and emissions mitigation investments provide insurance benefits. If, on the other hand, growth risk is always dominant because catastrophic damages are essentially impossible and minor climate damages are more likely to occur when growth is strong, times are good, and marginal utility is low, then the 'beta' of climate

rate for climate change have found support for discount rates in the IWG's range or lower. Most famously, Weitzman (2001) surveyed 2,160 PhD economists on the appropriate discount rate to use for climate mitigation projects, and found a highly skewed distribution with a mean of 4%, a median of 3%, and a mode of 2%. More recently, Drupp et al. (2015) in a survey of 200 experts (defined as having published on social discounting in a leading economic journal) finds a long-term real social discount rate of approximately 2% (mean and median) with strong support of a range of 1 to 3%. Similarly, Howard and Sylvan (2015) in a survey of over 350 experts[20] (defined as having published on climate change in a leading economics or environmental economic journal) finds a mean and median of 3% and 2%, respectively, as the appropriate constant discount rate for calculating the social cost of carbon (SCC); see Figure 1.[21] Finally, as discussed in the previous sub-section, uncertainty around the correct discount rate pushes the rate lower still (through the precautionary effect), potentially even declining over time (Cropper et al., 2014; IPCC, 2014).

Figure 1. Histogram of responses (with bottom 1% and 99% trimmed) to the question "If benefits to future generations are to be discounted using a constant discount rate, the appropriate discount rate to use when calculating the social cost of carbon is…." (Howard & Sylvan 2015).



risk is positive, the discount rate should be higher than the risk-free rate, and the price of carbon dioxide emissions should be lower" (Litterman, 2013).

In IAMs, the current specification of damages as a percent of GDP implies that climate damages and economic growth are positively correlated, suggesting a higher discount rate than calculated under the Ramsey Rule (IPCC, 2014, Working Group III, 3.6.2). Alternatively, some IAMs implicitly assume that the ability to adapt increases with income, implying a negative correlation and a lower discount rate; see the use of income elasticities in FUND (Anthoff and Tol, 2012; Anthoff and Tol, 2015).

[20] Of the 365 respondents to the survey, approximately 220 answered this open-ended discount rate question.

[21] The higher mean value in Howard and Sylvan (2015) is driven by several extreme outliers, such that "[i]f we trim the full data set to eliminate outliers, the consensus estimate gets even lower. When excluding the 1st percentile and 99th percentile estimates, we find that the mean and median are 2.3% and 2%, respectively" (Howard and Sylvan, 2015). Interestingly, this matches their mean and median responses of experts publishing in economics journals (i.e., excluding environmental journals) without trimming outliers.

The IWG (2010) rejects these lower discount rates based on the "original" Ramsey equation. Specifically, the IWG argues that based on this equation there must be minimum values on the elasticity of the marginal utility of consumption to ensure an appropriate savings rate. Failure to consider a more "realistic" set of assumptions—which lead to more complex Ramsey equations—may partially explain why the IWG (2010) "find[s] it difficult to justify rates at the lower end of [the 1.4 and 3.1 percent] range under the Ramsey framework." Specifically, recent research demonstrates that more realistic preferences than the standard isoelastic utility function—i.e., a CES utility function to capture changing relative prices of non-market and market goods over time and/or an Epstein-Zin utility function to capture observed empirical differences in risk, intra-generational, and inter-generational inequality aversion—and accounting for stochasticity (see our Recommendation 3.2 above) imply extended (and thus more complex) Ramsey discount rate equations. These more realistic discount rate specifications can potentially allow for lower discount rates, while being consistent with current savings behavior (Traeger, 2014; Hoel & Sterner, 2007; Sterner & Persson, 2008; Arrow et al., 2013; Arrow et al., 2014; Gollier & Hammitt, 2014; Cropper et al., 2014).[22]

Given the new evidence—from surveys, research on preferences, and research on declining discount rates—the NAS should recommend that the IWG consider a wider range of descriptive discount rates, particularly on the lower end of the spectrum.

Recommendation 3.4: The NAS Should Recommend that the IWG Consider Including the Normative Approach to Discounting in Addition to the Positive Approach

There is a split among economists between the normative (i.e., prescriptive) approach and the positive (i.e., descriptive) approach to discounting. In general, the normative approach is appropriate "when [a] new project is financed by an increase in savings from the current generation, so the marginal rate of intertemporal substitution determines the discount rate" (Gollier & Hammitt, 2014). Such is the case in integrated assessment models, which assume a representative agent model that maximizes the present value of utility over multiple centuries (and hence generations). Consequently, the base versions of DICE, FUND, and PAGE use the Ramsey discount rate equation. In addition to theoretical reasons to at least consider using the normative approach, recent surveys found support among relevant groups of experts for the normative approach. In a survey 200 experts on social discounting, Drupp et al. (2015) found that the majority of economists think that both frameworks are relevant, but that the government should place greater weight on the normative approach. Similarly, in a survey of experts on the economics of climate change, Howard and Sylvan (2015) found that experts support calibrating discount rates using ethical norms relative to market rates at a ratio of approximately 2 to 1.

Given the considerable uncertainty in the appropriate normative discount rate (due to uncertainty over the growth path of consumption and differing opinions over ethical parameters such as the pure rate of time preference and the elasticity of the marginal utility of consumption), the IWG should conduct sensitivity analysis over these parameters and variables. There are several options available to the IWG in addition to its current assumptions of a pure rate of time preference of 2.5%, 3% and 5% and an elasticity of marginal utility of consumption of 0 (risk neutral planner) (Kopp et al., 2012). The range of options is laid out on page 21 of the IWG's 2010 Technical Support Document: (1) an elasticity of the marginal utility of consumption between 0.5 to 3, (2) a pure rate of time preference from 0 to 3, and (3) a growth rate of between 1.5% to 2% annually. Given the current assumptions of declining growth rates over time implied by the socio-economic scenarios adopted by the IWG (2010, 2013), these differing assumptions will

[22] For example, introducing an Epstein-Zin utility function tends to imply a discount rate lower than the standard Ramsey formula while potentially solving the equity premium puzzle, though this is somewhat complicated by the correlation between project payoff (i.e., climate damages) and economic growth (Traeger, 2014).

imply a declining discount rate over time when the elasticity of marginal utility of consumption is positive (Nordhaus, 2014; Marten, 2014).

It is necessary for the IWG to consider a more complex Ramsey equation if the normative approach is employed. Recent work demonstrates that the simple Ramsey Rule produces an overly simple view of discount rates, and that the approach should be modified to account for uncertainty (see our Recommendation 3.2 above) and more complex preferences, including relative prices and untangling Arrow-Pratt risk aversion from intertemporal risk aversion (see our Recommendation 3.3 above and Section 8 below) (Drupp et al., 2015; Hoel & Sterner, 2007; Traeger, 2014).

4. An Expansion of the Use of Modules to Climate Damage Functions

In its first report, the NAS suggests (it is not a formal recommendation) that the IWG develop a common climate module to model the relationship between CO_2 emissions and global mean surface temperature over time and the underlying uncertainty in this relationship. According to the NAS, this module should be simple, transparent, and easily updatable, such that the module reflects the best available science with respect to the central tendency and uncertainty in an easy to understand way. The NAS committee further provides specific diagnostic criteria to assess whether the module achieves these goals.

The IWG would benefit from an expansion of this module system to other aspects of IAMs: particularly a damage function module, as well as potentially adaptation, structural, and tipping point modules in the future. Like the climate module, these modules should be simple, transparent, and easy to update, such that they reflect the best available science. Unlike the climate module that is designed to capture central tendency and uncertainty, some of these modules should be designed to primarily reflect the uncertainty currently omitted in current IAMs that systematically bias the SCC (IWG, 2015b). Given the challenge of developing such modules, the IWG would also greatly benefit from explicit directions and/or specific diagnostic criteria.

Given our recommendations in section 2, it is important that including these modules does not result in a further expansion of the number of SCC estimates. Instead, these modules should add to the uncertainty underlying the SCC distributions corresponding to each discount rate. If the NAS recommends a certainty-equivalent SCC (Recommendation 2.2), the additional modular uncertainty would likely increase the IWG's SCC estimate.

Relative to other potential modules (adaptation, structural, and tipping points), it is of great importance to develop a damage function module. This priority is due to the out-of-date nature of current damage functions with respect to the climate damage literature, and the considerable uncertainty underlying damage functions with respect to both calibration and extrapolation (i.e., the choice of the damage function) (Kopp et al., 2012).

As is well known in the literature, the calibration of the current climate damage functions in the IAM literature dates back to the 1990s (Dietz et al., 2007; Revesz et al., 2014). This is true for all three of the models used by the IWG (2013): see Table 1 below for a list of studies used to estimate FUND 3.5; see Table 2 below for calibration sources of DICE-99, upon which DICE-2010 is based; PAGE09 relies on author Chris Hope's discretion to combine various damage estimates, consisting mostly of earlier damage estimates of FUND and DICE (Howard, 2014). Given that many of the economic studies from the 1990s cited by model developers in turn cite scientific literature that predates them, portions of these damage functions may rely on research even greater than two decades old (Revesz et al., 2014). Given that three IPCC assessment reports (2001, 2007, and 2013-2014) have been released since the 1995 report, these damage estimates are likely to omit key information.

There are two general approaches to calibrating climate damage functions: the bottom-up approach (estimating sector and region damage estimates) and the top-down approach (analyzing the total economy using coarser methods) (Mendelsohn et al., 2000). Both of these approaches employ a variety of identification strategies, including enumerative, expert elicitation, meta-analysis, and statistical strategies (Tol, 2009; Howard & Sterner, 2016). For example, with respect to global climate damage estimates, early damage estimates mostly employed the enumerative strategy (e.g., Fankhauser, 1995; Nordhaus & Boyer, 2000) and to a lesser extent surveys (e.g., Nordhaus, 1994) to develop global damage estimates. Second generational damage estimates generally employed cross-sectional estimation techniques (e.g., Rehdanz & Maddison, 2005; Nordhaus, 2008) and continued employing the enumerative strategy (via traditional IAMs and CGE models) (Tol, 2009). Recently, a new generation of statistical studies has used more sophisticated statistical techniques, such as panel methods, to identify climate damages (e.g., Dell et al., 2012; Burke et al., 2015). A similar progression of estimation techniques has been employed at the sector and regional levels, including the latest statistical revolution in regional (e.g., Houser et al., 2014) and sector damages (e.g., for U.S. agriculture, Schlenker & Roberts, 2009). Much of this literature and estimates are currently ignored by DICE, FUND, and PAGE, particularly the most up-to-date damage estimates.

Table 1. Studies Used to Estimate FUND 3.5 Damage Functions

Sector	Source of Damage Estimate
Agriculture	Kane et al. (1992), Reilly et al. (1994), Morita et al. (1994), Fischer et al. (1996), and Tsigas et al. (1996)
Forestry	Perez-Garcia et al. (1995) and Sohngen et al. (2001)
Water	Downing et al. (1995) and Downing et al. (1996)
Energy Demand	Downing et al. (1995) and Downing et al. (1996)
Sea-level rise	Hoozemans et al. (1993), Bijlsma et al. (1995), Leatherman and Nicholls (1995), and Nicholls and Leatherman (1995)
Ecosystems	Weitzman (1998; 1992; 1993) and Pearce and Moran (1994)
Health	Martin and Lefebvre (1995), Martens et al. (1995, 1997), Martens (1998), Morita et al. (1995), Link and Tol (2004), and Cline (1992)
Extreme Weather	Toya and Skidmore (2007), WMO (2006), CRED EM-DAT database, and Cline (1992)

Table 2. Damage Studies and Income Elasticities Used to Estimate DICE-1999 Damage Function

Sector	Source of Damage Estimate (2.5 degrees Celsius)	Notes	Income Elasticity
Agriculture	Darwin et al (1995) and Dinar et al (1998)	Sub-regional impact estimates: Darwin et al (1995) and Dinar et al (1998); mainly uses Appendix Table B6 from Darwin et al (1995) assuming second most unfavorable GCM and land use is unrestricted.	0.1
Other Market Sectors	Author discretion	Unknown sources for sub-regional damage estimates. No damages to temperate climates based on Cline (1992), Nordhaus (1991), and Mendelsohn and Neumann (1999). Damages in non-temperature climates (cold, tropical, and semi-tropical) based on energy sector alone.	0.2
Coastal Vulnerability	Author discretion	Not directly based on one specific study, but highly influenced by Yohe and Schlesinger (1998); study omits storms, undeveloped land, and settlement so accounted for by author discretion.	0.2
Health	Murray and Lopez (1996)	Assign regional impacts based on the region from Murray and Lopez (1996) with which it most overlaps.	0
Non-market Impacts	Nordhaus (1998)	Use the Nordhaus (1998) estimate from climate-related time use in the U.S.; focusing mainly on increased outdoor recreation.	0
Human Settlement and ecosystems	Author discretion	Cite their own unpublished estimates of the capital value of climate sensitive human settlements and natural ecosystems in each sub-region, and estimate that each sub-region has an annual WTP of 1% of the capital value of the vulnerable system for a 2.5 degrees increase.	0.1
Catastrophic Climate Change*	Nordhaus (1994)	Assume 30% loss of global GDP for such an event and a rate of relative risk aversion of 4 for catastrophic risk. They use expert opinions of probabilities of a cataclysmic change drawn from Nordhaus (1994); the authors double the probabilities in the study for increasing concerns about these events for both 2.5 (measured at 3 degrees in study) and 6 degrees.	0.1

*Calibration sources are provided for 2.5 degrees of warming, but not 6 degrees of warming. The one exception is catastrophic events.

Source: Nordhaus and Boyer (2000) and Warren et al (2006)

There is reason to believe that current IAM damage functions underestimate the magnitude of climate impacts. Contrary to Tol (2009), a forthcoming meta-analysis by Howard and Sterner (2016) finds that climate damage estimates are, if anything, increasing over time (though this result was statistically insignificant). Furthermore, a recent expert elicitation by Howard and Sylvan (2015) of 350 experts on the economics of climate change found that, relative to survey results from Nordhaus (1994), expert consensus estimates increased over the last twenty years on the most likely climate impact (measured as a percentage of GDP loss) and the probability of a catastrophic impacts (defined as a GDP loss of 25% or more) for a 3°C increase (relative to the pre-industrial period) by 2090.[23] These increases in expected impacts over time may partially be driven by the new generation of statistical estimates detailed above (Revesz et al., 2014). Yet given the outdated nature of studies used to calibrate DICE, FUND, and PAGE, including their failure to include this new generation of studies, there is the strong possibility that current IAMs underestimate the magnitude of damages from climate impacts.

In addition to under-estimating the magnitude of current climate damages, IAMs and their corresponding damage functions omit a variety of climate impacts, including impacts on economic growth and input productivity, social conflict, weather variability, ocean acidification, inland flood, and catastrophic impacts (from a variety of sources, such as tipping points) (Howard, 2014; Revesz et al., 2014); some of these omitted impacts are captured by the latest generation of statistical estimates, including conflict (e.g., Hsiang et al., 2011; Hsiang & Burke, 2014), violence (e.g., Cane et al., 2014), and growth (e.g., Dell et al., 2012; Burke et al., 2015; Hsiang & Jina, 2014). But since these impacts are still omitted from current IAMs, the IWG (2015b) has acknowledged that current SCC estimates are systematically biased downwards. In its 2010 and 2013 analyses, the IWG partially addressed these omissions by asking agencies to include the 95th percentile of the SCC distribution corresponding to the 3% discount rate distribution. However, this methodology is potentially eliminated or watered down if the NAS maintains the current wording of its fourth recommendation in the first NAS report (see Section 2 above) and if the IWG adopts this recommendation. Regardless, the IWG may be relying on the 95th percentile estimate to compensate for too many omissions.

The other source of damage uncertainty is due to the relative arbitrariness of damage functional forms (Kopp et al., 2012). Like calibration, this source of uncertainty can also significantly affect the SCC. IAM damage functions are usually calibrated with one point estimate (i.e., at one temperature level), though DICE-1999 is calibrated with two point estimates (i.e., at two temperature levels). In both cases, the lack of damage estimates from climate change at high temperatures makes results unreliable at high temperature (Kopp & Mignone, 2012). On the one hand, if analysts use a point estimate (i.e., damage estimates at a particular temperature increase) to calibrate damage functions, the functional form determines damages at high future temperatures. However, without estimates at higher temperatures, analysts cannot determine the correct functional form (Kopp & Mignone, 2012). On the other hand, if analysts use multiple point estimates, analysts must extrapolate from low temperature damage estimates to high temperatures; this requires a multitude of assumptions, as in DICE-1999, making damage estimates at high temperature unreliable. Regardless of how analysts select the shape of damage functions, some level of author discretion is currently necessary.[24]

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[23] Of the 356 respondents, approximately 230 answered these two open-ended global climate damage questions.

[24] For example, the choice of a quadratic damage function in DICE is more due to historical precedent than empirical validation, whereby Nordhaus (1992;1993) selected this functional form to capture the observation that impacts are increasing at an increasing rate; he cites Cline (1992) based on his finding that damages increase at a power of approximately 1.3 (Nordhaus, 1992). Nordhaus has maintained this assumption throughout the various updates of the DICE model.

Recommendation 4.1: The NAS Should Recommend that the IWG Develop Several Climate Damage Modules that Use Bottom-Up and Top-Down Estimation Approaches to Calibrate Up-To-Date Damage Functions

In addition to estimating each of the IAMs with their base damage function, the IWG should develop climate damage modules to address the problems of outdated and omitted impact estimates. Given the current status of damage functions, substantial updates in the IAMs' damage functions are unlikely to occur by the next iteration of the IWG without substantial funding (Revesz et al., 2014). Furthermore, updating the underlying damage functions has the potential to significantly increase the SCC, given that Nordhaus (2015) finds that different damage functions is the key driver in the difference in SCC estimates between DICE, FUND, and WITCH.

The NAS should recommend that the IWG develop climate damage modules using both the bottom-up and top-down approaches. This multiple-prong approach should be employed for several reasons. First, as demonstrated from the range of past estimates (Tol, 2009; Tol, 2014, Howard & Sterner, 2016), differing estimation strategies may result in substantially different impact estimates, and the subsequent analysis should be robust to the estimation strategy (Howard & Sterner, 2016). Second, as noted by Anthoff and Hope at the NAS's third committee meeting in Washington, D.C. on November 13, 2015, improving damage estimates will likely take decades, and bottom-up and top-down approaches have differing strengths and weaknesses. In particular, bottom-up estimates cannot capture climate impacts that are omitted due to lack of data, which may be partially accounted for in top-down approaches like expert elicitation. Last, the use of multiple methodologies to estimate benefits of a regulation is consistent with previous cost-benefit practices by federal agencies. For example, EPA developed a concentration-response function to estimate mortality caused by particulate matter exposure by using published epidemiological studies (Pope et al., 2002; Laden et al., 2006; Walton, 2009) and EPA's own expert elicitation (Roman et al., 2008; Walton, 2009).[25] Each of the employed methodologies should be transparent and systematic to make them easily updatable.

To develop a bottom-up damage function, the IWG should conduct a systematic review of the empirical regional-sectoral damage literature. Rather than relying on author discretion to combine estimates (a method commonly favored in the enumerative approach), statistical methods including meta-analysis should be used. Examples for the United States include Houser et al. (2014) and EPA (2015), which could potentially be expanded globally. An advantage of this methodology is that it builds up regional-sectoral estimates that can be used to calibrate the different regional-sectoral damage functions of DICE, FUND, and PAGE (by disaggregating empirical estimates to the regional-sectoral breakdowns of each of these models). The disadvantages of this method are that it is time intensive, it can omit key impacts that currently lack empirical estimates, and it may be difficult to extrapolate to developing regions that lack the necessary data.

Currently, the models do not reflect recent research on agricultural changes, which suggest the CO_2 fertilization is overestimated, particularly in the FUND model, and that much, if not all, of the fertilization benefits may be cancelled out by negative impacts on agriculture (e.g., extreme heat, pests, and weeds)

[25] "EPA benefits estimates are the monetized human health co-benefits of reducing cases of morbidity and premature mortality among populations exposed to PM2.5 [fine particulate matter] . . . . The anchor points for these estimates are derived from two empirical (epidemiological) studies of the relationship between ambient PM2.5 and premature mortality (the extended analyses of the Harvard Six Cities study by Laden et al. (2006) and the American Cancer Society cohort by Pope et al. (2002)). Since 2006, EPA had calculated benefits based on these two empirical studies, but derived the range of benefits, including the minimum and maximum results, from an expert elicitation of the relationship between exposure to PM2.5 and premature mortality (Roman et al., 2008). Using alternate relationships between PM2.5 and premature mortality supplied by experts, higher and lower benefits estimates are plausible . . . but most of the expert-based estimates fall between the two epidemiology based estimates (Roman et al., 2008)" (Walton, 2009).

(Ackerman & Stanton, 2013; Schlenker et al., 2005; Fisher et al., 2012). Given the importance of agriculture in previous estimates, special care should be taken to accurately model the effects of temperature, precipitation, weather variability, and CO_2 fertilization on food production (as well as farmer adaptation and trade). If the IWG is not able to adequately model all agricultural impacts it should, at a minimum, conduct a sensitivity analysis whereby it removes CO_2 fertilization benefits.

Two top-down approaches that are easily reproducible and less time intensive are expert elicitation (Nordhaus, 1994; Howard & Sylvan, 2015) and meta-analysis at the global scale (Tol, 2009; Tol, 2014; Newbold & Marten, 2014; Howard & Sterner, 2016). While both method are clearly advantageous from the reproducibility perspective, only surveys allow for the estimation of omitted climate impacts—though only to the extent that they are considered by experts.[26] There is also the potential to derive regional-sectoral estimates, though this has only been done in a general sense up to now for developed versus developing regions and market versus non-market impacts (Nordhaus, 1994). However, in addition to benefiting and suffering from many of the advantages and shortcomings of stated preference, surveys are also dependent on who is defined as an expert: the results differ by academic field, area of expertise, and level of expertise (Nordhaus, 1994; Howard & Sylvan, 2015). To fully capture the level of uncertainty in the climate community, one should ask a broad section of experts, as is done in Nordhaus (1994) and Howard and Sylvan (2015). If instead the IWG is interested in knowing only the view of experts on IAMs, a more objective methodology may be to conduct a meta-analysis of global damage estimates (many of which are authored by these experts).

A meta-analysis of global damage estimates benefits from a rigorous treatment of the literature that is both transparent and reproducible (e.g., Tol, 2009; Tol, 2014; Howard & Sterner, 2016). Any meta-analysis of climate damage estimates—regional, sectoral, or global—by the IWG should meet the standards set by the EPA (2006) and the economic literature (Nelson & Kennedy, 2009; Stanley et al., 2013). At a minimum, this requires accounting for heteroscedasticity, dependence of observations, omitted variable bias, and outliers. Additional care should be taken to address multiple publication bias (Howard & Sterner, 2016). An example of such an analysis is Howard and Sterner (2016). The disadvantages of this methodology are specification error, small samples, and the inability to address omitted impacts in a transparent way. Furthermore, a meta-analysis of global impact estimates does not allow the IWG to break down impacts by region or sector, making this methodology primarily useful for IAMs with one aggregate damage function, like DICE.

Recommendation 4.2: The NAS Should Recommend that the IWG Develop a Damage Module to Explore the Possible Impacts of Climate Change on the Social Cost of Carbon Through Its Effect on Economic Growth.

There is growing empirical evidence that higher temperatures affect labor productivity (Kjellstrom et al., 2009), the growth rate of economic output (Hsiang, 2010; Bansal & Ochoa, 2011;[27] Dell et al., 2012), and the growth rate of exports (Jones & Olken, 2010). Some of these negative effects on growth continue into the medium-run and long-run (Dell et al., 2012; Burke et al., 2015). Most recently, Burke et al. (2015) estimates that temperature and precipitation changes due to climate change could decrease global GDP by 23% by 2100 for a business-as-usual scenario, though this estimate is highly uncertain and is much higher than previous macro-estimates by Dell et al. (2012).[28] Given this evidence, it is not surprising that a recent

[26] Not only does the methodology produce a measure of central tendency that represents the wisdom of the crowd, we can accurately measure subjective probabilities of losses by calibrating probability density functions of damages for each respondent (potentially for a variety of temperature levels) (Howard & Sylvan, 2015).

[27] "Bansal and Ochoa (2011) find that national temperature shocks reduce growth by 0.9 percentage points per °C" (Moyer et al., 2013).

[28] Dell, Jones, and Olken (2012) find a 1.3 percent decline in the economic growth rate of poor countries for a one degree Celsius increase in annual average temperature. However, Burke et al. (2015) is more consistent with previous macro-estimates, and challenges assumptions that climate change will not affect the growth rates of

survey found that 78% of experts on the economics of climate change believe that climate change will affect economic growth (Howard & Sylvan, 2015).

The mechanism through which climate change affects economic growth is still unclear. There are several hypothesized mechanisms in the literature, including input (land, labor, and capital) productivity and stock, social conflict, resources available for adaptation, and returns to investment. See Howard (2014) for a more in-depth discussion.

In their default versions, the popular IAMs (DICE, FUND, and PAGE) all assume the relentless march of output growth (Howard, 2014). Given that current IAMs fail to model the potential effects of climate change on economic growth—a dynamic phenomenon—and instead focus on the effect of climate change on the level of output (Fankhauser & Tol, 2005; Tol, 2009; Moyer et al., 2013), it unsurprising that they find that the future is always richer than the present, due to a growth path of per capita consumption that is rarely overwhelmed by climate change. The consequence of this unthreatened growth path is that it is not optimal to divert resources for mitigation purposes in the short-run, but rather to continue higher levels of current consumption (and, according to DICE, current investments in capital) (Moyer et al., 2014).

Papers that model the potential impact of climate change on economic growth in the context of IAMs consistently find significant effects on the SCC. Several papers have modified DICE to include the potential impacts of climate change on economic growth, and have found significant effects on the SCC or the optimal tax (which equals the SCC on the optimal emissions path) (Dietz & Stern, 2015; Moyer et al., 2014; Moore & Diaz, 2015).[29] Two alternative IAMs, ENVISAGE and ICES, model the effects of climate change on economic growth via shocks to labor, capital, and total factor productivity in a general equilibrium model, GTAP. Using ENVISAGE, Roson and van der Mensbrugghe (2010) estimate damages of 1.5 percent and 3.5 percent of global GDP for increases of 2.3 degrees Celsius and 4.9 degrees Celsius, respectively, above 2000 temperatures, due to labor productivity alone. Thus, the impact of climate change on economic growth is significant.

The NAS should recommend that the IWG include the potential impact of climate change on economic growth as an additional damage function module. Part of this module would require the IWG to make structural changes to some IAMs included in the analysis (including DICE, FUND, and PAGE), though the exact changes depends on the assumptions made by the IWG about the mechanisms by which climate change affects economic growth (e.g., capital productivity). To develop a specific means of implementation, the IWG could look to papers that have modified DICE and the CGE literature. Care

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wealthy nations. In particular, Burke et al. (2015) argues that Dell et al. (2012) does not disentangle the impact of climate change on economic growth from the observation that poor nations tend to already be hotter. In other words, it is not clear from Dell et al. (2012) whether developing nations suffer more because they are more dependent on climate-sensitive sectors or because they are exposed to more frequent damaging climate events due to their already high temperatures (Moore & Diaz, 2015). Burke et al. (2015) finds evidence of the latter explanation, implying that developed nations will experience greater losses as they move to higher temperatures, and are not in fact "more" resilient.

[29] Dietz and Stern (2015) find that the optimal price of carbon in 2015 increases by 73% to 168% depending on whether climate damages affect the global capital stock (i.e., 30% of DICE damages allocated to capital loss) or total factor productivity (i.e. 5% of DICE damages allocated to productivity loss), respectively. Moyer et al. (2014) find that much higher SCC estimates are possible if even a small share of climate damages indirectly affects economic output through the level or growth rate of total factor productivity, instead of the level of output directly. Moore and Diaz (2015) find a multi-fold increase in the SCC when they calibrate the damage function of their simplified version of DICE (gro-DICE) to the results of Dell et al. (2012), whereby climate change affects economic growth through total factor productivity declines or capital depreciation; however, they find that this increase depends on whether shifting from developing to developed nation status (i.e., increasing per capita income) makes an economy more resilient to climate change impacts.

should be taken to continue to model non-market and catastrophic damages separately from growth impacts on GDP.

Recommendation 4.3: The NAS Should Recommend that the IWG Develop a Climate Damage Module to Conduct a Sensitivity Analysis to Functional Forms of the Damage Function(s)

Due to the lack of damage estimates for high temperature increases, extrapolation of damages to high temperatures is necessary regardless of the methodology for estimating climate impacts. This is true even for methodologies that can test functional forms, like meta-analysis (e.g., Tol (2014), that still rely on damages corresponding to low temperature to fit their damage functions. Therefore, in addition to conducting a sensitivity analysis with respect to the calibration of damage functions (for low temperature increases), the IWG should conduct sensitivity analysis over the functional form of damage functions using functions common in the literature (see Tol, 2014; Kopp et al., 2012). This additional sensitivity analysis is essential given Kopp et al. (2012)'s finding that functional form shape can greatly affect SCC estimates when the IAM's central planner is risk averse.

Recommendation 4.4: The NAS Should Recommend that the IWG Use Modules (Climate, Damage, etc.) as Additional Sensitivity Analysis Rather than Replacing IAM Components Altogether, or Else Recommend Explicit Selection Criteria for Replacing Components with Modules

Clearly, there is an advantage to sensitivity analysis with respect to modeling components. Specifically, the modules demonstrate the true range of uncertainty in the literature. However, the IWG should not simply replace the IAMs' climate model components with its climate module altogether, nor should it replace IAM damage functions with the damage modules. The point of using three IAMs was to capture the full range of modeling decisions in the literature,[30] and replacing modeling components altogether (i.e., in the base runs instead of in sensitivity analysis runs) would erode this goal.

Another reason for not engaging in the wholesale replacement of particular modeling components of IAMs is that it is unclear where such a process stops. All components in IAMs could be modulized, so it is unclear why the IWG should replace one IAM component and not another. If the NAS does recommend the wholesale replacement of particular IAM components, it should develop criteria for modulization, to answer several key questions: What are the criteria necessary for the modulization of an IAM component? Where does the IWG stop in its modulization of IAMS? At what point would the IWG be better off developing its own IAM?

5. The IWG's Choice of Three IAMs Was Fully Justified, but the Choice of IAMs Should Be Revised Using a Transparently Developed Selection Criteria Developed *A Priori*

In its calculations of the SCC, the IWG relied on the three Integrated Assessment Models (IAMs) available at the time, all with a long record of peer-reviewed publications that link physical and economic effects: the Dynamic Integrated Model of Climate and the Economy (DICE), the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND), and Policy Analysis of the Greenhouse Effect (PAGE) (Nordhaus, 2014; Anthoff & Tol, 2012; Hope, 2006). DICE, FUND, and PAGE are well-established, peer-reviewed models, developed over decades of research. They represent the state-of-the-art IAMs. The government's first SCC estimates, published in 2010, used the then-current versions of the models; the recent 2013 update employed revised, peer-reviewed versions of the models but maintained the underlying assumptions of the 2010 IWG analysis.

[30] The IWG (2010) clarifies this intention when it declares that "a key objective of the interagency process was to enable a consistent exploration of the three models while respecting the different approaches to quantifying damages taken by the key modelers in the field."

Recommendation 5.1: The NAS Should Recommend that IWG Consider Expanding the Set of IAMs Used to Calculate the SCC to Include Similarly Peer Reviewed State-of-the-Art IAMs; the NAS Should Provide Model Selection Criteria

Each update of the SCC should also consider including models that, like DICE, FUND, and PAGE, are similarly peer reviewed and based on the state of the art of climate-economic modeling. There are several candidate for inclusion: Climate and Regional Economics of Development (CRED);[31] World Bank's ENVironmental Impact and Sustainability Applied General Equilibrium (ENVISAGE) model;[32] Fondazione Eni Enrico Mattei (FEEM)'s Intertemporal Computable Equilibrium System (ICES);[33] A Model for Evaluating the Regional and Global Effects of GHG Reduction Policies (MERGE);[34] and Fondazione Eni Enrico Mattei (FEEM)'s World Induced Technical Change Hybrid model (WITCH).[35]

To aid in this decision, the NAS should suggest model selection criteria (much like it provided "specific diagnostic criteria" to assess a potential climate module) that should be applied to all models, including currently included models (i.e., DICE, FUND, and PAGE). These criteria should answer a variety of difficult questions. First, and foremost, when is a model sufficiently up-to-date to be used in the IWG analysis? For example, does the model reflect the science and economics laid out in the latest IPCC report? Second, given that models differ in the sets of impacts that they capture, what are the necessary impact categories for a model's inclusion? For example, should ICES and ENVISAGE be omitted because they exclude non-market impacts of climate change? Third, given that many IAMs borrow components from other IAMs and calibrate to similar underlying datasets, when is a model too similar to other IAMs with respect to its structure and/or calibration to be included? For example, should models that are partially calibrated to (i.e., WITCH[36] and PAGE[37]), use similar datasets as (ICES[38] and ENVISAGE[39]), or borrow portions of (i.e., CRED[40]) already included IAMs be treated as independent

[31] CRED borrows its fundamental structure from William Nordhaus's DICE and RICE models but also offers significant changes. For one, it uses updated damage functions and Marginal Abatement Cost Curves (MACC). Moreover, it uses different global equity weights, and uses additional state-of-the-art methodologies (Ackerman et al., 2013).

[32] ENVISAGE represents a broader modeling effort by the World Bank, where perhaps the largest contribution is a more detailed sectoral breakdown, using 57 different sectors. This level of analysis allows for a more detailed view of agriculture as well as food and energy sectors that are particularly important to any climate-economy modeling (World Bank, 2014; Roson & Mensbrugghe, 2012). The model captures only market impacts.

[33] ICES is modeling effort by FEEM, and like ENVISAGE is a computer generated equilibrium model with 25 regions and 20 sectors (Eboli et al., 2010; Bosello et al., 2012; FEEM, 2016a). Like ENVSIAGE, the model captures only market impacts.

[34] MERGE is a 9 region integrated assessment model that captures impacts to market and non-market sectors, while explicitly assuming that impacts reach 100% of GDP at 17.7 °C (Manne, 2005).

[35] WITCH—another IAM developed by FEEM—consists of 12 strategically interacting regions within a dynamic economic growth model, which explicitly models the energy section, endogenous technological change, and various mitigation tools. WITCH is unique in that it models endogenous technological change (FEEM, 2106b; Bosetti et al., 2009). The latest version includes an adaptation module (Bosello & Cian, 2014).

[36] According to Bosello and Cian (2014), the latest market damage functions of WITCH are calibrated using versions of DICE (Nordhaus, 2008) and ICES (Bosello et al., 2012).

[37] The market and non-market damage functions of PAGE-2009 are partially calibrated using earlier versions of DICE and FUND (Howard, 2014).

[38] Some ICES damage functions are calibrated using similar datasets as FUND, including agriculture, health, and sea-level rise (Tol, 2002; Bosello et al., 2006; Eboli et al., 2010; Anthoff & Tol, 2013).

[39] Like ICES, ENVISAGE calibrates its health damage function using results from Bosello, Roson and Tol (2006), which uses data from Tol (2002), which provides the basis for calibrating FUND's health impact estimates. Also like ICES, ENVISAGE uses similar data as FUND to estimate impacts from sea level rise (Bosello et al., 2007). Also, ENVISAGE uses similar data to calibrate climate impacts on tourism and energy demand (Eboli et al.,

SCC estimates? Last, how does the potential modularization of IAMs by the IWG affect the selection of models? Given the wide range of potential considerations, it would be helpful for the NAS to lay out its preferred selection criteria in its second report to the IWG to ensure transparency and objectivity. Currently included models should also be re-selected based on these criteria, and dropped if they do not meet these criteria.

Recommendation 5.2: The NAS Should Insist that the IWG Include a Section Discussing How IAMs Are Related

The economic-climate modeling community is small and often relies on a handful of studies to calibrate their models. Many IAM damage functions are at least partially calibrated using similar underlying data, including PAGE (partially based on DICE and FUND), WITCH (partially based on DICE), and ICES and ENVISAGE (partially based on FUND) (Howard, 2014; Eboli et al., 2010; Bosello et al., 2007). Also, many IAMs share similar climate or damage function structures. As a consequence, the various IAMs in the literature are not independent from one another (Hisschemöller et al., 2001). Similar to NAS's recommendation to the IWG to include an explicit section in all future technical supporting documents discussing modeling uncertainty, the NAS should recommend a discussion of how models overlap. If the current "explicit" weighting assumptions are maintained (i.e., equally weighting each IAM and scenario), this overlap is key to understanding the implicit weighting of various assumptions. This discussion becomes ever more important as more climate-economic models are included by the IWG.

6. The IWG Should Update Its Socio-Economic Assumptions

One key input is the use of socio-economic scenarios reflected in the choice of economic growth rates and emissions trajectories. Current IWG socio-economic and emissions scenarios were chosen from the Stanford Energy Modeling Forum exercise (EMF-22) and consist of projections for income/consumption, population, and emissions (CO_2 and non-CO_2). The IWG selected five sets of trajectories, four of which represent business-as-usual (BAU) trajectories (MiniCAM, MESSAGE, IMAGE, and MERGE models) and a fifth that represents a CO_2 emissions pathway with CO_2 concentrations stabilizing at 550 ppm.

Recommendation 6.1: The IWG Should Update Its Socio-Economic Assumptions to Reflect the Latest Shared Socio-Economic Pathways (SSPs)

The assumptions used in calculating the SCC should be updated regularly to reflect the latest thinking around possible scenarios, reflecting the latest Shared Socio-economic Pathways (SSPs) (Ebi et al., 2014). These SSPs should represent the latest, consistent pathways, for example, feeding into the latest IPCC report (e.g., Moss et al., 2008). Ideally, a source of emission pathways, such as the IPCC, would be selected to make it clearer when an update of SSPs is necessary.

Recommendation 6.2: The IWG Should Explicitly Weight the Current Socio-Economic Scenarios Considering the Full Range of Possibilities

By using four BAU trajectories and a fifth declining emissions trajectory, the IWG implicitly places an 80% probability on BAU continuing, a 20% probability on future global commitment to reduce emissions, and a 0% probability on greenhouse gas emissions increasing above BAU. Given the possibility of increases in emissions above those expressed by BAU scenarios, a high-CO_2 emissions pathway should also be considered (or the decision to exclude such a possibility explicitly discussed).

2010; Roson & Mensbrugghe, 2012) using the Hamburg Tourism Model (Hamilton, Maddison & Tol, 2005) and De Cian et al. (2007), respectively.

[40] CRED borrows its fundamental structure from William Nordhaus's DICE and RICE models (Ackerman et al., 2013).

Ideally, the IWG would provide explicit weight for these various scenarios (potentially using expert elicitation), rather than an implicit weighting as currently employed.

7. Future Social Cost of Carbon Research and Funding

The NAS could encourage the IWG, and the federal government more generally, to improve the current research on the SCC.

Recommendation 7.1: The NAS Should Call for Increased Funding of Climate-Economic Research, Distributed to a Broader and Interdisciplinary Community of Researchers

First and foremost, increased funding of climate-economic research is necessary. Currently, funding of economic research on climate change is small relative to the physical sciences (Anthoff, 2013). Given the current lack of funding of climate-economic research, climate-economic modelers do not have the resources to update the structure of their models or the underlying data. This is compounded by publication incentives that do not reward updating models but instead reward developing and testing new theories and questions. This has partially led to integrated assessment models that are outdated (Revesz et al., 2014). Ideally, a funding source would be developed exclusively for climate-economic research, perhaps through the National Science Foundation framework. This funding source should be broad enough to not only fund IAM development and updating, but also improving damage function and other parameter estimation.

Second, the funding of climate-economic research should be distributed to a broader community than just the current IAM community. Currently the IAM community is small: four authors account for the three IAMs used by the IWG (2010; 2013), and only a slightly larger community has worked on climate-economics more broadly. According to David Anthoff, one of the developers of FUND, it is not good for a policy community to be so small; science models of similar importance dwarf IAMs in terms of man hours (Anthoff, 2013). A wider community would provide a greater number of perspectives, while simultaneously increasing the amount of hours spent on these models.

Third, the NAS should recommend that any such funding source should be allocated primarily to interdisciplinary research teams (Revesz et al., 2014). Currently, scientists and economists work independently in the field of climate-economics, with scientists and economists typically citing one another's published work without even communicating. For example, the chain of steps in calibrating the agricultural damage function in an IAM may involve four or more researchers, likely including at least: (1) a scientist who develops a climate scenario, (2) an agronomist and/or economist who uses this scenario to estimate yield and revenue impacts (often regionally), (3) an economist who uses these yield or revenue impacts in a trade model to estimate general equilibrium impacts on regional food consumption, and (4) an integrated assessment modeler who uses these CGE estimates to calibrate their regional-agricultural damage function. This process results in considerable information loss and incompatibility. For example, an estimate of agricultural yield impacts for various crops at the global scale is unusable in IAMs because climate-economists require regional-revenue impacts, which do not currently exist. The NAS should encourage interdisciplinary teams that work from the ground up to develop comprehensive damage estimates for IAMs with each step in mind. This would resemble larger scientific efforts in other fields.

Recommendation 7.2: The NAS Should Highlight Key Areas for Future Research

There are several specific areas of research that the NAS should highlight as needing improvement for the next iterations of the IWG's Technical Support Document. Specifically, research should be focused on improving damage estimation, structural improvements in IAMs, and out-of-sample tests where possible.

A. Future Research on Net Damages

Anthoff and Hope at the NAS's third committee meeting in Washington, D.C. on November 13, 2015 both indicated that improving damage estimates will likely take decades. Thus, bottom-up approaches and top-down approaches to estimating climate damage functions are likely to be necessary estimation strategies for many more decades to come, and both have significant room for improvement. Therefore, considerable investment in the improvement of these approaches to damage estimation is necessary. These approaches should rely on rigorous empirical estimation methods or expert elicitation, rather than relying on author discretion as was common in earlier enumerative studies.

In addition to improving these estimation methods, there are several areas upon which new research should focus.

Key Omitted Impacts: One way that the NAS could greatly improve these damage estimates is to highlight the need for the inclusion of currently omitted climate damages (Howard, 2014). There are several omitted impacts that should be included given their potential to significantly affect the magnitude of damage estimates, including socially contingent impacts (e.g., migration, conflict, and violence), growth effects, and other omitted categories like weather variability, ocean acidification, and wildfires.[41] There are also other impacts that are included in IAMS using only the coarsest of methods (e.g., ecosystems, biodiversity, and tipping points). See Howard (2014) for a complete list of omitted impacts, and an extensive discussion of their relative importance.

In some cases, empirical estimates are available (or increasingly so). However, many of these impacts are omitted for tractability/identification reasons. Specifically, climate change impacts are more likely omitted if they are more difficult to measure scientifically or economically. Thus, impacts that are more scientifically uncertain (e.g., socially contingent impacts and tipping points) and/or more difficult to value (e.g., ecosystem services and biodiversity) are more often omitted, resulting in the inclusion of only relatively certain, market impacts (Yohe & Tirpak, 2007). In general, work is necessary to address these omissions given that they are implicitly valued as zero in the current IAMs used by the IWG.

The NAS should advocate that funds not only be distributed to IAM developers to re-calibrate their models, but to scientists and economists jointly working together to improve the underlying estimation techniques. Until all potentially significant impacts are addressed, the SCC should be understood as a lower-bound estimate (Howard, 2014; Revesz et al., 2014).

Catastrophic Impacts: Catastrophic impacts and climate tipping points (in addition to ecosystem services) are currently only partially captured due to the coarse methodologies employed in their measurement. The IAMs currently model tipping points in differing ways: DICE-2010 explicitly models certainty equivalent damages of catastrophic events as estimated in a survey of experts by Nordhaus (1994); PAGE09 explicitly models a singular, discrete discontinuous event that has a probability of occurring in each time period when the realized temperature is above a specified temperature threshold (beyond which the probability is increasing in temperature); and FUND potentially captures tipping points by modeling the uncertainty of almost 900 parameters (Howard, 2014; Lenton & Ciscar, 2013). Also, several papers have modified these IAMs to explicitly model the effects of particular tipping points, including Nicholls et al. (2008), Link and Tol (2011), and Lemoine and Traeger (2011).

Considerable work is still necessary on this topic, and the NAS could aid the IWG in identifying several research directions (Nordhaus, 2013). First, the NAS should clarify the difference between tipping points,

[41] While the NAS should greatly encourage further research into the impacts of climate change on economic growth (i.e., determining the magnitude of the impact), it is also important to identify the mechanism by which climate change affects economic growth (e.g., capital productivity).

catastrophic impacts, and black swan events[42] (Kopp et al., 2016; Howard, 2014), and require an explicit discussion of these concepts and how they are or are not captured by the IWG. Second, the NAS should suggest that the IWG focus on rapid tipping points that have potential impacts during the time frame of the IAMs (i.e., Gladwellian tipping points),[43] rather than slow tipping points (i.e., tipping elements) (Kopp et al., 2016). Key Gladwellian tipping points include climate system tipping points (Atlantic Meridional Overturning Circulation, Regional North Atlantic convection, West African monsoon, El Niño-Southern Oscillation, Arctic sea ice, coral reefs) and social tipping points (adaptation, migration, conflict) (Kopp et al., 2016). Feedback processes that result in more rapid warming than expected should also be included (Nordhaus, 2013), though this is partially captured by the equilibrium climate sensitivity parameter's probability distributions and the NAS's proposed climate module. Third, work on identifying the appropriate distributions for climate and economic parameters should be conducted following the IWG (2010; 2013) approach for the climate sensitivity parameters. Too often distributions like the triangular distribution (i.e., a probability distribution shaped like a triangle defined by its minimum, maximum, and mode) are chosen (see PAGE and FUND) for reasons of computational simplicity that eliminate the possibility of fat tails (Howard, 2014). Finally, future work is necessary to identify what are catastrophic damages—often measured using expert elicitation (Nordhaus, 2014; Howard & Sylvan, 2015)—and to determine if they overlap with tipping points and fat tails.

Given their potential significance, improved modeling of catastrophic and tipping point impacts should be directly integrated into IAMs. If this does not occur, a module should be developed by the IWG, like the damage and structural modules discussed earlier. Otherwise, climate tipping points, like other omitted impacts, are implicitly valued at zero.

Impacts for High Temperatures: Few damage estimates exist for high temperatures. The vast majority are for a 3°C increase in global average surface temperature relative to the pre-industrial period (i.e., the most likely level of long-run warming from a doubling of CO_2 equivalent emissions) or less (Tol, 2009; Howard & Sterner, 2016).

A very promising direction for future climate damage research—used by Ackerman and Stanton (2012) and Weitzman (2012)—is to assume that climate damages reach 100 percent of GDP when temperatures reach levels inhospitable to humans. Globally, Sherwood and Huber (2010) find that humans cannot live on planet Earth for at least some portion of the year if temperatures increase by 12°C or more. This type of research can also inform regional damage estimates (and migration estimates). Recent work by Pal and Eltahir (2015) find that the Persian Gulf will reach the limits of physical human adaptation to temperature (specifically wet-bulb temperature) by the end of the century under business-as-usual conditions. Identifying when regions become too humid for human life should be a priority of future research, particularly regionally. This will also aid in the estimation of the shape of climate damage functions.

Adaptation: The three IAMs used by the IWG (2010; 2013) are often accused of being overly optimistic in their adaptation assumptions, particularly for the versions used by the 2010 IWG (Dietz et al., 2007; Ackerman, 2010; Warren et al., 2006; Hanemann, 2008; Ackerman et al., 2009; Masur & Posner, 2011). Recent empirical evidence finds limited adaptation to climate change in the context of agriculture (Schlenker & Roberts, 2009) and economic growth (Burke et al., 2015).

In the IAMs currently used by the IWG (2013), the modelers account for adaptation in different ways. In DICE, adaptation is implicit in the damage estimates such that adaptation costs are captured in the

[42] Black swan events refer to unknown catastrophic impacts, via unknown tipping point events or parameters with unknown probability distribution functions.

[43] Named after the concept defined by Gladwell, Kopp et al. (2016) define Gladwellian tipping points as "critical thresholds, beyond which realized change keeps pace with committed change." In other words, Gladwellian climate tipping points are climate thresholds beyond which the climate "exhibit[s] rapid shifts between states: specifically, from a state in which" a climate effect "is rare to one in which it is widespread."

underlying estimates used to calibrate their damage functions (Warren et al., 2006). In earlier versions of DICE (DICE-1999, DICE-2007, and DICE-2010),[44] Nordhaus essentially assumed high levels of human adaptation at virtually no cost (IWG, 2010).[45] In FUND, Tol models adaptation explicitly (agriculture, ecosystems, and sea level rise) and implicitly (energy, forestry, human health sectors, water, and storms) in the damage estimates and by allowing regional sector costs to be a function of regional wealth (Anthoff & Tol, 2012); this latter type of adaptation assumes that wealthier societies are better able to adapt to climate change (IWG, 2010). According to Warren et al., (2006), FUND assumes perfectly efficient adaptation without accounting for adjustment costs, except in the agriculture and ecosystem sectors. In PAGE09, unlike DICE and FUND, Hope (2011) explicitly models climate adaptation and its costs. For each non-catastrophic damage sector (sea level rise, market, and non-market), he specifies a temperature level up to which adaptation is 100 percent effective, a temperature level up to which adaptation is partially effective, and a level of effectiveness (the percentage of damages not incurred) for temperature increases between these two levels. If the three IAMS overestimate society's ability to adapt to climate change, current SCC estimates from DICE-2013, FUND 3.6, and PAGE09 are likely biased downward due to a tendency to be overly optimistic about adaptation (Masur & Posner, 2011).

The NAS should encourage climate research on adaptation. First and foremost, the NAS should encourage the IWG to incentivize IAM developers to make their adaptation assumptions explicit, as in PAGE. In the case of DICE, this may be easily done by updating the current versions of AD-DICE (de Bruin et al., 2009) and AD-RICE (de Bruin, 2014), which modify DICE-2007 and RICE-2010, respectively, to explicitly model adaptation. By doing so, the IWG should be able to modify IAM adaptation assumptions or conduct a sensitivity analysis using an adaptation module, similar to the damage module. Second, climate damages are currently only partially a function of the rate of climate change in some IAMs (Anthoff & Tol, 2013, Hope, 2011),[46] and not at all in other IAMs (such as DICE). Given that the rate of climate change is essential in determining the cost and limits of human adaptation, future work is necessary to identify how the rate of climate change affects climate damages through adaptation. This is particularly relevant with the recent U.S. shift towards natural gas, which increases methane emissions relative to CO_2 emissions (methane has a stronger global warming potential than carbon dioxide, but a shorter lifespan). Third, the NAS should argue that some portion of climate-economic funding should be allocated to empirical work on climate adaptation in order to identify the level and limits of such adaptation. This empirical work should not only focus on adaptation, but the potential for maladaptation, potentially barriers to adaptation, and inefficiency. To a great extent, IAMs often assume that adaptation will be perfectly efficient (see FUND's sea level rise adaptation assumptions). Yet adaptation, like output-emissions ratios and backstop technologies, are products of a political-social-economic process for which many barriers exist (Dupris, 2011; Biesbroek et al., 2013).[47] Furthermore, even successful adaptation may raise new risks, such as the increased costs of levee / sea wall failures (e.g., Hurricane Katrina) from building sea walls, or increased social pressures from migration (e.g., the current Syrian migrant crisis observed in Europe).

[44] It is less clear the extent to which the DICE-2013 damage function captures these adaptation costs due to the use of a meta-analysis. In all versions of DICE, adaptation is not effective enough to eliminate damages.

[45] According to IWG (2010) and Warren et al., (2006), this is particularly evident for the other market sectors. Though the IWG (2010;2013) modifies the DICE model such that emissions are exogenous, the base version DICE makes strong assumptions about the potential for human mitigation, assuming that 100% mitigation is possible this century and that 120% mitigation is possible in 150 years (Ackerman et al., 2013).

[46] In general, climate damages are not a function of the rate of temperature change. The exception is the agriculture and ecosystem sectors in FUND. However, adaptation will be particularly difficult for faster-than-expected temperature increases (Anthoff & Tol, 2012; Hope, 2011).

[47] Dupuis (2011) states "Barriers to adaptation exist in both the developed and developing world, but they appear to be different. If a lack of material resources might still be the main hindrance to the development and implementation of adaptation measures in less developed countries, in developed countries where the need to act is not as obvious, the political feasibility and acceptance of adaptation policies is of greater relevance."

B. Future Research on Structural Modules

Like damage estimates, structures of many IAMs (i.e., the equations that make up climate-models and how these equations connect) are rigid over their various updates. In particular, the three IAMS used by the IWG are relatively stable since their founding in the 1990s (Revesz et al., 2014). This is despite a rich literature exploring structural assumptions and growing evidence that some assumptions may not hold, particularly in the case of impacts of climate change on growth (addressed above in our Recommendation 4.2), utility functional form, and tipping points (discussed above). Given this literature, the IWG currently understates the potential uncertainty underlying the SCC, often systematically underestimating its impact (IWG, 2015b).

Recently, Gillingham et al. (2015) have argued that parametric uncertainty is a more significant driver of the social of carbon than structural assumptions. This argument is based on analysis of six models, of which three have damage functions (DICE, FUND, and WITCH). Many of these models make similar economic assumptions—e.g., the WITCH damage function (Bosello & Cian, 2014) is calibrated using DICE (Nordhaus, 2008) and ICES (Bosello et al., 2012)—resulting in an under-analysis of potential structural uncertainty as represented by the broader IAM and climate-economic literature. While Gillingham et al. (2015) correctly state that in their subset of models structural uncertainty is less important than parametric uncertainty, it is far too early to dismiss model structure as a key determinant of the SCC. In fact, there is reason to believe that alternative structural assumptions are likely to significantly affect the SCC, particularly with respect to the functional form of the utility function and its implications for the discount rate.

Currently, the IAM literature (particularly DICE, FUND, and PAGE) rely on the "standard intertemporally additive expected utility" function with isoelastic preferences (Traeger, 2014). While simple models are more tractable and sometimes lead to easier to understand, more transparent results, they can also omit key details. For example, current IAMs ignore variable relative prices (Hoel & Sterner, 2007)[48] and heterogeneity in risk aversion (Arrow-Pratt, intertemporal, and ambiguity) (Traeger, 2014). Adopting more complex utility functions potentially results in more realism, but at the cost of calibration (which is not always possible) and more complex discount rate specifications (Hoel & Sterner, 2007; Sterner & Persson, 2008; Traeger, 2014).

With respect to relative prices, climate change is predicted to affect market and non-market goods produced outdoors more than market goods produced indoors; market goods insensitive to climate change account for the majority of GDP (Nordhaus & Boyer, 2000). As a consequence, non-market goods and outdoor-produced goods will become relatively scarcer than indoor-produced goods over time. Based on the law of scarcity, the value of non-market and outdoor-produced goods and services will increase relative to indoor-produced market goods. However, current damage estimates to climate-sensitive goods and services reflect the current ratio of their economic value to climate-insensitive goods, which is based on the current ratio of their quantities. By extrapolating these estimates to future time periods without making any explicit adjustment for relative prices (that is, without accounting for relative change in value of non-market and outdoor-produced goods and services to indoor-produced goods over time), the developers of the IAMs implicitly assume constant relative prices, and bias the SCC downward. This bias may be significant given that Sterner and Persson (2008)—who replace the isoelastic utility function in DICE with a CES utility function calibrated using reasonable parameter values—find that allowing a change in relative prices can approximately double costs of climate change relative to a model assuming

[48] Discussions about changing relative prices date back to earlier literatures. Neumayer (1999) calls this argument the "Krutilla-Fisher rationale," from Krutilla and Fisher (1975). In the context of manufactured and public goods, Baumol (1967) describes a similar phenomenon called "Baumol's disease." The discussion of changing relative prices also has roots in the earlier literatures of weak sustainability and strong sustainability.

constant relative prices (at a 2.5°C increase), though their results are highly dependent on the assumed elasticity of substitution (Neumayer, 1999).[49]

With respect heterogeneity in risk aversion, it is a well-known short coming of current IAMs that their overly simplistic structures imply identical aversion to current risk (Arrow-Pratt relative risk),[50] intra-generational inequality (distributive society within time periods), and inter-generational inequality (distribution society between periods)[51] (Sterner & Persson, 2009; Traeger, 2014; Ackerman et al., 2013b). Empirical work testing this equality find little support for the current equality assumption (Ackerman & Stanton, 2013; Crost & Traeger, 2014). Furthermore, the standard utility assumption implies that society is neutral with respect to inter-temporal risk and ambiguity (i.e., deep uncertainty), though empirical work shows that people are risk averse in these respects, though they are less risk adverse to consumption fluctuations than to risk within a given time period. Beyond the climate change literature, these problems are also well known in the finance literature due to the equity-premium and risk-free rate puzzles (Ackerman & Stanton, 2013; Traeger, 2014; Traeger, 2014b). By introducing one of the solutions to the equity premium puzzle (Epstein Zinn preferences) into DICE, several papers demonstrated that relaxing the current equality assumption significantly increases the SCC.[52]

To capture the true range of uncertainty over the SCC, the NAS should recommend that, at some time in the future, the IWG should develop a structural module, like the climate module and the proposed damage module, that will allow for a sensitivity analysis over various key structural assumptions. This module should allow for more complex utility functional forms, including an explicit model of relative prices and an Epstein-Zin utility function. The NAS should qualify this recommendation given the need for additional empirical work to: (1) identify the elasticities of substitution between indoor-produced market goods, outdoor-produced market goods, and non-market goods, (2) estimate the aversion to risk, intra-generational inequality, and inter-generational inequality, and (3) improve the computational methods (for purposes of tractability). Before requiring the development of a structural module, empirical issues such as these should be resolved to some satisfactorily level, given their significant effect on the resulting SCC estimates (Neumayer, 1999; Ackerman et al., 2013b).

As a side note, relative prices have implications for the portion of the NAS's charge about the relative advantages of aggregate and disaggregate damage functions (Gillingham, 2015). While relative prices do not imply that the IWG should use one or the other of these approaches, the specification of disaggregate damages functions (such as in FUND or PAGE) [53] not only facilities the modeling of relative prices, but

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[49] The lower the actual elasticity of substitution is (i.e., the more difficult it is to substitute market goods for lost non-market goods to make society as equally well off under climate change), the more likely the current integrated assessment models are to underestimate the environmental cost of climate change by assuming perfect substitutability.

[50] This is the risk that society experiences within a time period, such as the flip of a coin. In other words, this is the risk aversion that humans experience to gambling (Crost & Traeger, 2014).

[51] This measures humans' desire for smooth consumption over time (Crost & Traeger, 2014), which is why it is also known as the intertemporal elasticity of substitution (Ackerman et al., 2013b).

[52] Using DICE, Ackerman et al. (2013b) calibrate an Epstein-Zin utility function for 5 possible future states of the climate sensitivity parameter (where uncertainty resolves by 2075), and find a four-fold increase in the SCC. Crost and Traeger (2014) find a more than doubling of the optimal tax (the SCC on the optimal emissions path) from the use of the Epstein-Zin utility function in the context of uncertainty over the damage function. Jensen and Traeger (2014) find an increase in the optimal tax in the context of uncertainty growth.

[53] While FUND and PAGE specify multiple damage functions, DICE specifies an aggregate damage function. However, in some cases, this damage function can be interpreted as the aggregation of multiple damage functions. On the one hand, Nordhaus calibrated the DICE-2007 and DICE-2010 damage functions using the enumerative approach, such that sector-regional (or just sector) damage functions can be disaggregated if all damage functions are assumed to be quadratic. On other hand, Nordhaus calibrated the DICE-2013 damage function using the meta-analysis approach, making such a disaggregation impossible.

almost necessitates the modeling of relative prices by maximizing the value of this approach. Specifically, if the NAS recommends specifying a disaggregate damage function and the perfect substitutability assumption, it would be advocating for throwing out valuable information.

C. Future Research on Testing Climate Models

Considerable work is necessary to test climate-economic models' predictive powers. Ideally economic models would conduct back-casting or out-of-sample prediction, as in the science literature. However, this is difficult to do given that, unlike climate science variables such as sea-level rise and temperatures, long-run time series data on climate damage is unavailable and because of the long time horizon relevant for climate change. Given the difficulty of conducting the types of tests employed in the science literature, the NAS should recommend other means by which to test IAMs.

First and foremost, statistical work is necessary to empirically test whether current structural assumptions hold in the past. For example, empirical work is necessary to identify the mechanism by which climate change affects economic growth. In doing so, modelers will be able to integrate the impacts of climate change on economic growth in a realistic manner to improve their predictive capacity. Additionally, analysts should test whether more complex preferences are necessary by: (1) testing the equality of societal aversion to intergenerational and intergenerational risks and inequality, and (2) testing whether the elasticity of substitution between market goods and non-market goods is infinite. If these equalities do not hold, more empirical work is necessary to estimate these parameter values to integrate them into IAMs through Epstein-Zin preferences and relative prices, respectively.

Second, the NAS should recommend that IAMs test their models against real-world scientific results. For example, the NAS recommended that the IWG develop a climate module to match the current consensus on climate impacts. Similarly, the NAS could recommend that IAMs replicate when particular regions and the Earth will become inhospitable, following the work of Sherwood and Huber (2010) and Pal and Eltahir (2015). This would ensure that climate damage functions are consistent in some way with physical science predictions.

Sincerely,

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Exhibit H

Think Global:

International Reciprocity as Justification for a Global Social Cost of Carbon

By Dr. Peter H. Howard and Jason A. Schwartz

Working Paper No. 2016/3

Think Global:

International Reciprocity as Justification for a Global Social Cost of Carbon

by Peter Howard and Jason Schwartz[1]

Abstract

U.S. climate regulations present a special case of federal agencies applying a global, rather than exclusively domestic, perspective to the costs and benefits in their regulatory impact analyses. Since 2010, federal agencies have emphasized global valuations of climate damages for policies that affect carbon dioxide emissions, using a metric called the "Social Cost of Carbon." More recently, agencies have also begun to use a global valuation of the "Social Cost of Methane," for methane emissions. Yet lately, these global metrics have come under attack in courtrooms and academic journals, where opponents have challenged the statutory authority and economic justification for global values. This paper defends a continued focus on the global affects of U.S. climate policy, drawing on legal, strategic, and economic arguments.

International reciprocity presents the strongest justification for a global focus. Because the world's climate is a single interconnected system, the United States benefits greatly when foreign countries consider the global externalities of their greenhouse gas pollution and cut emissions accordingly. Game theory predicts that one viable strategy for the United States to encourage other countries to think globally in setting their climate policies is for the United States to do the same, in a tit-for-tat, lead-by-example, or coalition-building dynamic. In fact, most other countries with climate policies already use a global social cost of carbon or set their carbon taxes or allowances at prices above their domestic-only costs. President Obama's administration has explicitly chosen to adopt a global social cost of carbon to foster continued reciprocity in other countries' climate policies. Charged by the U.S. Constitution with managing foreign affairs and coordinating executive branch activities, President Obama deserves political and judicial deference on his choice to calculate the global benefits of U.S. climate regulations.

As for legal authority, the United States has already signed and ratified one international treaty that commits it to the consideration of global climate effects of its domestic actions. Two key statutes for U.S. climate policy—the Clean Air Act and the National Environmental Policy Act—do the same, and the other statutes most used to date for climate regulation give agencies enough discretion to consider global effects. Executive orders further show that administration priorities for international harmonization should shape U.S. regulatory analysis and decisionmaking. Finally, because of the inevitability of significant "spillover" effects and U.S. willingness to pay to prevent climate damages occurring outside U.S. borders, a domestic-only social cost of carbon or methane would fail to transparently disclose the true scope of climate-related costs and benefits that matter to U.S. policymakers and the public.

[1] Peter Howard is the Economics Director and Jason Schwartz is the Legal Director at the Institute for Policy Integrity at NYU School of Law. This report does not necessarily reflect the views of NYU School of Law, if any.

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Introduction

To control U.S. emissions of carbon dioxide, methane, and other greenhouse gases despite the absence of any new, meaningful congressional legislation on climate change, President Obama has increasingly turned to regulatory authorities that already exist under current statutory provisions. The President's 2013 Climate Action Plan called for new regulations of, for example, carbon dioxide emissions from power plants, methane emissions throughout the economy, transportation fuel economy, and energy efficiency in appliances, lighting, and buildings.[2] Using existing authorities under the Clean Air Act, the Energy Policy and Conservation Act, and other statutes, the Environmental Protection Agency ("EPA"), Department of Energy, Department of Transportation, and Department of the Interior have responded with dozens of regulations that will protect our economy, health, security, and the environment.

By presidential order, every major regulation must be accompanied by an economic analysis showing that the rule's benefits justify its costs.[3] To evaluate the benefits of climate regulations as well as the costs of other federal actions that may increase greenhouse gas emissions, a federal interagency working group developed a metric called the "social cost of carbon," which attempts to measure the marginal global damages of each additional ton of carbon dioxide—that is, the worldwide damages to agriculture, property values, health, and so forth. The value is currently about $40 per ton of carbon dioxide.[4] EPA has also developed a "social cost of methane" metric, currently around $1200 per ton of methane (methane is, pound for pound, a much more potent greenhouse gas than carbon dioxide).[5] Like the social cost of carbon, the social cost of methane values global damages.

Typically, U.S. regulatory impact analyses focus on costs and benefits to the United States, since many U.S. regulations only or predominately affect the United States.[6] However, the federal government has reasoned that climate regulations are a special category requiring an international perspective on costs and benefits. Greenhouse gases mix freely in the atmosphere and affect worldwide climate: U.S. emissions affect every other country, and foreign emissions affect the United States. If every country considers only the domestic costs of emissions within its own borders (or, conversely, only the domestic benefits of emissions reductions) and ignores the global externality, no country will ever reach the efficient level of emissions reductions. As the interagency working group on the social cost of carbon explained, "Emphasizing the need for a global solution to a global problem, the United States has been actively involved . . . in encouraging other nations . . . to take significant steps to reduce emissions. When these considerations are taken as a whole, the interagency group concluded that a global measure of the benefits from reducing U.S. emissions is

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[2] EXEC. OFFICE OF THE PRESIDENT, THE PRESIDENT'S CLIMATE ACTION PLAN (June 2013), https://www.whitehouse.gov/sites/default/files/image/president27sclimateactionplan.pdf.

[3] Exec. Order 12,866 § 6(a)(3)(C) (1993); Exec. Order 13,563 § 1(b) (2011) (affirming Executive Order 12,866's requirements).

[4] INTERAGENCY WORKING GROUP ON SOCIAL COST OF CARBON, TECHNICAL SUPPORT DOCUMENT: SOCIAL COST OF CARBON FOR REGULATORY IMPACT ANALYSIS UNDER EXECUTIVE ORDER 12,866 (2010) [hereinafter "2010 TSD"], https://www.whitehouse.gov/sites/default/files/omb/inforeg/for-agencies/Social-Cost-of-Carbon-for-RIA.pdf.

[5] 80 Fed. Reg. 56,593, 56,644, tbl. 6 (Sept. 18, 2015).

[6] For example, as explained by the U.S. Office of Management and Budget & Secretariat General of the European Commission in their 2008 *Review of Application of EU and US Regulatory Impact Assessment Guidelines on the Analysis of Impacts on International Trade and Development*, despite trade treaties, U.S. regulatory impact assessments do not usually consider the extra-territorial costs or benefits or trade impacts of regulation. However, U.S. regulatory impact assessments do typically give equal consideration to costs and benefits experienced by foreign entities operating in the United States: for example, when the Department of Transportation issues fuel economy regulations, costs to Toyota count equally as costs to Ford. *Id.* at 13.

preferable."[7] Moreover, given our multiple global interconnections—through the economy, national security, migration patterns, and communicable disease transmission—harms experienced in other parts of the world can quickly become costs to the United States, and so as a practical matter it is nearly unworkable to isolate accurately a domestic-only portion of the social costs of carbon or methane.[8] Thus, since 2010, nearly every U.S. regulatory impact analysis of climate controls has focused on the global social cost of carbon or the global social cost of methane.

This global focus has recently and increasingly come under attack. In May 2015, industry groups filed a brief in the U.S. Court of Appeals for the Seventh Circuit, challenging the Department of Energy's efficiency standards for commercial refrigeration equipment, which the agency promulgated under the Energy Policy and Conservation Act ("EPCA"). The challengers, among other claims, objected to the alleged "mismatch in the SCC [social cost of carbon] analysis looking to global benefits. . . . EPCA authorizes [the agency] to conduct only a national analysis. There are no references to global impacts in the statute."[9] On August 8, 2016, the Seventh Circuit held that the agency "acted reasonably" in calculating the "global benefits" of its energy efficiency standards;[10] it remains to be seen whether other courts will follow this ruling. Notably, in February 2016, industry groups and several states filed a brief in the U.S. Court of Appeals for the D.C. Circuit, challenging EPA's Clean Power Plan regulation of carbon dioxide from the electricity sector, which the agency promulgated under the Clean Air Act ("CAA"). The challengers, among other claims, objected that "the CAA expressly forecloses use of the Global Social Cost of Carbon because foreign benefits exceed the cost-benefit analysis' permissible scope. The Act's purpose is exclusively domestic. . . . Only 10% of the claimed global benefits from reducing CO_2 [carbon dioxide] emissions accrue to the United States."[11] That case is still pending.

Moving from the courthouse to academia, though much of the academic literature to date strongly supports a global social cost of carbon,[12] economists Ted Gayer and W. Kip Viscusi have recently led a small academic charge against the global valuation. In a 2015 working paper, they lambast the global valuation as unauthorized by statute, inconsistent with past best practices, unjustified economically due to "illusive" international reciprocity and "fractional" altruism, and likely to lead

[7] 2010 TSD, *supra* note 4, at 11.

[8] *Id.*

[9] AHRI Opening Brief at 28-30, in *Zero Zone v. Dep't of Energy*, case 14-2147, 7th Cir. (filed May 28, 2015).

[10] *Zero Zone v. Dep't of Energy*, case 14-2147 at 43 (opinion Aug. 8, 2016). In our roles as staff at the Institute for Policy Integrity, the authors participated in this case as *amicus curiae*, and the court credited our brief as "highlight[ing]" the issues surrounding the agency's use of the SCC, including a defense of the global SCC. *Id.* at 40 n.23.

[11] Petitioners Brief on Procedural and Record-Based Issues at 70, in *West Virginia v. EPA*, case 15-1363, D.C. Cir. (filed February 19, 2016).

[12] *E.g.*, Michael Greenstone, Elizabeth Kopits & Ann Wolverton, *Developing a Social Cost of Carbon for US Regulatory Analysis: A Methodology and Interpretation*, 7 REV. ENVTL. ECON. & POL'Y 23 (2013) (reviewing the policy justifications for a global value and the practical complications of a domestic-only value); Frank Ackerman & Elizabeth A. Stanton, *Climate Risks and Carbon Prices: Revising the Social Cost of Carbon,* 6 ECONOMICS E-JOURNAL 1 (2012)("The analysis by the federal Interagency Working Group is significant . . . for its recognition that policy should be based on global, rather than domestic, impacts."); Laurie Johnson & Chris Hope, *The Social Cost of Carbon in U.S. Regulatory Impact Analyses: an Introduction and Critique*, 2 J. ENVTL. STUD. SCI. 205, 208 (2012)("Empirical, theoretical, and ethical arguments strongly support the use of a global value."); William Pizer, Matthew Adler, Joseph Aldy, David Anthoff, Maureen Cropper, Kenneth Gillingham, Michael Greenstone, Brian Murray, Richard Newell, Richard Richels, Arden Rowell, Stephanie Waldhoff, Jonathan Wiener, *Using and Improving the Social Cost of Carbon*, 346 SCIENCE 1189, 1190 (2014) ("the moral, ethical, and security issues . . . [and the] strategic foreign relations question . . . are compelling reasons to focus on a global SCC [social cost of carbon]."); Robert Kopp & Bryan Mignone, *Circumspection, Reciprocity, and Optimal Carbon Prices*, 120 CLIMATIC CHANGE 831, 831 (2013) ("the domestically optimal price approaches the global cooperative optimum linearly with increasing circumspection and reciprocity"); Celine Guivarch, Aurelie Mejean, Antonin Pottier, Marc Fleurbaey, *Letter: Social Cost of Carbon: Global Duty*, 351 SCIENCE 1160 (2016).

to a parade of horribles that would radically impoverish the United States for the sake of foreign welfare.[13] Joined by five other policy experts,[14] they published a letter to the editor in *Science*[15] and a column in *Forbes*[16] and submitted a letter to a National Academies of Science committee charged with reviewing the social cost of carbon[17]—all calling for at least an equal emphasis on the domestic-only social cost of carbon. NERA Economic Consulting has picked up on these arguments and applied them as a critique against the global social cost of methane as well.[18]

Even within the federal government there has recently been a potential break from the global focus. Some federal agencies have declined to include the social costs of carbon or methane in their environmental impact statements, perhaps because of global versus domestic concerns. In November 2015, under court order to consider the climate costs of approving new coal mines on federal lands, the U.S. Forest Service prepared an environmental impact statement that applied the social cost of carbon. However, after presenting both global and domestic-only estimates of the climate effects, the Forest Service concluded that "if concerns are limited to potential GHG [greenhouse gas] damages to the U.S. population, the proposed action is acceptable (or neutral). If decisions account for the potential impacts of the proposed action on populations outside the U.S., as represented by the Global boundary stance, then present net value results suggest that no-action might be the preferred alternative."[19] The Forest Service proceeded to propose the actions necessary to authorize the new coal mines, thus suggesting its decision had been based on a domestic-only perspective, rather than the global framework used in virtually every other federal climate regulation since 2010.

This paper responds to these various challenges and defends a global focus for the social costs of carbon and methane. Part One offers background on the social costs of carbon and methane and their use to date by federal agencies. Parts Two, Three, and Four detail the various economic, strategic, ethical, and legal justifications for U.S. agencies to focus on the global value of greenhouse gas emissions. Specifically: Part Two details international reciprocity as a justification; Part Three explains that U.S. and international laws at least allow—and may require—consideration of the global effects of U.S. climate policy, especially in light of strategic goals like reciprocity; and Part Four provides additional policy justifications, including the inevitability of significant "spillover" effects and the U.S. willingness to pay to prevent climate damages occurring outside U.S. borders. The economy, public health, national security, environmental quality, and general social welfare of the United States all stand to benefit tremendously if foreign countries take efficient action on climate change. One prudent strategy to encourage efficient international reciprocity is for the United States to continue taking a global perspective on its own climate actions. In short, to

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[13] Ted Gayer & W. Kip Viscusi, *Determining the Proper Scope of Climate Change Benefits* (Vanderbilt Law and Economics Working Paper 14-20, 2015).

[14] Art Fraas, Randall Lutter, Susan Dudley, John Graham, and Jason Shogren.

[15] Art Fraas et al., *Social Cost of Carbon: Domestic Duty*, 351 Science 569, Feb. 5, 2016; *see also* Susan Dudley & Brian Mannix, *The Social Cost of Carbon*, Engage: the Journal of the Federalist Society Practice Group 14-18 (2014).

[16] Susan Dudley et al., *How Much Will Climate Change Rules Benefit Americans?*, Forbes, Feb. 9, 2016.

[17] Letter to the Nat'l Acad. of Sci., Engineering & Medicine, from Art Fraas et al., "Should the Federal Regulatory Agencies Report Benefits to Americans from Mandated Reductions in Greenhouse Gas Emissions?", Feb. 8, 2016.

[18] Anne E. Smith, Sugandha D. Tuladhar, Scott J. Bloomberg, *Technical Comments on the Social Cost of Methane as used in the Regulatory Impact Analysis for the Proposed Emissions Standards for New and Modified Sources in the Oil and Natural Gas Sector,* NERA (December 3, 2015), http://www.nera.com/content/dam/nera/publications/2015/NERA_TechnicalComments_ProposedMethaneRegs_Dec3_FinalReport.pdf.

[19] USDA, *Rulemaking for Colorado Roadless Areas: Supplemental Draft Environmental Impact Statement* 100 (November 2015), http://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fseprd485194.pdf.

safeguard its own national interests and maximize benefits locally, the United States should continue to think globally.

Part One: Development and Use of the Social Cost Metrics

Carbon dioxide and methane are the two greenhouse gases most responsible for the heat-trapping effects that drive global climate change.[20] The "social cost of carbon" (SCC) is a framework for estimating the monetized, global damages caused by releasing an additional ton of carbon dioxide into the atmosphere. Similarly, the "social cost of methane" (SCM) is a framework for estimating the monetized, global damages caused by releasing an additional ton of methane into the atmosphere. A complete list of such damages would include all economic impacts from climate change: lost agricultural and labor productivity, property losses from sea-level rise, trade and energy supply disruptions, negative public health consequences, ocean acidification, extreme weather events, flooding, wildfires, increased pests and pathogens, water shortages, migration, regional conflicts, and loss of biodiversity and ecosystem services, among others.

This part details the development of the SCC and SCM metrics, the standard rationale for choosing global values, and the use of the metrics in over 80 regulatory analyses and environmental impact statements. (Note that while valuations for additional greenhouse gases, such as nitrous oxide, have also been discussed, they have not yet been fully incorporated into agencies' economic analyses.[21])

History and Development of the Social Cost of Carbon

Through 2007, agencies' regulatory analyses did not typically quantify, let alone monetize, greenhouse gas emissions.[22] For instance, when the Department of Transportation's National Highway Traffic Safety Administration finalized new fuel economy standards for light-duty trucks in 2006, it did not assign a dollar value to the rule's climate benefits. While acknowledging that the rule would significantly reduce carbon dioxide emissions, the agency concluded that too much uncertainty existed to monetize those benefits.[23] The rule was challenged by a group of states and environmental organizations, and in 2007 the U.S. Court of Appeals for the Ninth Circuit held that the agency had arbitrarily "assigned no value to the most significant benefit of more stringent [fuel economy] standards: reduction in carbon emissions."[24] The Court explained that while there was uncertainty in the "range of values, the value of carbon emissions reduction is certainly not zero."[25]

Following that ruling, agencies began to develop their own estimates of the value of carbon reductions, with inconsistent results. Some agencies initially refused to consider anything beyond the domestic climate benefits. For example, in 2008 the Department of Energy began estimating the

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[20] IPCC, *Summary for Policymakers* 14 (2013), https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_SPM_FINAL.pdf.

[21] Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles—Phase 2, 80 Fed. Reg. 40,137, 40,458 (Sept. 11, 2015) (conducting a sensitivity analysis that incorporated a social cost of nitrous oxide, both directly valued and indirectly valued through nitrous oxide's relative global warming potential; however, these numbers were used in the sensitivity analysis only, not the main analysis).

[22] U.S. Gov't Accountability Office, GAO-14-663, Regulatory Impact Analysis: Development of Social Cost of Carbon Estimates 5 n.11 (2014) ("According to EPA officials, other regulations at the time [in 2006] did not typically quantify changes in carbon emissions.").

[23] Average Fuel Economy Standards for Light Trucks Model Years 2008-2011, 71 Fed. Reg. 17,566 (Apr. 6, 2006).

[24] *Center for Biological Diversity v. NHTSA*, 508 F.3d 508, 532 (9th Cir. 2007); the Ninth Circuit withdrew and replaced its 2007 opinion with a new one in 2008, with some changes to other parts of the ruling, but the opinion remained effectively unchanged on the issue of valuing carbon emissions. *CBD v. NHTSA,* 538 F.3d 1172, 1199 (9th Cir. 2008) ("Yet, NHTSA assigned no value to the most significant benefit . . . .").

[25] *CBD*, 508 F.3d at 533.

value of carbon reductions at $0-$20 per ton in its energy efficiency standards. This range reflected domestic-only effects. The agency concluded, without much explanation, that "the value should be restricted to a representation of those costs/benefits likely to be experienced in the United States," simply because the agency takes a domestic-only focus on "most of the estimates of costs and benefits" in its rules.[26] Similarly, in a 2008 proposed rule on passenger car fuel economy, the National Highway Traffic Safety Administration estimated $7 as the domestic benefits of reducing a ton of carbon dioxide, derived as the midpoint of a range of $0-$14. The agency found that, while the global benefits were unlikely to be zero, it was still possible that U.S. benefits would be zero or even negative; $14 was an estimate of worldwide benefits and, according to the agency, therefore a maximum upper-bound estimate of U.S. benefits.[27]

However, by 2009, both the National Highway Traffic Safety Administration and the Department of Energy were considering global as well as domestic values. When the National Highway Traffic Safety Administration finalized its passenger car fuel economy standards in 2009, the agency noted that "no [public] commenters supported NHTSA's use of $0/ton as the lower bound estimate."[28] Instead, the agency used both a domestic estimate of $2 per ton and a global estimate of $33 per ton (along with a sensitivity analysis at $80 per ton). The agency concluded that it alone could not resolve the global versus domestic argument, and called for coordination among federal agencies and "leadership from the Administration."[29] The agency noted that the current state of "negotiations regarding effective international cooperation" could affect this decision; at the time, the agency felt such considerations necessitated at least some domestic-only estimate, on the assumption that ambitious "unilateral" action by a single country would not be matched by other countries.[30] Later that year, the Department of Energy copied the National Highway Traffic Safety Administration's approach and "concluded it was appropriate to consider the global benefits of reducing [carbon dioxide] emissions, as well as the domestic benefits."[31]

Beginning in its first advanced notice of proposed regulation of greenhouse gas emissions in 2008 (under the George W. Bush administration), the Environmental Protection Agency (EPA) considered both global values ($48 or $60 per ton of carbon dioxide, depending on discount rate) and domestic values ($1 or $4 per ton, depending on discount rate).[32] EPA explained it was appropriate to consider a global value because "economic principles suggest that the full costs to society of emissions should be considered in order to identify the policy that maximizes the net

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[26] Energy Conservation Program for Commercial and Industrial Equipment: Packaged Terminal Air Conditioner and Packaged Terminal Heat Pump Energy Conservation Standards, 73 Fed. Reg. 58,772, 58,813 & n.22 (Oct. 7, 2008); *see also* Energy Conservation Program for Commercial and Industrial Equipment: Energy Conservation Standards for Commercial Ice-Cream Freezers; Self-Contained Commercial Refrigerators, Commercial Freezers, and Commercial Refrigerator-Freezers Without Doors; and Remote Condensing Commercial Refrigerators, Commercial Freezers, and Commercial Refrigerator-Freezers, 74 Fed. Reg. 1092 (Jan. 9, 2009); Energy Conservation Program: Energy Conservation Standards for Certain Consumer Products (Dishwashers, Dehumidifiers, Microwave Ovens, and Electric and Gas Kitchen Ranges and Ovens) and for Certain Commercial and Industrial Equipment (Commercial Clothes Washers), 74 Fed. Reg. 16,040 (Apr. 8, 2009).

[27] Average Fuel Economy Standards, Passenger Cars and Light Trucks; Model Years 2011-2015, 73 Fed. Reg. 24,352, 24,414 (May 2, 2008).

[28] Average Fuel Economy Standards Passenger Cars and Light Trucks Model Year 2011, 74 Fed. Reg. 14,196, 14,341 (Mar. 30, 2009). Nor did any commenters support $14 as the upper-bound estimate.

[29] *Id.* at 14,349.

[30] *Id.*

[31] Energy Conservation Program: Energy Conservation Standards and Test Procedures for General Service Fluorescent Lamps and Incandescent Reflector Lamps, 74 Fed. Reg. 34,080, 34,163 (July 14, 2009); *see also* Energy Conservation Program for Certain Industrial Equipment: Energy Conservation Standards and Test Procedures for Commercial Heating, Air-Conditioning, and Water-Heating Equipment, 74 Fed. Reg. 36,312, 36,343 (July 22, 2009).

[32] Regulating Greenhouse Gas Emissions Under the Clean Air Act, 73 Fed. Reg. 44,354, 44,446 (July 30, 2008).

benefits to society, i.e., achieves an efficient outcome." The agency further explained that a global estimate better captured the fact that U.S. citizens value international impacts, due to tourism and other concerns; that the United States itself has international interests, such as national security and economic disruptions in other countries that could affect the U.S. economy; and that "domestic mitigation decisions [may] affect the level of mitigation and emissions changes in general in other countries (i.e., the benefits realized in the U.S. will depend on emissions changes in the U.S. and internationally)."[33] EPA continued this approach in its 2009 proposed renewable fuel standards, only with different estimates: global estimates (ranging from -$4 to $159 per ton) and domestic estimates (ranging from $0 to $16 per ton).[34]

By 2009, the need to harmonize the divergent estimates and approaches across federal agencies was apparent. The Obama White House's Council of Economic Advisers and Office of Management and Budget convened an interagency working group to calculate a consistent and transparent range of SCC values to use in setting and evaluating all U.S. climate regulations. With input from the Environmental Protection Agency; the Departments of Agriculture, Commerce, Energy, Transportation, and Treasury; and the White House's Office of Information and Regulatory Affairs, Council on Environmental Quality, National Economic Council, Office of Energy and Climate Change, and Office of Science and Technology Policy, the interagency group finalized its first SCC estimates in 2010 (preliminary estimates had been released in 2009), followed by an update in 2013 to use the newest versions of the underlying methodological tools, and a slight update again in 2015.[35]

Because of how carbon dioxide accumulates in the atmosphere over time and how climate damages escalate as temperature rises, a ton of carbon dioxide emitted next year is marginally more damaging than one emitted today, and so the SCC estimates rise over time. The interagency group calculates a range of four estimates, largely based on different discount rate assumptions.[36] Focusing on the central of the four estimates (corresponding to a 3% discount rate) and adjusting the calculations for inflation, the interagency values for the marginal global benefits of mitigating an additional ton of carbon dioxide are:[37]

Chart 1: Global SCC by Year of Emission

Year of Emission:	2010	2015	2020	2025	2030	2035	2040	2045	2050
Global SCC (2016$):	$36	$43	$49	$53	$59	$64	$70	$74	$80

These estimates reflect much of the latest, peer-reviewed scientific and economic literature. Nevertheless, experts widely acknowledge that these SCC numbers are almost certainly underestimates of true global damages—perhaps severe underestimates.[38] Using different discount rates; selecting different models; applying different treatments to uncertainty, climate sensitivity,

[33] *Id.* at 44,415; *accord.* Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program, 74 Fed. Reg. 24,094, 25,096 (May 26, 2009).

[34] Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program, 74 Fed. Reg. 24,904, 25,094 (May 26, 2009).

[35] *See* 2010 TSD, *supra* note 4; INTERAGENCY WORKING GROUP ON THE SOCIAL COST OF CARBON, TECHNICAL SUPPORT DOCUMENT: TECHNICAL UPDATE OF THE SOCIAL COST OF CARBON FOR REGULATORY IMPACT ANALYSIS UNDER EXECUTIVE ORDER 12,866 (2013) [hereinafter "2013 TSD"]; INTERAGENCY WORKING GROUP ON THE SOCIAL COST OF CARBON, TECHNICAL UPDATE OF THE SOCIAL COST OF CARBON FOR REGULATORY IMPACT ANALYSIS UNDER EXECUTIVE ORDER 12,866 (2015) [hereinafter "2015 TSD"].

[36] Discount rates reflect the fact that a dollar today is worth more than a dollar tomorrow, and translate a stream of future costs and benefits into their net present value.

[37] Estimates from the 2015 TSD, *supra* note 35, have been adjusted for inflation to 2016$.

[38] *See* Richard L. Revesz, Peter H. Howard, Kenneth Arrow, Lawrence H. Goulder, Robert E. Kopp, Michael A. Livermore, Michael Oppenheimer & Thomas Sterner, *Global Warming: Improve Economic Models of Climate Change*, 508 NATURE 173 (2014).

and the potential for catastrophic damages; and making other reasonable assumptions could yield very different, and much larger, SCC estimates.[39] For example, a recent report found current SCC estimates omit or poorly quantify damages to the following sectors:

> agriculture, forestry, and fisheries (including pests, pathogens, and weeds, erosion, fires, and ocean acidification); ecosystem services (including biodiversity and habitat loss); health impacts (including Lyme disease and respiratory illness from increased ozone pollution, pollen, and wildfire smoke); inter-regional damages (including migration of human and economic capital); inter-sector damages (including the combined surge effects of stronger storms and rising sea levels); exacerbation of existing non-climate stresses (including the combined effect of the over pumping of groundwater and climate-driven reductions in regional water supplies); socially contingent damages (including increases in violence and other social conflict); decreasing growth rates (including decreases in labor productivity and increases in capital depreciation); weather variability (including increased drought and inland flooding); and catastrophic impacts (including unknown unknowns on the scale of the rapid melting of Arctic permafrost or ice sheets).[40]

Though currently still incomplete, the SCC methodology aspires to reflect the full global costs of any additional ton of carbon dioxide released from any source anywhere in the world—or, conversely, the full global benefits of any avoided emissions. Citing both the global impacts of climate change and the coordinated global action needed to mitigate climate change, the interagency working group concluded that calculating the full global effects of U.S. emissions (as opposed to only domestic effects) is the most justified and preferred approach for measuring the benefits of U.S. climate regulations, and is consistent with legal obligations.[41]

The interagency working group did calculate a domestic estimate. Using the results of one economic model as well as the U.S. share of global GDP, the group generated an "approximate, provisional, and highly speculative" range of 7-23% of the global SCC as an estimate of the purely direct climate effects to the United States.[42] Yet, as the interagency group acknowledged—and as discussed more thoroughly in Part IV of this article—this range is almost certainly an underestimate, because it ignores significant, indirect costs to trade, human health, and security likely to "spill over" to the United States as other regions experience climate change damages.[43] The global estimate remains the preferred metric of both the interagency working group and federal agencies.

Development of the Social Cost of Methane

Carbon dioxide is the most common greenhouse gas emitted by human activity, but it is not the most potent greenhouse gas per unit of mass. Adjusting for the comparative potency of various pollutants (also called their "global warming potentials"), the SCC can be roughly applied to calculate damages from "carbon dioxide-equivalent" amounts of other greenhouse gases besides

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[39] *Id.*; *see also* Joint Comments from Institute for Policy Integrity et al., to Office of Information and Regulatory Affairs, on the Technical Update of the Social Cost of Carbon, OMB-2013-0007-0085, Feb. 26, 2014.

[40] Peter Howard, *Omitted Damages: What's Missing from the Social Cost of Carbon* 5 (Cost of Carbon Project Report, 2014), http://costofcarbon.org/.

[41] See 2010 TSD, *supra* note 4, at 10-11; 2013 TSD, *supra* note 35, at 14-15

[42] 2010 TSD, *supra* note 4, at 11.

[43] Indeed, the integrated assessment models used to develop the global SCC estimates largely ignore inter-regional costs entirely. *See* Howard, *supra* note 40. Though some positive spillover effects are also possible, such as technology spillovers that reduce the cost of mitigation or adaptation, *see* S. Rao et al., *Importance of Technological Change and Spillovers in Long-Term Climate Policy*, 27 ENERGY J. 123-39 (2006), overall spillovers likely mean that the U.S. share of the global SCC is underestimated, *see* Jody Freeman & Andrew Guzman, *Climate Change and U.S. Interests*, 109 COLUMBIA L. REV. 1531 (2009).

carbon dioxide, such as methane (which is about 28-87 times more potent than carbon dioxide per ton[44]). On a few past occasions, both EPA and the National Highway Traffic Safety Administration used global warming potential-adjusted estimates of methane's costs and benefits.[45] Economic experts, however, argue that the full social costs of specific, non-carbon dioxide gases should be assessed directly through separate models, which would more accurately account for varying atmospheric life spans, among other differences.[46]

In 2015, EPA began using a social cost of methane estimate (currently valued around $1200 per ton), first in sensitivity analyses,[47] and then in its primary economic analyses.[48] EPA's estimate derived from an analysis published in 2014 by A.L. Marten et al. in the peer-reviewed journal *Climate Policy*. Marten et al. based their analysis on the same techniques developed by the interagency working group for the social cost of carbon. Specifically, Marten et al. used the same three integrated assessment models, five socioeconomic-emissions scenarios, equilibrium climate sensitivity distribution, three constant discount rates, and aggregation approach that were selected for the social cost of carbon through the interagency working group's transparent, consensus-driven, and publically reviewed process. Therefore, like the SCC, Marten et al.'s SCM is a global valuation. EPA also conducted its own internal and peer reviews of the Marten et al. approaches before using them in analyses.[49]

The Interior Department's Bureau of Land Management was the first agency to copy EPA's approach to the social cost of methane,[50] followed by the Department of Transportation in a

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[44] *See* Intergovernmental Panel on Climate Change, *Climate Change 2013: The Physical Science Basis*, tbl. 8.7 (2013) (part of the 5th Assessment Report). Methane's global warming potential relative to carbon dioxide depends principally on the timescale of analysis (methane has a shorter lifespan compared to carbon dioxide and so is relatively more potent over a twenty-year horizon versus a one hundred-year horizon), as well as on the source of methane (fossil methane has a higher potency than agricultural methane) and whether climate-carbon feedback is included.

[45] NAT'L HIGHWAY TRAFFIC SAFETY ADMIN., FINAL ENVIRONMENTAL IMPACT STATEMENT FOR FUEL EFFICIENCY STANDARDS FOR PASSENGER VEHICLES (July 2012), http://www.nhtsa.gov/staticfiles/rulemaking/pdf/cafe/FINAL_EIS.pdf at 9-77; *see also* NAT'L HIGHWAY TRAFFIC SAFETY ADMIN., PHASE 2 FUEL EFFICIENCY STANDARDS FOR MEDIUM- AND HEAVY-DUTY ENGINES AND VEHICLES: DRAFT EIS (June 2015), http://ntl.bts.gov/lib/55000/55200/55224/Draft_Environmental_Impact_Statement_for_Phase_2_MDHD_Fuel_Efficiency_Standards.pdf. *See also* Envtl. Prot. Agency, 2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards, 77 Fed. Reg. 62,624, 62,929, 63,088 (Oct. 15, 2012) ("The methane co-benefits were presented for illustrative purposes and therefore not included in the total benefit estimate for the rulemaking.").

[46] *See* Disa Thureson & Chris Hope, *Is Weitzman Right? The Social Cost of Greenhouse Gases in an IAM World* 21 (Örebro University-Swedish Business School Working Paper 3/2012).

[47] Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles: Phase 2, 80 Fed. Reg. 40,138, tbl. IX-19 (July 13, 2015). The SCM estimates are higher but of a roughly similar magnitude as global warming potential adjusted-estimates for methane. *See id*. at 40,462 ("[C]ompared to the use of directly modeled estimates, the GWP-based approximation approach underestimates the climate benefits of the CH_4 emission reductions by 12 percent to 52 percent."). Importantly, unlike the global warming potential-adjusted estimates, the direct estimation of the SCM accounts for the quicker time horizon of methane's effects compared to carbon dioxide, including the indirect effects of methane on radiative forcing, and so reflect the complex, nonlinear linkages along the pathway from methane emissions to monetized damages.

[48] Emission Guidelines, Compliance Times, and Standards of Performance for Municipal Solid Waste Landfills, 80 Fed. Reg. 52,100 (proposed Aug. 27, 2015); Standards of Performance for Municipal Solid Waste Landfills, 80 Fed. Reg. 52,162 (Aug. 27, 2015); Oil and Natural Gas Sector: Emission Standards for New and Modified Sources, 80 Fed. Reg. 56,593 (Sept. 18, 2015).

[49] EPA, *Valuing Methane Emissions Changes in Regulatory Benefit-Cost Analysis, Peer Review Charge Questions, and Responses* (2015), http://www3.epa.gov/climatechange/pdfs/social%20cost%20methane%20white%20paper%20application%20and%20peer%20review.pdf.

[50] Waste Prevention, Production Subject to Royalties, and Resource Conservation, 81 Fed. Reg. 6615, 6624 (Feb. 8, 2016).

regulatory impact analysis.[51] Though the interagency working group on the social cost of carbon has long expressed its "hopes to develop methods to value these other greenhouse gases,"[52] it has not yet taken up the social cost of methane.

Use of the Metrics in Regulatory and Related Proceedings

Though the SCC was first developed for use in regulatory impact analyses,[53] the methodology used by the interagency working group was in no way unique to the regulatory process, and the estimates are applicable to other decision-making contexts. Notably, the Council on Environmental Quality approved of using the SCC metric in environmental impact statements prepared for a variety of land and natural resource use planning and other decisions under the National Environmental Policy Act (NEPA).[54] In fact, applying both the SCC and SCM metrics in environmental impact statements may be essential to fulfilling NEPA's goals of transparent and informed decision-making.[55] Several agencies have used the SCC and SCM in their environmental impact statements, in addition to their regulatory impact analyses.

Catalogued more fully in Appendix A to this paper, at least 83 separate regulatory or planning proceedings conducted by six different federal agencies have used the SCC or SCM in their analyses.

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51 Dept. of Transportation, Preliminary Regulatory Impact Analysis on Safety of Gas Transmission and Gathering Pipelines 62 (2016).

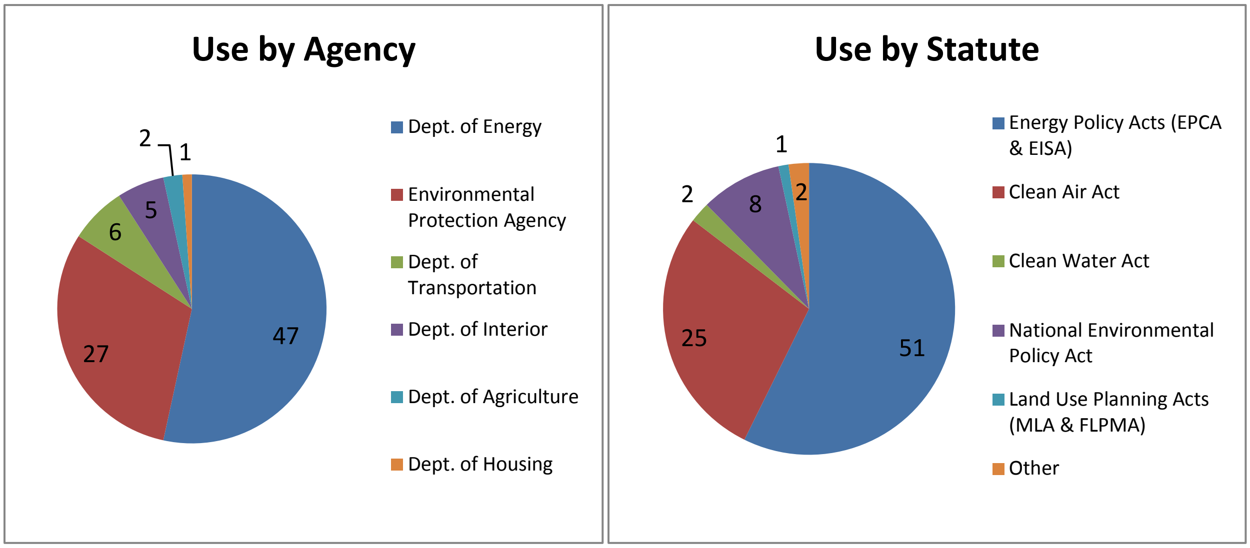
52 2010 TSD, *supra* note 4.

53 INTERAGENCY WORKING GROUP, TECHNICAL SUPPORT DOCUMENT: SOCIAL COST OF CARBON *FOR REGULATORY IMPACT ANALYSIS—UNDER EXECUTIVE ORDER 12866* (2010) (emphasis to title added).

54 CEQ, *Final Guidance for Federal Departments and Agencies on Consideration of Greenhouse Gas Emissions and the Effects of Climate Change in National Environmental Policy Act Reviews*, 33 n.86 (2016) ("Developed through an interagency process committed to ensuring that the SCC estimates reflect the best available science and methodologies and used to assess the social benefits of reducing carbon dioxide emissions across alternatives in rulemakings, it provides a harmonized, interagency metric that can give decision makers and the public useful information for their NEPA review.").

55 *See* Joint Comments from Institute for Policy Integrity et al., to U.S. Forest Service, on the Use of the Social Costs of Carbon and Methane in the Supplemental Draft Environmental Impact Statement for the Colorado Roadless Rule, Jan. 15, 2016, at 4-6 (explaining how monetization best promotes NEPA's goals of presenting information to facilitate comparison across alternatives).

Chart 2: SCC & SCM in Regulatory Proceedings by Agency & Statute (2009-July 2016)[56]



The Department of Energy is responsible for over half of those usages, followed by EPA with about a third. Notably, the Department of Energy always includes domestic calculations of the SCC in its regulatory impact analyses, even while emphasizing the global value. For example, a recent analysis of the agency's proposed energy efficiency standards for housing includes estimates of both "global net present value of reduced emissions of CO_2" (table 14.4) and "domestic net present value of reduced emissions of CO_2" (table 14.5).[57] Other agencies, including the EPA, have also at times included in their regulatory proposals a discussion or calculation of the domestic SCC. For example, EPA's 2011 proposed air quality performance standards for the oil and gas sector first estimated the global value of the rule's climate co-benefits, but also discussed the "provisional and highly speculative" domestic range developed by the interagency working group.[58] Nevertheless, by and large federal agencies have focused predominantly if not exclusively on the global SCC and SCM estimates (see Appendix A). As this paper demonstrates, this focus on the global metrics is well justified by legal obligations and economic principles.

Part Two: Strategic Use of the Global SCC Can Foster International Cooperation Benefiting the United States

The world's climate is a single interconnected system, and the United States benefits greatly when foreign countries consider the global externalities of their greenhouse gas pollution and cut emissions accordingly. Game theory predicts that one viable strategy for the United States to encourage other countries to think globally in setting their climate policies is for the United States to do the same, in a tit-for-tat, lead-by-example, or coalition-building dynamic. In fact, most other countries with climate policies already use a global social cost of carbon or set their carbon taxes or allowances at prices above their domestic-only costs. President Obama's administration has

[56] Note that numbers in graphs may add up to more than 83 rulemakings, because some rulemakings involve multiple agencies and multiple statutes.

[57] Dept. of Energy, Technical Support Document for Notice of Proposed Rulemaking Establishing Energy Conservation Standards for Manufactured Housing (2016).

[58] Oil and Natural Gas Sector: New Source Performance Standards and National Emissions Standards for Hazardous Air Pollutants Reviews, 76 Fed. Reg. 52,737, 52,792 (proposed Aug. 23, 2011).

explicitly chosen to adopt a global social cost of carbon to foster continued reciprocity in other countries' climate policies. Charged by the U.S. Constitution with managing foreign affairs and coordinating executive branch activities, President Obama deserves political and judicial deference on his choice to calculate the global benefits of U.S. climate regulations.

The Economics of Avoiding a Tragedy of the Global Climate Commons

The Earth's climate is a shared global resource.[59] All countries may enjoy the benefits of stable atmospheric concentrations, temperatures, and weather patterns; yet any one country's use or depletion of Earth's climate stability—specifically, by emitting greenhouse gas pollution—can impose great harms on the polluting country as well as on the rest of the world.[60] Greenhouse gases like carbon dioxide and methane do not stay within geographic borders or dissipate quickly. Over life spans stretching tens, hundreds, or even thousands of years, greenhouse gases become well mixed through the planet's atmosphere and so affect climate worldwide. As a result, each ton of carbon pollution emitted by the United States, for example, not only creates domestic harms, but also imposes additional and large damages on the rest of the world. Conversely, each ton of greenhouse gases abated in any other country will benefit the United States along with the rest of the world.

To avoid a global "tragedy of the commons" and an economically inefficient degradation of the world's climate resources, all countries should set policy according to the global damages caused by their emissions. If all countries instead set their greenhouse gas emissions levels based on only their domestic costs and benefits, ignoring the large global externalities, the collective result would be substantially sub-optimal climate protections and significantly increased risks of severe harms to all nations, including to the United States. "[E]ach pursuing [only its] own best interest . . . in a commons brings ruin to all."[61] Only by accounting for the full damages of their greenhouse gas pollution will countries collectively select the efficient level of worldwide emissions reductions needed to secure the planet's common climate resources.[62]

Foreign Countries' Existing Policies and Pledges Promise Carbon Reductions Worth Trillions to the United States

As detailed in the authors' recent report published by the Institute for Policy Integrity,[63] the United States has already benefited from foreign climate action and will continue to benefit tremendously if foreign countries fulfill their existing pledges for future action. Based on a dataset from *Climate Action Tracker*,[64] our previous report calculates that existing foreign policies (like the European Union's Emissions Trading Scheme), during the last five years alone, have likely reduced up to 24 billion metric tons of carbon dioxide-equivalent emissions, thereby directly benefiting the United

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[59] The Earth's oceans (at risk of acidification from carbon pollution) are also global common resources. Common resources are goods that are non-excludable but rivalrous. To the extent that the social cost of carbon does not fully reflect damages from ocean acidification, this report does not capture the additional benefits to the United States as foreign actions to address climate change simultaneously mitigate the acidification of the world's shared oceans.

[60] A handful of geographic regions may experience short-term benefits from climate change, such as temporary agricultural gains in colder regions, but even in those areas, long-term, catastrophic scenarios would bring significant harms.

[61] Garrett Hardin, *The Tragedy of the Commons*, 162 Science 1243 (1968).

[62] *See, e.g.*, Matthew Kotchen, *Which Social Cost of Carbon? A Theoretical Perspective* 7, NBER Working Paper, May 2016 ("The result is intuitive: the marginal benefit of emissions is equated across all countries and equal to the sum of the marginal damages of emissions. . . .That is, all countries must internalize the GSCC [global SCC], which then defines a unique level of Pareto optimal emissions for each country.").

[63] Peter Howard & Jason Schwartz, *Foreign Action, Domestic Windfall* (2015).

[64] CLIMATE ACTION TRACKER, http://climateactiontracker.org.

States by at least $60 to $231 billion. Over the next fifteen years, direct U.S. benefits from global climate policies already in effect could reach over $2 trillion.

Our previous work also forecasted the future emissions reductions from pledges and commitments made by foreign countries, and estimated the direct U.S. share of those benefits. In advance of the December 2015 Paris meeting of the United Nations Framework Convention on Climate Change, member nations, including many countries most responsible for greenhouse gas emissions, announced numerical pledges to meet their share of necessary emissions reductions. One hundred eighty-seven countries have submitted plans, including China, India, Brazil, Australia, Japan, Europe, and the United States;[65] submissions cover countries responsible for over 95% of global emissions.[66] Though these pledged reductions are not fully enforceable (nor may they be sufficient on their own to completely solve the threats to global climate), they help put in perspective what is at stake in an international agreement to address climate change. Based on Climate Action Tracker data, we calculated that if these foreign reduction pledges are achieved, over the years 2015-2030 the United States could gain direct benefits of at least $54-$544 billion.[67] Multiplied over many decades of emissions reductions, direct U.S. benefits from existing and pledged foreign actions to combat climate change could easily reach into the trillions of dollars.

While there is much uncertainty in all these estimates, it is worth remembering that two key figures—the social cost of carbon and the U.S. share—are based on conservative methodologies and are very likely to underestimate actual benefits to the United States of foreign action of climate change. For example, not only does the social cost of carbon framework currently omit many significant, un-quantified climate effects and inter-regional spillovers, but it also does not factor in a number of important ancillary benefits to U.S. health and welfare, including the reduction of co-pollutants like mercury that also drift into the United States from foreign countries.

In short, the United States has much at stake in securing efficient levels of foreign action on climate change. Game theory predicts that one viable strategy to foster reciprocity is for the United States to consider the global effects of its policies as well.

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[65] *INDCs as Communicated by Parties*, UNFCCC, http://www4.unfccc.int/submissions/indc/Submission%20Pages/submissions.aspx (last visited Oct. 6, 2015).

[66] *Tracking INDCs*, Climate Action Tracker, http://climateactiontracker.org/indcs.html (last visited June 1, 2016).

[67] These estimates are consistent with estimates from employing alternate methodologies and datasets. For example, according to estimates used by the OECD and compared to a business-as-usual scenario, pledges from the 2009 Copenhagen Accords could result in reductions in the year 2020 of between 2.3 billion metric tons of carbon dioxide-equivalents (for the least ambitious end of the pledges) to 9 billion metric tons (in the most optimistic scenario). Int'l Transp. Forum, OECD, *Reducing Transport Greenhouse Gas Emissions: Trends and Data* 25 (2010); *see also* Joeri Rogelj et al., *Analysis of the Copenhagen Accord Pledges and Its Global Climatic Impacts—A Snapshot of Dissonant Ambitions*, 5 ENVTL. RESEARCH LETTERS 1, 5-6 (2010); Joeri Rogelj et al., *Copenhagen Accord Pledges are Paltry*, 464 NATURE 1126 (2010); M.G.J. den Elzen et al., *Pledges and Actions: A Scenario Analysis of Mitigation Costs and Carbon Market Impacts for Developed and Developing Countries* (Netherlands Research Programme on Scientific Assessment and Policy Analysis for Climate Change WAB-500102-032, 2009). The U.S. share of these pledges is equal to about a 1.1 billion metric ton reduction in the year 2020 on the low-ambition end, and 1.3 billion on the high-ambition end. *See id.* at 35-36, 38 tbls. 2.1 & 2.2 (citing a business-as-usual baseline for the United States in 2020—as developed for analysis of the Waxman-Markey legislative proposal—at 7.39 billion tons, and listing low- and high-ambition pledges for the United States as 0% to 3% below 1990 levels) *compare* U.S. EPA, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2012* at ES-7 (2014) (setting the 1990 baseline at 6.23 billion tons). That means that under Copenhagen, foreign countries alone pledged between a 1.2 billion metric ton and 7.7 billion metric ton reduction in the year 2020. If all Copenhagen pledges were achieved (including U.S. pledges), total global benefits will be between $110 billion and $432 billion from worldwide carbon reductions just in the year 2020. The direct U.S. share of purely foreign emissions reductions would be at least between $4 billion and $85 billion, again just in the year 2020 alone. The magnitude of the estimates from this alternate methodology is consistent with our previous report's preferred methodology based on Climate Action Tracker data, and so supports this report's overall conclusions.

Game Theory and International Reciprocity

Economic models of strategic behavior and real-world experiments suggest the United States may be able to stimulate cooperative international action by: leading by example; building trust, a reputation for equity, and a critical mass of initial actors; and promoting a tit-for-tat dynamic of mutually beneficial reciprocity between nations.

Mathematical models of strategic behavior can help predict how economic agents and governments will act when their welfare depends on the decisions of others.[68] Such methods have been used extensively to model informal and formal negotiations among countries over climate change. One recent article identified 25 distinct basic structures that could apply to climate change negotiations, including well-known interactions like "the prisoner's dilemma" and "chicken."[69] Precise predictions about the likely results of climate negotiations are highly dependent on a number of key assumptions, such as forecasting which negotiation structure applies, how many nations will negotiate, whether negotiators have complete information and will behave purely rationally, how much time or how many rounds of negotiation will occur, which decision pathways will be open to policymakers, and how negotiators will perceive the payoffs of various outcomes. In short, there is no clear consensus in the economic literature about the most likely result of climate negotiations, or indeed even about which structure best models the negotiations.

Nevertheless, under a number of scenarios and assumptions, a strategy of leading by example with unilateral action could successfully induce international cooperation on climate change. For instance, in the "coordination" strategic model, all parties realize mutual welfare gains if they all choose mutually consistent strategies. A classic version is when two drivers meet on a narrow road: only when both swerve in the same direction (e.g., both to their own right) can they avoid collision. In a coordination model of climate negotiations, unilateral abatement by one major emitting country or bloc of countries can increase the incentive for other governments to also abate. In this strategy, good faith signals can build credibility and trust with other nations, which can increase those countries' perceptions of whether a broadly cooperative outcome is probable, which in turn actually induces cooperation. Trust-building exercises and signals can be especially useful when players are risk adverse.[70] Calculating the global costs of U.S. emissions could provide a good faith signal that the United States cares about the welfare of other countries, and finalizing U.S. regulations that utilize the global SCC value can further increase the incentives for other governments to follow suit.

In a number of additional negotiation structures, a "tit-for-tat" strategy can prove successful in inducing cooperation, once the model reflects more realistic assumptions allowing repeat, dynamic negotiations over time. A "tit-for-tat" strategy entails matching whatever action your fellow negotiators/players took most recently: if your adversary cooperated, then you cooperate; if your adversary defected, you punish the defection by also defecting.[71] For instance, when the "prisoner's dilemma" model assumes that two decision-makers will each have only a single opportunity to choose a strategy, both actors unfortunately perceive that defection is their best personal option, which ultimately leaves both worse off. The classic version involves two criminal co-conspirators being questioned by police in separate rooms, where each end up implicating the other since their physical separation prevents them from collaboratively making a mutually beneficial agreement to

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[68] This discipline is known as "game theory."

[69] Stephen J. DeCanio & Anders Fremstad, *Game Theory and Climate Diplomacy*, 85 ECOLOGICAL ECONOMICS 177 (2013).

[70] *See id.*; *see also* Richard B. Stewart, Michael Oppenheimer & Bryce Rudyk, *Building Blocks for Global Climate Protection,* 32 STANFORD ENVTL. L.J. 341, 346 (2013).

[71] Kotchen, *supra* note 62, at 18, refers more generally to strategies with punishment schemes and explains that, in the dynamic setting, a greater set of potential solutions exists than the sub-game perfect Nash equilibrium.

both stay silent. Yet when the model is extended dynamically over multiple rounds of decision-making instead, a tit-for-tat strategy allows the actors to punish in future rounds those who fail to cooperate.[72] Experiments suggest that tit-for-tat is a very robust strategy in most negotiating environments.[73]

By matching the global SCC values already in use in some other countries, the United States could be seen as continuing a tit-for-tat dynamic designed to reinforce those countries' existing commitments and to encourage reciprocal action from additional countries. In fact, for the United States to now depart from this collaborative dynamic by reverting to a domestic-only SCC estimate could undermine long-term U.S. interests in future climate negotiations and could jeopardize emissions reductions underway in other countries, which are already benefiting the United States. A domestic-only SCC value could be construed as a signal that the United States does not recognize or care about the effects of its policy choices on other countries, and could signal that it would be acceptable for other countries to ignore the harms they cause the United States. Further, a sudden about-face could undermine the United States' credibility in negotiations. If the United States sees the climate negotiations as a repeated dynamic of tit-for-tat, using the global SCC value is a rational strategy.

A related and potentially successful strategy in climate negotiations is to build small, stable coalitions of key actors. Coalitions can then lead by example through joint initial commitments to act. Coalitions also foster communication and trust among nations, and they allow member nations to learn by doing and to apply those lessons in future negotiations with other countries.[74] Moreover, a coalition of major emitters will build critical mass that may tip the scales toward a global agreement. Some evidence exists that the small coalition strategy is more likely to be successful in climate negotiations if nations' initial commitments are close to their actual optimal emissions reductions and are not mere half-measures.[75] By joining other nations in using global SCC values and adopting meaningful greenhouse gas limitations, the United States may be employing a coalition-building strategy. Thus, the United States need not hold out for the promise of immediately inducing complete reciprocity among all countries before it is justified in using the global SCC; using the global SCC now can help build a small coalition of key actors, which will both benefit the United States in the short term and help build toward global agreement. (Similarly, after factoring in reasonable predictions on how climate change damages will unfold in the future, even partial reciprocity can justify using a global SCC estimate.[76])

Applying assumptions more grounded in real-world behavior also makes cooperation more likely. For example, in real negotiations among repeat players and among highly-skilled negotiators, negotiators may have even greater foresight with respect to counter-moves than classic models of

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[72] *See* Peter J. Wood, *Climate Change and Game Theory*, 1219 ANNALS N.Y. ACAD. SCI. 153 (2011); Robert Axelrod, THE EVOLUTION OF COOPERATION 10-11 (1984) (on repeated prisoner's dilemma games).

[73] *See* Axelrod, *supra* note 72.

[74] *See* Marco Grasso & Timmons Roberts, *A Compromise to Break the Climate Impasse*, 4 NATURE CLIMATE CHANGE 543 (2014); E. Ostrom, *A Polycentric Approach for Coping with Climate Change*, 15 ANNALS ECON. & FINANCE 97 (2014); Stewart, Oppenheimer & Rudyk, *supra* note 70; M. Finus, *Game Theoretic Research on the Design of International Environmental Agreements: Insights, Critical Remarks, and Future Challenges*, 2 INT'L REV. ENVTL. & RESOURCE ECON. 29 (2008).

[75] *See* Rory Smead et al., *A Bargaining Game Analysis of International Climate Negotiations*, 4 NATURE CLIMATE CHANGE 442 (2014) ("If too many players are too far away from their proportional share of reductions, negotiations are likely to break down. Any mechanism that encourages initial demands closer to the target values will increase the likelihood of success.").

[76] *See* Kopp & Mignone, *supra* note 12 at 841 ("If marginal benefits are declining, however, increasing reciprocity leads the optimal domestic carbon price to approach the global policy SCC concavely, meaning that even imperfect reciprocity can come close to supporting the global policy SCC. . . . The possibility of greater-than-quadratic climate damages and the expectation of weakening carbon sinks can both give rise to declining marginal damages.").

strategic behavior may predict. One recent article concludes that, applying more realistic assumptions about foresight with respect to counter-moves, every one of the 25 possible basic structures that may describe the climate negotiations has at least one cooperative solution.[77] More specifically, theoretical work by economist Matthew Kotchen demonstrates the rationality of individual nations choosing an SCC equal to—or even greater than—the global SCC, under various conditions like repeat and strategic games, and further shows that "all countries have a strategic SCC greater than their domestic SCC."[78]

Experiments also show that real negotiators balance fairness considerations against pure self-interest. In the classic "ultimatum game" experiment, one player is offered a sum of money to split with another player; only if the second player accepts the split will either get any money. Economic theory would predict that a purely rational first player would offer just one cent to the second player, and a purely rational second player would accept the single penny rather than get nothing. In fact, real first players rarely offer anything less than 30% of the money, and real second players rarely accept any split perceived as unfair. Multiple studies find that, regardless of the amount at stake in the ultimatum game, first players from industrialized countries typically offer around a 50% split, and second players frequently reject anything less than a 20% share.[79] This experiment "provides evidence that an international environmental agreement is more likely to be stable if it is perceived by its parties to be fair."[80] By counting the full global damages of its emissions, the United States may be able to improve its reputation for fairness, building the trust and credibility essential to secure reciprocal actions from other countries.

The United States can choose the global SCC as part of a prudent strategy designed to secure international cooperation in a number of different negotiation scenarios—and high-ranking officials in the Obama Administration seem to have done precisely that.

The Obama Administration Believes Using the Global SCC Can Spur Global Cooperation

In a number of pronouncements, from formal administration documents and plans to public speeches and interviews, White House officials from President Obama on down have declared that the United States will lead international negotiations by example, both by calculating the global costs of its own greenhouse gas emissions and by proposing regulations based in part on the global SCC.

- **President Obama:** "[M]y goal has been to make sure that the United States can genuinely assert leadership in this [climate] issue internationally, that we are considered part of the solution rather than part of the problem. And if we are at the table in that conversation with

[77] Kaveh Madani, *Modeling International Climate Change Negotiations More Responsibly: Can Highly Simplified Game Theory Models Provide Reliable Policy Insights?*, 90 ECOL. ECON. 68 (2013); *see also* Kotchen, supra note 62, ("the assumption of Nash behavior is also quite arbitrary and perhaps more questionable in the context of international climate policy, where some degree reciprocity among countries is clearly at work.").

[78] Kotchen, *supra* note 62, at 1.

[79] *See* Alan G. Sanfey et al., *The Neural Basis of Economic Decision-making in the Ultimatum Game*, 300 SCIENCE 1755 (2003). The ultimatum experiment has been conducted in countries around the world, and though observations of acceptable splits vary by culture, the findings that fairness matters and that unfair splits will frequently be rejected are widespread across cultures and are robust. *See e.g.,* Hessel Oosterbeek et al., *Cultural Differences in Ultimatum Game Experiments: Evidence from a Meta-Analysis*, 7 EXPERIMENTAL ECON. 171 (2004).

[80] Wood, *supra* note 72, at n.18 (citing S. BARRETT, ENVIRONMENT AND STATECRAFT 299–301 (2003)).

some credibility, then it gives us the opportunity to challenge and engage the Chinese and the Indians."[81]

- **Administration-Wide *Climate Action Plan*:** "The Obama Administration is working to build on the actions that it is taking domestically to achieve significant global greenhouse gas emission reductions and enhance climate preparedness through major international initiatives focused on spurring concrete action."[82]
- **Administration-Wide Interagency Working Group on the Social Cost of Carbon:** "Emphasizing the need for a global solution to a global problem, the United States has been actively involved in seeking international agreements to reduce emissions and in encouraging other nations, including emerging major economies, to take significant steps to reduce emissions. When these considerations are taken as a whole, the interagency group concluded that a global measure of the benefits from reducing U.S. emissions is preferable."[83]
- **EPA Administrator Gina McCarthy:** "[A domestic value] was considered to be not the most appropriate way to look at it, it's looked at globally."[84]
- **Council of Economic Advisors Chair Jason Furman:** "It is entirely appropriate to include those [global benefits] because we're trying to motivate a range of countries all to act together. . . . If everyone did a social cost of carbon for their own country, everyone would have too low a number and everyone would act too little. And it would make everyone, including the U.S., worse off. . . . [The global SCC is] in effect like a proxy for not only looking at the domestic [benefits], taking into account that we'll get benefits not just from the reduced emissions in the U.S. from our rule, but that it will lead to policy changes . . . from other countries."[85]
- **Secretary of State John Kerry's Guidance to the Department:** "Lead by example through strong action at home and abroad—Making significant progress in combating climate change through domestic actions within the Department and at the federal, regional, and local level."[86]
- **Former Secretary of State Hillary Clinton:** "Part of what President Obama is doing [with the proposed regulation on power plant emissions]—and I fully support it—is making it

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[81] David Remnick, *The Obama Tapes*, NEW YORKER, Jan. 23, 2014 (quoting interview with President Obama); *see also* Press Release, Remarks by the President in Announcing the Clean Power Plan (Aug. 3, 2015), https://www.whitehouse.gov/the-press-office/2015/08/03/remarks-president-announcing-clean-power-plan ("And if we don't do it, nobody will. The only reason that China is now looking at getting serious about its emissions is because they saw that we were going to do it, too."; Pres. Barack Obama, Remarks to League of Conservation Voters (June 25, 2014) ("We've got to lead by example [on climate]. [Other countries are] waiting to see what America does. And I'm convinced when America proves what's possible, other countries are going to come along."); Pres. Obama, Remakrs at the U.S. Military Academy Commencement Ceremony, May 28, 2014 ("American influence is always stronger when we lead by example. We cannot exempt ourselves from the rules that apply to everyone else. We can't call on others to make commitments to combat climate change if a whole lot of our political leaders deny that it is taking place.").

[82] *The President's Climate Action Plan*, *supra* note 2, at 17.

[83] 2010 TSD, *supra* note 4, at 11.

[84] Gina McCarthy, Testimony at Senate Comm. on Environment & Public Works, "EPA's Proposed Carbon Pollution Standards for Existing Power Plants," July 23, 2014; *see also* Amena H. Saiyid, *"International Stature" of U.S. Would Benefit from Carbon Emissions Rule, McCarthy Says,* BLOOMBERG BNA (May 5, 2014) (quoting EPA Admin. Gina McCarthy as saying the Clean Power Plan will help the United States "regain its international stature"); *see also* Laura Barron-Lopez, *EPA Chief: Climate Rule is about Leadership*, THE HILL (June 16, 2014) (quoting EPA Admin. McCarthy as saying "This is about leadership. This about [the United States] being a leader on this issue and we believe and we already know it's going to leverage a much better opportunity for a global solution.").

[85] John Hendrixson, *White House, EPA Defend Using Global Climate Benefits for GHG Proposal,* INSIDE WASHINGTON PUBLISHERS (July 27, 2016).

[86] Sec'y of State John Kerry, Personal Message, Dipnote: U.S. Dep't of State Official Blog (Mar. 7, 2014), *available at* https://blogs.state.gov/stories/2014/03/07/we-need-elevate-environment-everything-we-do.

clear that the United States is going to act. . . . We're moving but we need to do so much more. . . . [T]he United States cannot go to an international forum unless we've done more."[87]

- **OIRA Administrator Howard Shelanski's Congressional Testimony on SCC:** "[Climate change] is a global problem, and it seems much easier to exercise global leadership and to get other countries around the world to recognize the social costs of carbon if we are doing so ourselves."[88]
- **Former Special Envoy for Climate Change Todd Stern:** Crediting domestic actions like the proposed regulation on power plant emissions with earning the United States "the best [international] standing we've been in in while."[89]
- **Former Chief Economist on the Council of Economic Advisers, Michael Greenstone:** "The tricky part of carbon reduction is that when we reduce a ton, we benefit China, and when China reduces a ton, they benefit us. It's a classic business deal. If we don't cooperate, we'll all be in a lesser state of the world. Cooperation in this case means accounting for the benefit we are providing for others. If one looks at international negotiations, the U.S. would not be able to show up and have much influence if we came and only talked about domestic damages. We're also asking the world to do things that make us better off. We spent 15 to 20 years trying the other strategy which is, 'You guys go first,' and I think it's not working. China and India have a pretty good case for not doing that much unless we come with something deliverable. Will we continue to have these rules if we learn that in no state of the world will China cut its emissions? Probably not. Just as in the classic prisoner's dilemma, we'd change our position."[90]

Similarly, the Obama administration has been trying to prioritize global action on methane reductions, because as "a powerful, short-lived greenhouse gas," methane has a greater potential to affect "warming in the near to medium term."[91] For example, the United States has highlighted its planned actions on methane in its joint statements on climate with China. [92] To demonstrate the U.S. commitment to reducing methane emissions specifically, and to encourage other countries to follow suit in prioritizing efforts on this powerful and fast-acting pollutant, it is strategically important for the United States to continue valuing the global effects of its methane regulations.

Notably, previous presidential administrations have made similar determinations on the ability of U.S. action to foster international reciprocity that will return benefits back to the United States. For example, during the George W. Bush administration, EPA's advanced notice of proposed rulemaking on carbon reductions acknowledged that "domestic mitigation decisions affect the level of mitigation and emissions changes in general in other countries (i.e., the benefits realized in the U.S. will depend on emissions changes in the U.S. and internationally)"[93] In an associated technical support document, EPA further explained "The economic literature on game theory describes this

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[87] Fmr. Sec'y of State Hillary Clinton, Speech at Aspen Ideas Festival, Colo. (June 30, 2014).

[88] *Hearing on Examining the Obama Administration's Social Cost of Carbon Estimates, Before the Subcomm. on Energy Policy, Health Care, and Entitlements of the H. Comm. on Oversight and Gov't Reform*, 113th Cong. 27-28 (2013) (response of OIRA Admin. Howard Shelanski).

[89] Greg Dalton, Climate One, Interview with Todd Stern (Feb. 18, 2014), *available at* http://www.climate-one.org/transcripts/going-paris-ambassador-todd-stern.

[90] G.I., *We Are the World: The Novel Accounting of Greenhouse Gas Regulations*, THE ECONOMIST (June 3, 2014) (quoting Michael Greenstone).

[91] *E.g.*, U.S. Dep't of State, *Joint Statement on Climate Change and the Arctic* (Aug. 31, 2015) (made following the GLACIER conference, at which Canada, Denmark, Finland, Iceland, Norway, Sweden, and Russia were also represented).

[92] White House Press Secretary, *U.S.-China Joint Presidential Statement on Climate Change*, Sept. 25, 2015.

[93] Advanced Notice of Proposed Rulemaking on Regulating Greenhouse Gas Emissions Under the Clean Air Act, 73 Fed. Reg. 44,354, 44,415 (July 30, 2008).

as an 'assurance' game. . . . [P]articipation is self-sustaining, as each participant will want to continue to participate over time if others continue to participate. This game theoretic structure can be a useful framework for thinking about . . . potential overall benefits associated with both domestic and potential international actions."[94]

Dealing with the analogous issue of ozone-depleting substances, the Food and Drug Administration under the George W. Bush administration also noted that the U.S. health gains "could be magnified if other countries follow suit and further reduce emissions." Importantly, in assessing the benefits of the proposed policy, the FDA considered how, if the United States delayed action on reducing ozone-depleting substances, "other Parties could attempt to delay their own control measures," which would carry "adverse environmental and human health consequences."[95]

In short, the federal government has long recognized that considering the global costs and benefits of actions that effect the Earth's climate systems is a useful strategy to promote U.S. interests in securing international reciprocity.

Other Countries Have Also Strategically Selected Using a Global SCC

As detailed more fully in Appendix B, numerous countries have priced carbon in a variety of ways. Canada has long followed the U.S. interagency working group's lead on the SCC, and recently Canada and Mexico joined the United States in explicitly "aligning methods for estimating the social cost of carbon."[96] Several other jurisdictions—Sweden, Germany, the United Kingdom, Norway, and the European Union—have independently developed or adopted social cost of carbon metrics for regulatory analysis. All of these valuations are close to or far above the U.S. valuation, indicating that they all reflect a global view of climate damages. Sweden and Germany have the highest valuations of carbon: $167-$168 per ton in the year 2030, or more than three times the U.S. estimate. Those countries that have developed a social cost of methane, like the United Kingdom, are also using a global value.[97]

Many other countries have adopted either carbon taxes or carbon allowances that seem to reflect concern for the extra-territorial effects of greenhouse gas pollution. Sweden, France, Switzerland, and Finland have carbon taxes set above the U.S. calculation of the global SCC. Sweden again leads the pack, with its carbon tax set at $130 per ton. Many other countries and jurisdictions—including Tokyo, Canadian provinces, Denmark, Ireland, Slovenia, Costa Rica, the EU, South Korea, Iceland, South Africa, Chile, Portugal, New Zealand, Latvia, Mexico, Kazakhstan, and Estonia—have either

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[94] EPA, *Technical Support Document on Benefits of Reducing GHG Emissions U.S. Environmental Protection Agency* (2008), https://www.uschamber.com/sites/default/files/legacy/CO2/files/TSDBenefits.pdf. *See also* Average Fuel Economy Standards Passenger Cars and Light Trucks Model Year 2011, 74 Fed. Reg. 14,196, 14,349, where NHTSA noted that the current state of "negotiations regarding effective international cooperation" could affect this decision; at the time, the agency felt such considerations necessitated at least some domestic-only estimate, on the assumption that ambitious "unilateral" action by a single country would not be matched by other countries.

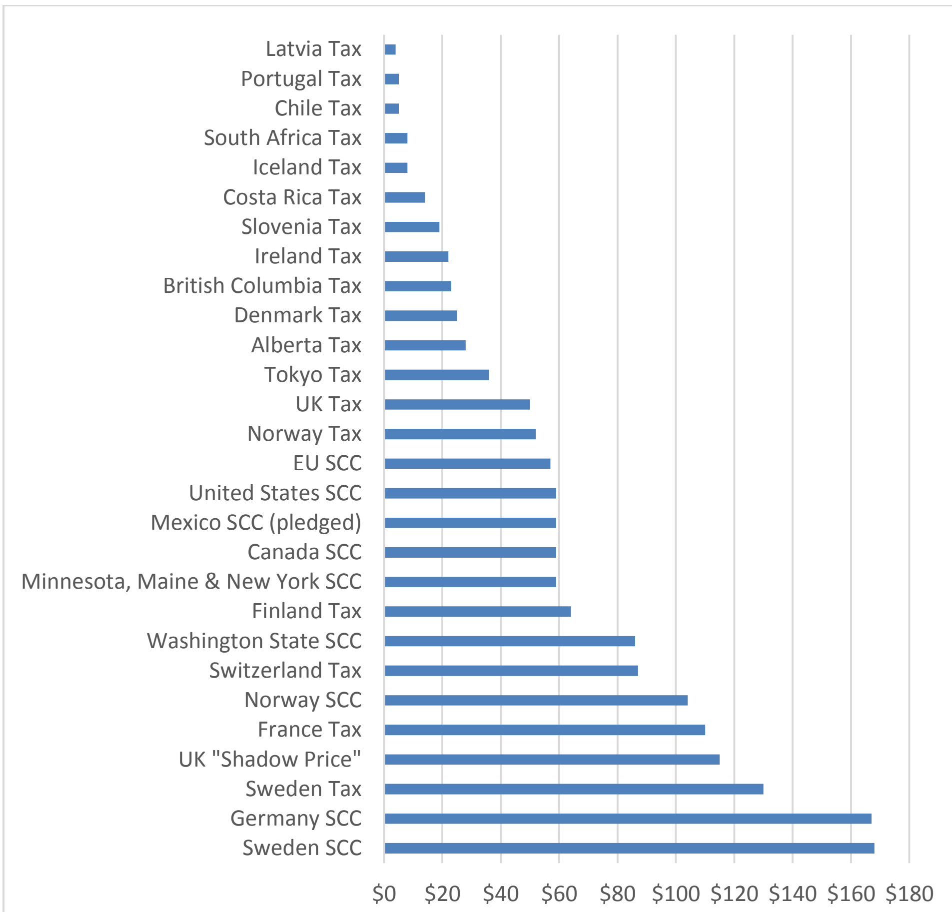
[95] Use of Ozone-Depleting Substances; Removal of Essential-Use Designations, 69 Fed. Reg. 33,602, 33,614 (June 16, 2004); Use of Ozone-Depleting Substances; Removal of Essential-Use Designations, 72 Fed. Reg. 32,030, 32,030-01 (June 11, 2007).

[96] Jason Furman & Brian Deese, *The Economic Benefits of a 50 Percent Target for Clean Energy Generation by 2025*, White House Blog, June 29, 2016 (summarizing the North American Leader's Summit announcement that U.S., Canada, and Mexico would "align" their SCC estimates), https://www.whitehouse.gov/blog/2016/06/29/economic-benefits-50-percent-target-clean-energy-generation-2025; *see also* White House Press Secretary, U.S.-Canada Joint Statement on Climate, Energy, and Arctic Leadership, Mar. 10, 2016, https://www.whitehouse.gov/the-press-office/2016/03/10/us-canada-joint-statement-climate-energy-and-arctic-leadership ("align approaches, reflecting the best available science for accounting for the broad costs to society of the GHG emissions that will be avoided by mitigation measures, including using similar values for the social cost of carbon and other GHGs for assessing the benefits of regulatory measures.").

[97] *E.g.*, Defra, U.K., *Methodological Approaches for Using SCC Estimates in Policy Assessment* 58 (2005) (reporting the PAGE results for the social cost of methane).

carbon taxes or carbon allowances priced higher than a rough approximate estimate of their domestic-only SCC (based on that country's share of world GDP). Only China, Japan (excluding the Tokyo trading program), and India have policies arguably priced at or below their domestic share of the SCC, but notably these carbon programs are new developments and prices could rise as targets strengthen with international reciprocity. (Poland and Thailand are uncertain cases.) Admittedly, taxes and allowance auctions may have revenue-generation motives separate from setting the globally efficient level of carbon reductions, but the number of countries with carbon priced above their domestic share of the SCC suggests widespread acknowledgement that countries must consider their global externalities.

Chart 3: Selected Carbon Values Worldwide (in 2016 US$, per tCO_2e, for year 2030 emissions; some tax values reflect current price)



As further evidence of how the United States' use of a global SCC value can influence other international actors to follow suit, the International Monetary Fund (IMF) applies in its policy reviews an SCC estimate based on the U.S. interagency numbers.[98] Given the potential influence of the IMF on the environmental policies of developing countries,[99] the pull that the United States'

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[98] *E.g.*, Benedict Clements et al., International Monetary Fund, *Energy Subsidy Reforms: Lessons and Implications* 9 (IMF Policy Paper, Jan. 28, 2013).

[99] *See* Natsu Taylor Saito, *Decolonization, Development, and Denial*, 6 FL. A & M U. L. REV. 1, 16 (2010) (quoting former IMF counsel as saying "today it is common to find these institutions [IMF and World Bank] requiring their borrowing member countries to accept and adhere to prescribed policies on environmental protection").

global estimate has at the IMF could be very advantageous to the United States, by motivating industrializing countries to use similar numbers in the future.

The President's Strategic Choice of Global SCC and SCM Values Deserves Political and Judicial Deference

The President's Constitutional powers to coordinate the executive branch and manage foreign affairs, as well as additional statutory powers specific to climate change, confirm that the President's strategic choice of global SCC and global SCM values deserves political and judicial deference.

The courts have long recognized

> the basic need of the President and his White House staff to monitor the consistency of executive agency regulations with Administration policy. . . . The authority of the President to control and supervise executive policymaking is derived from the Constitution; the desirability of such control is demonstrable from the practical realities of administrative rulemaking.[100]

Before the 2009 interagency process, different agencies used different SCC estimates in their regulatory analyses (when they in fact estimated the SCC at all[101]); some agencies even used low, domestic-focused estimates that were not necessarily consistent with the most up-to-date economic data and models.[102] Such inconsistency among agencies and with administration goals risked sending foreign countries mixed signals about the U.S. view of its own responsibility for global climate change and its commitment to forging global cooperation. In 2009, the White House convened officials from twelve federal agencies and offices, to develop jointly a consistent and transparent range of SCC estimates for use in all U.S. regulatory analysis. Application of the resulting estimates to policymaking and regulatory analysis was subjected to dozens of public comment periods, and the interagency process itself was further subject to public comments upon the 2013 revision. This high-level interagency process concluded that all U.S. regulatory analysis should preferentially use a global SCC value to calculate climate benefits. EPA's calculations of a global SCM are based on the same process as the interagency working group. Such determinations deserve deference as an exercise of the President's power to ensure government-wide regulatory consistency with the administration's priorities.

Similarly, the courts should defer to the President's exercise of his foreign affairs powers. Though the Constitution balances the delegation of foreign affairs power between the executive and legislative branches, "[t]he key to presidential leadership is the negotiation function. Everyone agrees that the President has the exclusive power of official communication with foreign governments."[103] The Supreme Court has "recognized the special importance of our nation speaking with one voice in the field of foreign affairs."[104] The courts are generally disinclined to interfere with matters of foreign affairs committed to the political branches, especially when doing so would

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[100] *Sierra Club v. Costle*, 657 F.2d 298, 405-06 (D.C. Cir. 1981).

[101] *E.g., Center for Biological Diversity v. NHTSA*, 538 F.3d 1172, 1200 (9th Cir. 2008) (noting the agency had arbitrarily calculated the social cost of carbon as zero).

[102] *See* Jason A. Schwartz et al., *The Price of Neglect: The Hidden Environmental and Public Health Costs of Bad Economics* 9-10 (Inst. for Policy Integrity Report 1, 2008) (explaining how one agency, NHTSA, had expressed a preference for a domestic-only SCC and had set the lower bound of its estimated range at $0, since it assumed domestic-only benefits might be only $0, see 73 Fed. Reg. at 24,414).

[103] Phillip R. Trimble, *The President's Foreign Affairs Power*, 83 AM. J. OF INTL. L. 750, 755 (1989).

[104] *See Made in the USA Found. v. United States*, 242 F.3d 1300, 1317-18 (11th Cir. 2001) (explaining the Supreme Court's holding in Baker v. Carr*,* 369 U.S. 186, 211 (1962)).

risk "the potentiality of embarrassment from multifarious pronouncements by various departments on one question."[105] The development and analysis of U.S. climate regulations are essential parts of the dialogue between the United States and foreign countries about climate change. By requiring agencies to use a global SCC value in their regulatory analyses, the President communicates a strong signal to the international community that the United States wishes to engage in reciprocal actions to mitigate the global threat of climate change. The President's constitutional powers to negotiate international agreements would be seriously impaired if the courts sought to upset how federal agencies calculate the benefits of U.S. climate actions.

In fact, Congress has already charged the President with directing EPA, the State Department, and other agencies in a coordinated national and international climate strategy. The Global Climate Protection Act of 1987, passed as part of an appropriations act by a margin of 303-111 in the House and 85-8 in the Senate, declared that the United States should "work toward multilateral [climate] agreements," and that "Effective United States leadership in the international arena will depend upon a coordinated national policy."[106] And as the Supreme Court has ruled, "Congress's express command to the President to take the initiative for the United States among the international community invest[s] him with the maximum authority of the National Government."[107]

In short, agencies and the courts should defer to the President on his selection of a global SCC value for use in all federal regulatory analysis. If the interagency working group adopts EPA's valuations of the global SCM, agencies and courts should likewise defer to that choice. In fact, as explored in the next section, in at least certain contexts, those choices may already be mandated by law.

Part Three: Binding Legal Obligations Prescribe Using a Global SCC Value

The United States has already signed and ratified one international treaty that commits it to the consideration of global climate effects of its domestic actions. Two key statutes for U.S. climate policy—the Clean Air Act and the National Environmental Policy Act—do the same, and the other statutes most used to date for climate regulation give agencies enough discretion to consider global effects. Executive orders further show that administration priorities for international harmonization should shape U.S. regulatory analysis and decisionmaking.

International Law Commits the United States to Account for Global Effects

Binding international agreements require consideration and mitigation of transboundary environmental harms. Notably, the United Nations Framework Convention on Climate Change—to which the United States is a party—declares that countries' "policies and measures to deal with climate change should be cost-effective so as to *ensure global benefits* at the lowest possible cost."[108] The Convention further commits parties to evaluating global climate effects in their policy decisions, by "employ[ing] appropriate methods, for example *impact assessments* . . . with a view to minimizing adverse effects on the economy, on public health and on the quality of the environment,

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105 *Id.* at 1318 (citing *Baker*).

106 Global Climate Protection Act of 1987, tit. XI of Pub. L. No. 100-204, 101 Stat. 1407, note following 15 U.S.C. § 2901; *see also Massachusetts v. EPA*, 549 U.S. 497 (2007) (citing the Act).

107 *Crosby v. Nat'l Foreign Trade Council*, 530 U.S. 363, 380 (2000).

108 United Nations Framework Convention on Climate Change, May 9, 1992, S. Treat Doc. No. 102-38, 1771 U.N.T.S. 107, Article 3(3) (emphasis added); *see also id.* at Article 3(1) ("The Parties should protect the climate system for the *benefit of present and future generations of humankind*, on the basis of *equity* and in accordance with their common but *differentiated responsibilities* and respective capabilities.") (emphasis added); *id.* at Article 4(2)(a) (committing developed countries to adopt policies that account for "the need for equitable and appropriate contributions by each of these Parties to the global effort").

of projects or measures undertaken by them to mitigate or adapt to climate change."[109] The unmistakable implication of the Convention is that parties—including the United States—must account for global economic, public health, and environmental effects in their regulatory impact assessments. In 2008, a group of U.S. senators—including Senator John Kerry, who helped ratify the framework convention on climate change—agreed with this interpretation of the treaty language, saying "Upon signing this treaty, the United States committed itself to considering the global impacts of its greenhouse gas emissions."[110]

The Convention reflects a basic ethical responsibility to prevent transboundary environmental harms that has been enshrined in customary international law.[111] For the United States to knowingly set pollution levels in light of only domestic harms, willfully ignoring that its pollution directly imposes environmental risks—including catastrophic risks—on other countries, would violate norms of comity among countries. The United States would be knowingly causing foreseeable harm to other countries, without compensation or just cause. Given that the nations most at risk from climate change are often the poorest countries in the world, such a policy would also violate basic and widely shared ethical beliefs about fairness and distributive justice. Indeed, taking a global approach to measuring climate benefits is consistent with the ideals of transboundary responsibility and justice that the United States commits to in other foreign affairs.[112]

Two Key Statutes Require Consideration of Global Climate Costs

Many of the most important climate regulations issued to date have been developed by EPA under the authority of the Clean Air Act. Clean Air Act regulations make up nearly a third of all regulatory proceedings that have used the SCC or SCM. Environmental impact statements required under the National Environmental Protection Act have recently begun to feature use of the SCC and SCM, and may increasingly do so in the future. Both statutes to some degree require agencies to consider the global effects of U.S. greenhouse gas emissions.

The Clean Air Act is arguably the most important statute for U.S. climate policy. In 2007, the Supreme Court ruled that greenhouse gases were indisputably "pollutants" under the Act.[113] Since then, EPA has regulated greenhouse gases from cars, trucks, power plants, and other sources under the Act's Section 111, Section 202, and "prevention of significant deterioration" program. All three of those provisions charge EPA with protecting the public "welfare,"[114] where "welfare" is defined to include "effects on . . . weather . . . and climate."[115] When interpreting Section 202, the Supreme Court found "there is nothing counterintuitive to the notion that EPA can curtail the emission of

[109] *Id.* at Article 4(1)(f) (emphasis added); *see also id.* at Article 3(2) (requiring parties to give "full consideration" to those developing countries "particularly vulnerable to the adverse effects of climate change"). *See also* North American Agreement on Environmental Cooperation (1993), 32 I.L.M. 1480, art. 10(7) (committing the United States to the development of principles for transboundary environmental impact assessments).

[110] Senators Feinstein, Snowe, Nelson, Cantwell, Sanders, Kerry, Durbin, Reed, Boxer, and Cardin, Comment Letter on Proposed Rule for Average Fuel Economy Standards, Passenger Cars and Light Trucks; Model Years 2011-2015 (July 30, 2008), https://www.regulations.gov/#!documentDetail;D=NHTSA-2008-0089-0454.

[111] *See* PHILIPPE SANDS, PRINCIPLES OF INTERNATIONAL ENVIRONMENTAL LAW 241 (2d ed. 2003) (noting that "the responsibility not to cause damage to the environment of other states or of areas beyond national jurisdiction has been accepted as an obligation by all states[;] . . . there can be no questions but that Principle 21 [of the Stockholm Declaration on the Human Environment] reflects a rule of customary international law").

[112] *See* Paul Baer & Ambuj Sagar, *Ethics, Rights and Responsibilities*, CLIMATE CHANGE SCIENCE AND POLICY (Stephen Schneider et al., eds., 2009).

[113] *Massachusetts v. EPA*, 549 U.S. 497 (2007).

[114] *E.g.* 42 U.S.C. §§ 7411, 7470, 7521.

[115] 42 U.S.C. § 7602(h); *Massachusetts v. EPA*, 127 S.Ct. at 1447.

substances that are putting the *global* climate out of kilter."[116] When industry challenged another EPA climate program by arguing that the Clean Air Act "was concerned about local, not global effects," the U.S. Court of Appeals for the D.C. Circuit had "little trouble disposing of Industry Petitioners' argument that the [Clean Air Act's prevention of significant deterioration] program is specifically focused solely on localized air pollution," finding instead that the statute was "meant to address a much broader range of harms," including "precisely the types of harms caused by greenhouse gases."[117]

Moreover, since 1965, the Act has explicitly provided for the consideration of how U.S. air pollution affects global health and welfare. The 1965 House Report declared that the "United States cannot in good conscience decline to protect its neighbors from pollution which is beyond their legal control," and the 1965 Senate Report explained that "It is important that we, in the interest of international amity and in fairness to the people of other countries, afford them the benefits of protective measures."[118] Congress recognized that international cooperation would yield "reciprocal benefits" for the United States.[119] Congress was clearly motivated by the desire to both fulfill ethical duties and advance international relations, and so charged EPA with taking a global perspective on air emissions.

The current version of the Clean Air Act's international air pollution provision comes at Section 115. That section directs EPA and the states to mitigate U.S. emissions that endanger the foreign health and welfare of countries that have granted the United States some reciprocal rights.[120] Though Section 115 has not yet been invoked by EPA as authority for its climate regulations, there is a strong legal case that Section 115's triggers have been satisfied, thus requiring the United States to take a global perspective on the effects of its greenhouse gas emissions.[121] The global perspective explicitly incorporated into Section 115 should be read to permeate the entire Clean Air Act. For example, if EPA's climate regulations under other parts of the Clean Air Act fail to control adequately the endangerment to foreign health and welfare, then Section 115 can be invoked. The global perspective on climate costs and benefits explicitly required by Section 115 therefore should inform all regulatory actions developed under any section of the Clean Air Act.[122]

As a brief but noteworthy aside, the Clean Air Act's sister statute, the Clean Water Act, contains a similar provision focused on international reciprocity.[123] Though the Clean Water Act has not yet been used directly to authorize greenhouse gas regulation, at least two Clean Water regulations of the energy sector indirectly affected greenhouse gas emissions, and the global social cost of carbon was used in the accompanying regulatory impact analyses.[124] Given climate change's impacts on sea-level rise as well as carbon dioxide-induced ocean acidification, this Clean Water Act provision could conceivably become a future source of authority for taking a global perspective on climate regulations.

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[116] *Mass. v. EPA* 127 S.Ct. at 1461 (emphasis added).

[117] *Coalition for Responsible Regulation v. EPA*, 684 F.3d 102, 138 (D.C. Cir. 2012), aff'd in part *Util. Air Regulatory Grp. v. EPA*, 134 S.Ct. 2427 (2014).

[118] H.R. Rep. No. 89-899 at 5 (1965); S. Rep. 89-192 at 6 (1965).

[119] S. Rep. 89-192 at 6 (1965).

[120] 42 U.S.C. § 7415.

[121] Michael Burger, Ann Carlson, Michael Gerrard, Jayni Hein, Jason Schwartz & Keith Benes, *Legal Pathways to Reducing Greenhouse Gas Emissions Under Section 115 of the Clean Air Act*, 28 Georgetown Environmental Law Rev. 359 (2016); Petition from the Institute for Policy Integrity, to EPA, for Rulemakings and Call for Information under Section 115, Title VI, Section 111, and Title II of the Clean Air Act to Regulate Greenhouse Gas Emissions (Feb. 19, 2013).

[122] *See* Nathan Richardson, *EPA and Global Carbon: Unnecessary Risk*, COMMON RESOURCES (Feb. 28, 2013) (explaining how Section 115 authorizes use of a global SCC value when regulating under other Clean Air Act provisions).

[123] 33 U.S.C. § 1320.

[124] See Appendix A.

The National Environmental Policy Act further supports interpreting agencies' statutory authorities to require a global perspective on costs and benefits. Enacted in 1970, the Act states in a provision on "International and National Coordination of Efforts" that "all agencies of the Federal Government *shall* . . . recognize the worldwide and long-range character of environmental problems."[125] Using a global SCC and SCM to analyze and set policy fulfills these instructions. Furthermore, the Act requires agencies to, "where consistent with the foreign policy of the United States, lend appropriate support to initiatives, resolutions, and programs designed to maximize international cooperation in anticipating and preventing a decline in the quality of mankind's world environment."[126] Given the Obama administration's strategic choice of the global SCC to "maximize international cooperation," federal agencies should "lend appropriate support" to this goal by continuing to use the global SCC. Agencies should similarly follow EPA's lead in using a global SCM value.

In addition to these general pronouncements on international and interagency coordination, the National Environmental Policy Act requires agencies to prepare environmental impact statements for major actions with significant environmental consequences. The Council on Environmental Quality is charged with developing guidance for agencies on their environmental impact statements. In guidance, the Council has approved of the use of the interagency working group's estimate of the social cost of carbon—an estimate of global damages—in any economic analyses included as part of agencies' environmental impact statements.[127]

Other Key Statutes Give Agencies Discretion to Consider Global Climate Costs

Energy efficiency is a powerful method of reducing greenhouse gas emissions. A majority of regulatory actions that use the SCC or SCM have been energy efficiency standards issued under energy policy laws, especially the Energy Policy and Conservation Act as modified by the Energy Independence and Security Act of 2007 (see Chart 2 above). The Department of Energy is charged with prescribing energy conservation standards for a wide range of consumer products and industrial equipment (besides cars, for which the Department of Transportation prescribes fuel efficiency standards). The statutes instruct the Department of Energy to prescribe "the maximum improvement in energy efficiency . . . [that] is technologically feasible and economically justified."[128] To determine what is "economically justified," the agency is instructed to measure "whether the benefits of the standard exceed its burdens," after considering "the need for national energy . . . conservation."[129] The key statutory term "need" is not defined,[130] and the agency generally deserves

[125] 42 U.S.C. § 4332(2)(f) (emphasis added).

[126] *Id.*; *see also Environmental Defense Fund v. Massey*, 986 F.2d 528, 535 (D.C. Cir. 1993) (confirming that Subsection F is mandatory); Natural Resources Defense Council v. NRC, 647 F.2d 1345, 1357 (D.C. Cir. 1981) ("This NEPA prescription, I find, looks toward cooperation, not unilateral action, in a manner consistent with our foreign policy."); *cf.* COUNCIL ON ENVIRONMENTAL QUALITY, GUIDANCE ON NEPA ANALYSIS FOR TRANSBOUNDARY IMPACTS (1997), *available at* http://www.gc.noaa.gov/documents/transguide.pdf; CEQ, DRAFT NEPA GUIDANCE ON CONSIDERATION OF THE EFFECTS OF CLIMATE CHANGE AND GREENHOUSE GAS EMISSIONS 2 (2010), *available at* http://www.whitehouse.gov/sites/default/files/microsites/ceq/20100218-nepa-consideration-effects-ghg-draft-guidance.pdf (defining climate change as a "global problem"); Exec. Order No. 12,114, *Environmental Effects Abroad of Major Federal Actions*, 44 Fed. Reg. 1957 §§ 1-1, 2-1 (Jan. 4, 1979) (applying to "major Federal actions . . . having significant effects on the environment outside the geographical borders of the United States," and enabling agency officials "to be informed of pertinent environmental considerations and to take such considerations into account . . . in making decisions regarding such actions").

[127] CEQ, *Final Guidance for Federal Departments and Agencies on Consideration of Greenhouse Gas Emissions and the Effects of Climate Change in National Environmental Policy Act Reviews*, *supra* note 54.

[128] 42 U.S.C. §§ 6295(o)(2)(A), 6313.

[129] 42 U.S.C. § 6295(o)(2)(B); also may consider any "other factors the Secretary considers relevant." 42 U.S.C. § 6295(o)(2)(B); *see also, e.g.* Energy Conservation Program: Energy Conservation Standards for Walk-In Coolers and Freezers, 78 Fed. Reg. 55,781, 55,789 (proposed Sept. 11, 2013) (defining the phrase "technologically feasible and

deference in interpreting such ambiguous language.[131] Since at least President George H.W. Bush's administration in 1989, the Department of Energy has considered "environmental effects," including the "national security" implications of "mitigating global warming and pollution," as part of the "economic justification" for efficiency standards, under the "need of the nation to conserve energy" prong.[132] Since at least 1991, the agency has not only "quantified"—"to the extent DOE had data"—the "social benefits" of environmental effects like "global warming" to help justify the selected standards, but further noted that environmental effects "have also been considered in the development of the selected standard levels."[133] The Department of Energy clearly has discretion to determine that part of the "need for national energy conservation" is to encourage reciprocal international commitments that will directly benefit the United States.[134] Certainly the statute nowhere bars the consideration of the global consequences of energy efficiency regulation. Given that economically efficient climate policies can result only if all countries consider the global externalities of their greenhouse gas emissions, and given the Obama administration's strategic choice to use the global measures of climate damages in its regulatory analyses, the Department of Energy can consider the global SCC and global SCM as part of the "need for national energy conservation." The Court of Appeals for the Seventh Circuit recently ruled that it had "no doubt" that the "need for conservation" prong authorizes the Department of Energy to consider the SCC, and further found that use of the global SCC was within the agency's discretion.[135]

Similarly, the energy policy statutes give the Department of Transportation nearly identical instructions to weigh "the need of the United States to conserve energy" in setting motor vehicle efficiency standards.[136] In defining that language, the agency has explained:

> As courts of appeal have noted in three decisions stretching over the last 20 years, [the Department of Transportation] defined the "need of the Nation to conserve energy" in the late 1970s as including ". . . environmental, and foreign policy implications . . . ." In 1988, [the agency] included climate change concepts in its [vehicle efficiency standards] . . . . Since then, [the agency] has considered the benefits of reducing tailpipe carbon dioxide emissions . . . pursuant to the statutory requirement to consider the nation's need to conserve energy by reducing fuel consumption.[137]

In 1988, the U.S. Court of Appeals for the D.C. Circuit highlighted that the Energy Policy and Conservation Act contains no statutory command prohibiting environmental considerations, and approving of the Department of Transportation's interpretation that the reference to "need of the Nation to conserve energy" "*requires* consideration of . . . environmental . . . implications."[138] More

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economically justified" under § 6313 by citing the factors listed under § 6295(o)(2)(B), and considering the global SCC in its regulatory analysis).

130 *See* 42 U.S.C. § 6291.

131 *See* Chevron U.S.A. Inc. v. Natural Res. Def. Council, Inc., 467 U.S. 837, 842-45 (1984).

132 54 Fed. Reg. 47,916, 47,924, 47,937, 47,940 (Nov. 17, 1989) (agreeing with commenters).

133 56 Fed. Reg. 22,250, 22,259 (May 14, 1991) (again at the behest of commenters).

134 *See Chevron U.S.A. Inc. v. Natural Resources Defense Council*, 467 U.S. 837, 842-45 (1984).

135 Zero Zone v. Dep't of Energy, at 40, 43. In addition to the "need for conservation" prong, the court also concluded that the agency "probably" had authority to consider environmental benefits under two other prongs of the "economically justified" test (i.e., economic impact on consumers, and "other factors"). *Id.* at 40 n.24. In our role as staff for the Institute for Policy Integrity, the authors helped prepare an *amicus* brief that "highlighted" these SCC issues for the court. *Id.* at 40 n.23.

136 49 U.S.C. § 32,902(f).

137 77 Fed. Reg. 62,624, 62,669-70 (Oct. 15, 2012).

138 *See Pub. Citizen v. Nat'l Highway Traffic Safety Admin*., 848 F.2d 256, 263 n.27 (D.C. Cir. 1988) (R.B. Ginsburg, J.) (quoting 42 Fed. Reg. 63,184, 63,188 (Dec. 15, 1977), adding emphasis to the word requires, and explaining that EPCA contains no statutory command prohibiting environmental considerations).

recently, in 2008, the U.S. Court of Appeals for the Ninth Circuit indicated that, due to advancements in "scientific knowledge of climate change and its causes," "[t]he need of the nation to conserve energy is even more pressing today than it was at the time of EPCA's enactment."[139] The court held that the Department of Transportation's failure to monetize climate benefits explicitly in its economic assessment of vehicle efficiency standards was arbitrary and capricious.[140] In that ruling, the court listed several estimates of the global SCC as values that the agency could have chosen.[141] Therefore, the Obama administration could conclude that the "need of the United States to conserve energy" includes the need to encourage reciprocal international action by first counting the global damages of U.S. emissions.

The Department of the Interior has only recently begun regulating greenhouse gas emissions from federal leases of energy resources. In prescribing methane venting and flaring limits for oil and gas operations on public land, the Bureau of Land Management weighed the social costs of methane and carbon. Neither the Mineral Leasing Act nor the Federal Land Policy and Management Act contain any language that would prohibit the Bureau's consideration of the full climate effects of its proposed regulations. The Federal Land Policy and Management Act, for example, instructs the Department of the Interior to "manage the public lands under principles of multiple use and sustainable yield."[142] "Multiple use" is defined as:

> the management of the public lands and their various resource values so that they are utilized in the combination that will best meet the present and future needs of the American people; . . . a combination of balanced and diverse resource uses that takes into account the long-term needs of future generations for renewable and nonrenewable resources, including, but not limited to, . . . the quality of the environment . . . .[143]

The act's "congressional declaration of policy" elaborates that the goal is to manage public lands "in a manner that will protect the quality of scientific, scenic, historical, ecological, *environmental, air and atmospheric*, water resource, and archeological values . . . . "[144] Congress clearly intended the agency to consider a full range of environmental factors in setting its land management policies.[145] Importantly, the reference to the "future needs of the American people" does not limit the Department of Interior to a domestic-only approach to the social costs of methane or carbon. Rather, much like under the energy policy statutes, "need" is undefined and left to the agency's discretion. Just as the Departments of Energy and Transportation may interpret "need" to include the strategy of securing reciprocal international action that will benefit the United States, so too may the Department of Interior consider the global climate consequences of its action in an effort to safeguard the need of future Americans who will benefit from international coordination on climate.

The energy policy statutes and land management statutes, therefore, all give agencies discretion on whether to consider a global SCC and a global SCM. Whenever a statute gives agencies discretion on whether to take a global perspective on costs and benefits, executive orders and priorities should compel use of the global SCC and the global SCM.

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[139] *Ctr. for Biological Diversity v. Nat'l Highway Traffic Safety Admin*., 538 F.3d 1172, 1197-98 (9th Cir. 2008).
[140] *Id*. at 1203.
[141] *Id. at* 1199.
[142] 43 U.S.C. § 1732(a).
[143] 43 U.S.C. § 1702(c) (emphasis added).
[144] 43 U.S.C. § 1701(a)(8) (emphasis added); *see also* the immediately preceding statement, 43 U.S.C. § 1701(a)(7) referencing the goal of multiple use.
[145] *See e.g.,* Jayni Foley Hein, *Harmonizing Preservation and Production* 4-5 (Policy Integrity Report, 2015).

Executive Orders Emphasize International Harmonization

As explained above, while some statutory authorities (Clean Air Act and National Environmental Policy Act) contain some requirements to consider global effects, other statutory authorities may leave agencies some discretion on the use of the global SCC and global SCM. However, to the extent agencies have such discretion under their statutory authorities, presidential orders on regulatory analysis and international harmonization should compel use of global SCC and global SCM values.

In 1993, President Clinton signed Executive Order 12,866, which remains the foundational order governing federal regulatory planning and review. Order 12,866 requires agencies to assess the costs and benefits of significant regulatory proposals, and empowers the Office of Information and Regulatory Affairs to review such proposals. While some critics of the global SCC or global SCM have highlighted the Order's requirement for federal agencies to "promulgate only such regulations as . . . protect or improve the health and safety of the public, the environment, or the well-being of the American people,"[146] as discussed above, the well-being of the American people is directly advanced by efforts to encourage international reciprocity on climate change. Order 12,866 never limits agencies to considering only domestic effects, instead instructing agencies to "assess *all* costs and benefits." The Order also repeatedly clarifies that all regulatory actions must be "consistent with . . . the President's priorities,"[147] and the Obama administration's priorities clearly include a global perspective on climate analysis.

The Office of Information and Regulatory Affairs has developed guidance for agencies on compliance with Executive Order 12,866, called *Circular A-4*. Published in 2003, the Circular assumes that most analyses would focus on domestic costs and benefits, but ultimately it defers to the discretion of regulatory agencies on whether to evaluate "effects beyond the borders of the United States."[148] The Circular notes that "facilitating U.S. participation in global markets should also be considered. Harmonization of U.S. and international rules may require a strong Federal regulatory role."[149]

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[146] Exec. Order No. 12866 § 1(a), *cited by* Gayer & Viscusi, *supra* note 13; Fraas et al., *supra* note 14.

[147] Exec. Order No. 12,866 §§ 2(a), (b), 4, 5, 6(b).

[148] OFFICE OF MGMT. AND BUDGET, CIRCULAR A-4 15 (2003), https://www.whitehouse.gov/sites/default/files/omb/assets/regulatory_matters_pdf/a-4.pdf; *see also* Advanced Notice of Proposed Rulemaking on Regulating Greenhouse Gas Emissions Under the Clean Air Act, 73 Fed. Reg. 44,354, 44,415 (July 30, 2008). ("Typically, because the benefits and costs of most environmental regulations are predominantly domestic, EPA focuses on benefits that accrue to the U.S. population when quantifying the impacts of domestic regulation. However, OMB's guidance for economic analysis of federal regulations specifically allows for consideration of international effects.").

In sharp contrast to the Circular's ultimate deferral to agencies on the issue of considering transboundary efficiency effects, the Circular makes very clear that international transfers and distributional effects should be assessed as costs and benefits to the United States: "Benefit and cost estimates should reflect real resource use. Transfer payments are monetary payments from one group to another that do not affect total resources available to society. . . . However, transfers from the United States to other nations *should* be included as costs, and transfers from other nations to the United States as benefits, as long as the analysis is conducted from the United States perspective." *Id.* at 38 (emphasis original). In other words, even if federal agencies use a global SCC value to assess efficiency effects relating to their climate policies, that global valuation will not prevent the agencies from also counting international transfers or distributional effects that confer benefits on the United States. *See* Comments from the Institute for Policy Integrity, to EPA, on Proposed Rulemaking to Establish Light-Duty Vehicle Greenhouse Gas Emission Standards, at 12-13 (Nov. 27, 2009) (explaining that, depending on the relevant statutory mandate, agencies may calculate a monopsony benefit to the United States even while using a global SCC value).

[149] Circular A-4, *supra* note 148. *See also* U.S. Office of Management and Budget & Secretariat General of the European Commission, *Review of Application of EU and US Regulatory Impact Assessment Guidelines on the Analysis of Impacts on International Trade and Development* 13 (2008) (explaining that EO 12866's reference to private markets and competitiveness obligates agencies to consider impacts on international trade).

Importantly, more recent Executive Orders and OIRA guidance clarify that a global perspective on climate costs is required. In 2012, President Obama issued Executive Order 13,609 on promoting international regulatory cooperation.[150] The Order built on his previous Executive Order 13,563, which in turn had affirmed Executive Order 12,866 in requiring benefit-cost analysis of significant federal regulations.[151] Executive Order 13,609, prioritizes international cooperation as a means of achieving U.S. regulatory goals. It explicitly recognizes that significant regulations can have "significant international impacts,"[152] and it calls on federal agencies to work toward "best practices for international regulatory cooperation with respect to regulatory development."[153] The Working Group on Executive Order 13,609 highlights that good regulatory analysis is a "prerequisite for effective international regulatory cooperation."[154] By employing a global SCC value in U.S. regulatory development, and by encouraging other countries to follow that best practice and account for the significant international impacts of their own climate policies, federal agencies will advance the mission of this presidential order on regulatory harmonization.

Finally, the Office of Information and Regulatory Affairs was also part of the interagency working group on the social cost of carbon. The working group was specifically charged with developing recommendations for "regulatory impact analysis under Executive Order 12,866."[155] The interagency working group's technical support documents, therefore, state the White House's official policy on conducting Executive Order 12,8666 analyses of climate regulations, and of course, the group has selected a global valuation for the social cost of carbon.

Part Four: Additional Justifications

International reciprocity provides the strongest policy justification for a global valuation of greenhouse gases, but additional arguments should also push federal agencies to look beyond domestic-only effects, including: the inevitability of significant "spillover" effects, U.S. responsibility for the global commons of the oceans and Antarctica, U.S. interests in conducting business and travel abroad, U.S. citizens living or owning property abroad, and the altruistic willingness to pay of U.S. citizens to protect some foreign welfare. For these reasons, emphasizing a domestic-only SCC or SCM would fail to transparently disclose the true scope of climate-related costs and benefits that matter to U.S. policymakers and the public. Moreover, even the "global" SCC contains some biases that give greater weight to U.S. effects; explicitly reverting to a domestic-only SCC would compound that bias.

Inevitably Significant "Spillover" Effects Justify a Broader Perspective

In 2010, the interagency working group used the results of one economic model as well as the U.S. share of global GDP to generate an "approximate, provisional, and highly speculative" range of 7-23% of the global SCC as an estimate of the purely direct climate effects to the United States.[156] Yet, as the interagency group acknowledged, this range is almost certainly an underestimate, because it

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[150] Exec. Order No. 13609, *Promoting International Regulatory Cooperation*, 77 Fed. Reg. 26,413 (May 4, 2012).

[151] *Id.* at § 1 (explaining the order intends to "promot[e] the goals of Executive Order 13563"); *see also* Exec. Order No. 13,563, *Improving Regulation and Regulatory Review*, § 1(b), 76 Fed. Reg. 3821 (Jan. 18, 2011) (reaffirming Exec. Order No. 12,866, 58 Fed. Reg. 51,741 (Sept. 30, 1993) and requiring benefit-cost analysis).

[152] 77 Fed. Reg. at 26,414, § 3(b).

[153] *Id*. at 26,413, § 2(a)(ii)(B) (defining the goals of the regulatory working group).

[154] *Regulatory Working Group Guidelines for Exec. Order 13609: Promoting International Regulatory Cooperation* (June 26, 2015), https://www.whitehouse.gov/sites/default/files/omb/inforeg/eo_13609/eo13609-working-group-guidelines.pdf.

[155] 2010 TSD *supra* note 4.

[156] *Id.* at 11.

ignores significant, indirect costs to trade, human health, and security likely to "spill over" to the United States as other regions experience climate change damages.[157]

The United States is not an island, contrary to the assumptions underlying the economic models used to calculate the SCC, which treat regions as isolated. Due to its unique place among countries—both as the largest economy with trade- and investment-dependent links throughout the world, and as a military superpower—the United States is particularly vulnerable to effects that will spillover from other regions of the world. Spillover scenarios could entail a variety of serious costs to the United States as unchecked climate change devastates other countries. Correspondingly, mitigation or adaptation efforts that avoid climate damages to foreign countries will radiate benefits back to the United States as well.[158]

As climate change disrupts the economies of other countries, decreased availability of imported inputs, intermediary goods, and consumption goods may cause supply shocks to the U.S. economy. Shocks to the supply of energy, technological, and agricultural goods could be especially damaging. For example, when Thailand—the world's second-largest producer of hard-drives—experienced flooding in 2011, U.S. consumers faced higher prices for many electronic goods, from computers to cameras.[159] A recent economic study explored how heat stress-induced reductions in productivity worldwide will ripple through the interconnected global supply network.[160] Similarly, the U.S. economy could experience demand shocks as climate-affected countries decrease their demand for U.S. goods. Financial markets may also suffer, as foreign countries become less able to loan money to the United States and as the value of U.S. firms declines with shrinking foreign profits. As seen historically, economic disruptions in one country can cause financial crises that reverberate globally at a breakneck pace.[161]

The human dimension of climate spillovers includes migration and health effects. Water and food scarcity, flooding or extreme weather events, violent conflicts, economic collapses, and a number of other climate damages could precipitate mass migration to the United States from regions worldwide, perhaps especially from Latin America. For example, a 10% decline in crop yields could trigger the emigration of 2% of the entire Mexican population to other regions, mostly to the United States.[162] Such an influx could strain the U.S. economy and will likely lead to increased U.S. expenditures on migration prevention. Infectious disease could also spill across the U.S. borders, exacerbated by ecological collapses, the breakdown of public infrastructure in poorer nations, declining resources available for prevention, shifting habitats for disease vectors, and mass migration.

Finally, climate change is predicted to exacerbate existing security threats—and possibly catalyze new security threats—to the United States.[163] Besides threats to U.S. military installations and

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[157] *Id*. Indeed, the integrated assessment models used to develop the global SCC estimates largely ignore inter-regional costs entirely. *See* Howard, *supra* note 40. Though some positive spillover effects are also possible, such as technology spillovers that reduce the cost of mitigation or adaptation, *see* S. Rao et al., *Importance of Technological Change and Spillovers in Long-Term Climate Policy*, 27 ENERGY J. 123-39 (2006), overall spillovers likely mean that the U.S. share of the global SCC is underestimated, *see* Jody Freeman & Andrew Guzman, *Climate Change and U.S. Interests*, 109 COLUMBIA L. REV. 1531 (2009).

[158] *See* Freeman & Guzman, *supra* note 157, at 1563-93.

[159] *See* Charles Arthur, *Thailand's Devastating Floods Are Hitting PC Hard Drive Supplies*, THE GUARDIAN, Oct. 25, 2011.

[160] Leonie Wenz & Anders Levermann, *Enhanced Economic Connectivity to Foster Heat Stress-Related Losses*, SCIENCE ADVANCES (June 10, 2016).

[161] *See* Steven L. Schwarz, *Systemic Risk*, 97 GEO. L.J. 193, 249 (2008) (observing that financial collapse in one country is inevitably felt beyond that country's borders).

[162] Shuaizhang Feng, Alan B. Krueger & Michael Oppenheimer, *Linkages Among Climate Change, Crop Yields and Mexico-U.S. Cross-Border Migration*, 107 PROC. NAT'L ACAD. SCI. 14,257 (2010).

[163] *See* CNA Military Advisory Board, *National Security and the Accelerating Risks of Climate Change* (2014).

operations abroad from flooding, storms, extreme heat, and wildfires,[164] President Obama has explained how climate change is "a creeping national security crisis, . . . as [the U.S. military will be] called on to respond to refugee flows and natural disasters, and conflicts over water and food."[165] The Department of Defense's 2014 Defense Review declared that climate effects "are threat multipliers that will aggravate stressors abroad such as poverty, environmental degradation, political instability, and social tensions—conditions that can enable terrorist activity and other forms of violence," and as a result "climate change may increase the frequency, scale, and complexity of future missions, including defense support to civil authorities, while at the same time undermining the capacity of our domestic installations to support training activities."[166] As an example of the climate-security-migration nexus, prolonged drought in Syria likely exacerbated the social and political tensions that erupted into an ongoing civil war,[167] which has triggered an international migration and humanitarian crisis.[168]

Because of these interconnections, attempts to artificially segregate a U.S.-only portion of climate damages will inevitably result in misleading underestimates. Some experts on the social cost of carbon have concluded that, given that integrated assessment models currently do not capture many of these key inter-regional costs, use of the global SCC may be further justified as a proxy to capturing all spillover effects.[169] Though surely not all climate damages will spill back to affect the United States, many will, and together with other justifications the existence of significant spillovers makes a global valuation the better, more transparent accounting of the full range of costs and benefits that matter to U.S. policymakers and the public.

U.S. Willingness to Pay to Prevent Climate Damages Beyond U.S. Borders

Estimates of costs and benefits in regulatory impact analyses, including the social cost of carbon and methane metrics, are fundamentally willingness-to-pay estimates. The willingness-to-pay framework places values on benefits "by measuring what individuals are willing to forgo to enjoy a particular benefit."[170] The climate-sensitive things that U.S. citizens are willing to pay for, however, do not fall neatly within our own geographic borders. A domestic-only SCC based on some rigid conception of geographic borders or U.S. share of world GDP will consequently fail to capture all the climate-related costs and benefits that matter to U.S. citizens.[171]

U.S. citizens have economic and other interests abroad that are not fully reflected in the U.S. share of global GDP. Gross Domestic Product (GDP) is a "monetary value of final goods and services—that is, those that are bought by the final user—produced in a country in a given period of time."[172] GDP therefore may not reflect significant U.S. ownership interests in foreign businesses, properties, and

[164] U.S. Gov't Accountability Office, GAO-14-446 *Climate Change Adaptation: DOD Can Improve Infrastructure Planning and Processes to Better Account for Potential Impacts* (2014).

[165] Pres. Barack Obama, Commencement Address, U.S. Military Academy at West Point, New York (May 28, 2014).

[166] U.S. Dep't of Defense, *Quadrennial Defense Review 2014* vi, 8 (2014).

[167] *See* Center for American Progress et al., *The Arab Spring and Climate Change: A Climate and Security Correlations Series* (2013); Colin P. Kelley et al., *Climate Change in the Fertile Crescent and Implications of the Recent Syrian Drought*, 112 PROC. NAT'L ACAD. SCI. 3241 (2014); Peter H. Gleick, *Water, Drought, Climate Change, and Conflict in Syria*, 6 WEATHER, CLIMATE & SOCIETY, 331 (2014).

[168] *See, e.g.*, *Ending Syria War Key to Migrant Crisis, Says U.S. General*, BBC.COM (Sept. 14, 2015).

[169] *See* Robert E. Kopp & Bryan K. Mignone, Circumspection, Reciprocity, and Optimal Carbon Prices, 120 CLIMATE CHANGE 831, 833 (2013).

[170] Circular A-4, *supra* note 148.

[171] A domestic-only SCC would fail to "provide to the public and to OMB a careful and transparent analysis of the anticipated consequences of economically significant regulatory actions." Office of Information and Regulatory Affairs, Regulatory Impact Analysis: A Primer 2 (2011).

[172] Tim Callen, *Gross Domestic Product: An Economy's All*, IMF, http://www.imf.org/external/pubs/ft/fandd/basics/gdp.htm (last updated Mar. 28, 2012).

other assets, as well as consumption abroad including tourism and eco-tourism,[173] and even the 8 million Americans living abroad.[174] At the same time, GDP is also over-inclusive, counting productive operations in the United States that are owned by foreigners. Gross National Income (GNI), by contrast, defines its scope not by location but by ownership interests. However, not only has GNI fallen out of favor as a metric used in international economic policy,[175] but using a domestic-only SCC based on GNI would make the SCC metrics incommensurable with other costs in regulatory impact analyses, since most regulatory costs are calculated by U.S. agencies regardless of whether they fall to U.S.-owned entities or to foreign-owned entities operating in the United States.[176] The artificial constraints of both metrics counsel against a rigid split based on either U.S. GDP or U.S. GNI.[177]

The United States also has some willingness to pay—as well as perhaps a legal obligation—to protect the global commons of the oceans and Antarctica from climate damages. For example, the Madrid Protocol on Environmental Protection to the Antarctic Treaty commits the United States and other parties to the "comprehensive protection of the Antarctic environment," including "regular and effective monitoring" of "effects of activities carried on both within and outside the Antarctic Treaty area on the Antarctic environment."[178] The share of climate damages for which the United States is responsible is not limited to our geographic borders.

Similarly, U.S. citizens value natural resources and plant and animal lives abroad, even if they never use those resources or see those plants or animals. For example, the existence value of restoring the Prince William Sound after the 1989 Exxon Valdez oil tanker disaster—that is, the benefits derived by Americans who would never visit Alaska but nevertheless felt strongly about preserving this pristine environment—was estimated in the billions of dollars.[179] Though the methodologies for calculating existence value remains controversial,[180] U.S. citizens certainly have a non-zero willingness to pay to protect rainforests, charismatic megafauna like pandas, and other life and environments existing in foreign countries. U.S. citizens also have a non-zero, altruistic willingness to pay to protect foreign citizens' health and welfare,[181] which—together with the other

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[173] "U.S. residents spend millions each year on foreign travel, including travel to places that are at substantial risk from climate change, such as European cities like Venice and tropical destinations like the Caribbean islands." David A. Dana, *Valuing Foreign Lives and Civilizations in Cost-Benefit Analysis: The Case of the United States and Climate Change Policy* (Northwestern Faculty Working Paper 196, 2009), http://scholarlycommons.law.northwestern.edu/cgi/viewcontent.cgi?article=1195&context=facultyworkingpapers.

[174] Assoc. of Americans Resident Oversees, https://www.aaro.org/about-aaro/6m-americans-abroad. Admittedly 8 million is only 0.1% of the total population living outside the United States.

[175] *GNI, Atlas Method (Current US$)*, THE WORLD BANK, http://data.worldbank.org/indicator/NY.GNP.ATLS.CD.

[176] U.S. Office of Management and Budget & Secretariat General of the European Commission, *Review of Application of EU and US Regulatory Impact Assessment Guidelines on the Analysis of Impacts on International Trade and Development* 13 (2008).

[177] Advanced Notice of Proposed Rulemaking on Regulating Greenhouse Gas Emissions Under the Clean Air Act, 73 Fed. Reg. 44,354, 44,415 (July 30, 2008) ("Furthermore, international effects of climate change may also affect domestic benefits directly and indirectly to the extent U.S. citizens value international impacts (e.g., for tourism reasons, concerns for the existence of ecosystems, and/or concern for others); U.S. international interests are affected (e.g., risks to U.S. national security, or the U.S. economy from potential disruptions in other nations).").

[178] Madrid Protocol on Environmental Protection to the Antarctic Treaty (1991), http://www.ats.aq/documents/recatt/Att006_e.pdf

[179] Richard Revesz & Michael Livermore, *Retaking Rationality* 121 (2008).

[180] *Id.* at 129.

[181] *See* Arden Rowell, *Foreign Impacts and Climate Change*, 39 Harvard Environmental Law Rev. 371 (2015); Dana, *supra* note 173 (discussing U.S. charitable giving abroad and foreign aid, and how those metrics likely severely underestimate true U.S. willingness to pay to protect foreign welfare).

justifications detailed in this report—provides further support strongly in favor of global SCC and SCM metrics.

Lack of Equity Weights Already Favors U.S. Interests

Finally, the methodologies for the global SCC and global SCM currently discount foreign welfare to some extent, and thus are arguably already somewhat biased toward a U.S.-centered perspective. Given decreasing marginal utility of consumption and heterogeneity in regional wealth, a dollar lost has heterogeneous welfare effects across regions. For example, the social cost of carbon reflects monetized values of preventing mortality risks that vary with the per capita income of the country where the risk would occur, because the methodologies estimate how much foreign persons are willing to pay themselves to avert risks to themselves. As a result, the social cost of carbon values eliminating a ten-in-a-million risk of death affecting a million people at $90 million if those people live in the United States, at $40 million if they live in Canada, and at only $0.9 million if they live in India.[182] Therefore, some modelers have proposed applying equity weights (i.e., weighting the dollar loss in each region by the expected welfare impact it will have in this region) in the calculation of the SCC to accurately measure the change in the "expected value of social welfare" from emissions.[183] Nevertheless, the interagency working group on the social cost of carbon rejected equity weighting.[184] Consequently, current calculations of the SCC and SCM already place relatively greater weight on domestic climate impacts, because they fail to apply equity weights to impacts experienced by foreign countries with lower GDP per capita. Any further weighting or emphasis of domestic impacts would therefore be theoretically and morally questionable.

Conclusion: Argument Against Using Global Values Are Short-Sighted and Fallacious

Though a handful of researchers, industry trade groups, and state governments have advanced arguments against the global valuation of greenhouse gases, two economists—Ted Gayer and Kip Viscusi—have made the most detailed case.[185] Nevertheless, their arguments run counter to U.S. negotiation strategy, long-term national interests, legal requirements, and economic theory. This conclusion distills the above analysis into specific counter-arguments to each claim made by opponents of the global SCC and global SCM.

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[182] Rowell, *supra* note 181, at 388.

[183] The non-equity-weighted SCC measures impacts in pure dollar terms (i.e., independent of the location of the impact), such that these impacts have differing welfare effects based on the recipients' initial wealth. The equity-weighted SCC measures impacts in welfare terms normalized to some common currency. Anthoff et al. recommend using current U.S. dollars as the appropriate base for cost-benefit analysis within the United States. Anthoff, D., Hepburn, C., & Tol, R. S. (2009). Equity weighting and the marginal damage costs of climate change. *Ecological Economics*, *68*(3), 836-849.

[184] The IWG (2010) states that "When quantifying the damages associated with a change in emissions, a number of analysts (e.g., Anthoff, et al. 2009a) employ "equity weighting" to aggregate changes in consumption across regions. This weighting takes into account the relative reductions in wealth in different regions of the world. A per capita loss of $500 in GDP, for instance, is weighted more heavily in a country with a per-capita GDP of $2,000 than in one with a per-capita GDP of $40,000. The main argument for this approach is that a loss of $500 in a poor country causes a greater reduction in utility or welfare than does the same loss in a wealthy nation. Notwithstanding the theoretical claims on behalf of equity weighting, the interagency group concluded that this approach would not be appropriate for estimating a SCC value used in domestic regulatory analysis. For this reason, the group concluded that using the global (rather than domestic) value, without equity weighting, is the appropriate approach."

[185] Ted Gayer & W. Kip Viscusi, *Determining the Proper Scope of Climate Change Benefits* (Brookings Institution Working Paper, June 3, 2014).

Opponents Make Inappropriate Judgments and Inaccurate Statements about Negotiation Strategy

Waiting for all countries to sign an enforceable global agreement before the United States uses a global SCC or SCM is not the only strategy for negotiations, and not the one the President has selected. Opponents like Gayer and Viscusi acknowledge that foreign reciprocity can justify use of a global SCC value in analyzing U.S. policy, but they insist that use of a global SCC must wait until after a comprehensive and enforceable international treaty has been signed, for fear of undermining U.S. efforts to secure action from other countries. This argument overlooks the many negotiation strategies involving an early U.S. commitment to use the global SCC that could successfully induce international reciprocity. If the existence of reciprocity would justify the use of the global SCC, then surely a workable strategy to secure reciprocity should also justify the use of the global SCC. Gayer and Viscusi's "doubt[s]"[186] about the success of these other strategies are based on a particular view of the free rider problem that does not account for tit-for-tat-type strategies in a repeated negotiation, for the role of building small, stable coalitions, or for more realistic assumptions about foresight and equity. Opponents are making a normative, political judgment about U.S. negotiation tactics, on which the President is entitled to substantial deference.

Other countries are already considering the benefits of their actions to the United States by using a global SCC and global SCM. Gayer and Viscusi assert that "[t]o the best of our knowledge, no other countries include the effects of the U.S. in evaluating their domestic climate policies."[187] In fact, Canada and Mexico have pledged to harmonize their SCC values with the U.S. global estimates, and Sweden, Germany, the United Kingdom, Norway, and the European Union have all independently chosen a global SCC for use in their regulatory analysis; the United Kingdom uses a global SCM as well. Other countries, like France and Switzerland, have implemented high carbon taxes or carbon allowance prices that effectively reflect the global damages of emissions.

Agencies in fact have presented domestic-only numbers in appropriate contexts, but rightly keep the focus on the global perspective. Opponents claim that agencies never report domestic-only climate benefits. Not only would a domestic-only approach be misleading, but this claim is factually incorrect. For example, the Department of Energy's recent Technical Support Document for its energy efficiency standards for residential furnace fans calculated the domestic present value of greenhouse gas reductions from various proposed stringencies (still worth hundreds of millions of dollars).[188] Nevertheless, the Department of Energy rightly emphasized the global benefits, and other agency regulations do appropriately focus exclusively on global climate benefits.

Emphasizing domestic-only presentations would be misleading and contrary to administration policy and strategy. The 7-23% range is, at best, imprecise and "highly speculative," and reflects the United States' *minimum share* of climate benefits because it ignores very significant indirect and spillover effects to the United States, as well as U.S. willingness to pay to prevent climate damages beyond its own borders.[189] Giving these preliminary and speculative domestic estimates too much

[186] Gayer & Viscusi, *supra* note 185, at 19.

[187] *Id.*

[188] U.S. Dep't of Energy, *Technical Support Document: Energy Efficiency Program for Consumer Products and Commercial and Industrial Equipment—Residential Furnace Fans* 14-7 (2013).

[189] Opponents like Gayer and Viscusi claim that the 7-23% range is likely an overestimate, because the U.S. GDP will likely decrease as a share of world GDP over the long timeframe assessed in climate regulations. Gayer & Viscusi, *supra* note 185, at 12. However, this assumption is very speculative and does not account for how climate change may depress the economic growth of rising nations like China. Moreover, it does not account for the many ways in which the range is an underestimate, by omitting damage categories and ignoring spillover effects. *See* Nordhaus (2014) ("The different estimates reflect the poor understanding of the impacts by region.").

attention risks creating false certainty and misguiding the public about what is at stake for the United States. It also fails to account for the U.S. interest in adopting policies that will spur international reciprocity and so create additional U.S. benefits from foreign actions. Moreover, failing to emphasize the global benefits could signal to other countries that the United States is not committed to a global approach on climate, and could invite other countries to also discount or disregard the effect of their emissions on the United States. Whether the United States is employing a strategy of tit-for-tat, coalition building, leading by example, or building a reputation for equity, it is in the United States' strategic interest to continue emphasizing global SCC and SCM values, rather than sending mixed signals.

Opponents Make Inaccurate Statements about Legal Requirements and Agency Practices

White House guidance on regulatory analysis supports, and certainly does not preclude, using the global SCC or SCM. Opponents cite Executive Order 12,866's preamble reference to the "American people" as evidence that presidential guidance narrows the scope of regulatory analysis to a domestic-only frame. They further cite to the Office of Management and Budget's 2003 guidance on that Executive Order, published as *Circular A-4*.[190] This argument ignores President Obama's more recent Executive Order on international cooperation, as well as Executive Order 12,866's more specific instructions for regulatory analysis and policy to be consistent with Presidential priorities. As part of the interagency working group, the Office of Management and Budget concluded that the administration's priorities for global climate action necessitated a global focus in calculating the costs and benefits of U.S. climate policy. Finally, certain statutory mandates, like the Clean Air Act's Section 115, will further override executive guidance in some regulatory contexts.

The Clean Air Act supports, and certainly does not preclude, using the global SCC or SCM. Opponents argue that the Clean Air Act is predominantly focused on protecting only domestic air quality, except for a limited provision that allows EPA to give some weight (though not equal weight) to foreign benefits in countries that have granted the United States reciprocal rights.[191] Yet, as discussed above, since 1965, the Clean Air Act has expressed a consistent concern for the effects of U.S. emissions on foreign health and welfare. Section 115 explicitly requires the United States to address the danger U.S. emissions cause to foreign health and welfare, so long as foreign countries take on some reciprocity responsibility. Moreover, the term "welfare," as used throughout the statute, has been interpreted by courts to cover not just the protection of local air quality, but precisely the type of global effects on climate caused by greenhouse gas emissions.

The Clean Water Act, though to date not central to U.S. climate regulations, would also support using the global SCC. Gayer and Viscusi claim that Section 311 of the Clean Water Act shows an exclusive focus on national interests.[192] Had they looked one section earlier in the statute, they would have seen that Section 310, titled "International Pollution Abatement," partly mirrors Section 115 of the Clean Air Act and requires certain actions where other countries have given reciprocal rights.[193] Similarly, Section 101 instructs the President to secure meaningful action from foreign countries to

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[190] *See, e.g.,* Gayer & Viscusi, *supra* note 185, at 5-6.

[191] Gayer and Viscusi, *supra* note 185, at 7, mistakenly say Section 115 can only be triggered by the Secretary of State. Section 115 also gives EPA power direct to call for action. 42 U.S.C. § 7415.

[192] They also claim the Exxon Valdez oil spill as legal precedent, since the monetary damages paid reflected only calculations of U.S. impacts (and not, for example, to Canada). Gayer & Viscusi, *supra* note 185, at 8-9. Not only do oil spills present a very different context than climate change, especially from an international negotiation strategy perspective, but a single consent decree from 25 years ago makes for a poor precedent, and would not preclude EPA or other agencies from assessing global damages today as appropriate.

[193] 33 U.S.C. § 1320.

prevent the pollution of international waters to the same extent that the United States does.[194] Since the Clean Water Act may apply to water acidification caused by carbon dioxide emissions,[195] the same legal and strategic factors explored above for the Clean Air Act could require use of the global SCC for future regulatory analysis done under the Clean Water Act. However, to date, the Clean Water Act has not been used directly to set U.S. climate policy, though a few Clean Water Act regulations have indirectly affected the energy sector and so have calculated the value of greenhouse gas reductions.

The Toxic Substance Control Act is likely irrelevant to climate regulation. Gayer and Viscusi cite a controversial judicial ruling under the Toxic Substance Control Act, which found that Canadian petitioners did not have standing to challenge EPA's regulations in court, because one of the statute's many factors references the national economy, and because the statute does not mention international concerns.[196] First, legal standing to sue in court is different from economic standing to be considered in a cost-benefit analysis. Second, concerns about the court's very narrow view of cost-benefit analysis in that particular case in part drove the recent congressional efforts to reform TSCA. Third, TSCA appears to be essentially irrelevant to greenhouse gas regulation. A search on LexisNexis did not reveal a single law review or newspaper article arguing for use of TSCA to regulate greenhouse gas emissions.[197] Even assuming that TSCA did foreclose consideration of international effects, that would in no way affect any agency's discretion when acting under any other statutory authority.

Past practices support, and do not preclude, using the global SCC and SCM. Gayer and Viscusi claim that only one environmental impact statement has ever considered non-U.S. effects.[198] Not only does past practice not tie the hands of current and future agencies, especially when faced with a very different kind of environmental and strategic problem like climate change, but there are examples of agencies considering foreign effects in their regulatory analyses. For example, even Gayer and Viscusi implicitly reference the fact that EPA has previously considered cross-border effects of pollutants like mercury.[199] Complexities in the scientific modeling and data limitations make quantification of the health benefits of mercury reductions very difficult. As a result, EPA only discussed the foreign health benefits of U.S. mercury reductions qualitatively; however, most of the domestic health benefits were also unquantified, for similar reasons.[200] In other contexts, agencies

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[194] 33 U.S.C. § 1251(c).

[195] *See* Allison Winter, *Some See Clean Water Act Settlement Opening New Path to GHG Curbs*, GREENWIRE (Mar. 12, 2010); EPA, *Questions and Answers on Ocean Acidification and the Clean Water Act 303(d) Program* (Nov. 15, 2010) (explaining that states should list waters for ocean acidification under § 303(d) when sufficient data exists).

[196] Gayer & Viscusi, *supra* note 185, at 9-10.

[197] The only exceedingly indirect connection between TSCA and greenhouse gases is the possible application of TSCA to regulate the effects of natural gas fracking on water (fracking may also release methane).

[198] Gayer & Viscusi, *supra* note 185, at 10.

[199] *Id.* at 17.

[200] For example, in the Mercury and Air Toxics Standards, EPA concluded that a reduction of mercury emissions from U.S. power plants would generate health benefits for foreign consumers of fish, both from U.S. exports and from fish sourced in foreign countries. EPA did not quantify these foreign health benefits, however, due to complexities in the scientific modeling. EPA, REGULATORY IMPACT ANALYSIS FOR THE FINAL MERCURY AND AIR TOXICS STANDARDS at 65 (2011) ("Reductions in domestic fish tissue concentrations can also impact the health of foreign consumers . . . [and] reductions in U.S. power plant emissions will result in a lowering of the global burden of elemental mercury . . . ."). Similarly, in the analysis of the Cross-State Air Pollution Rule, EPA noted—though could not quantify—the "substantial health and environmental benefits that are likely to occur for Canadians" as U.S. states reduce their emissions of particulate matter and ozone—pollutants that can drift long distances across geographic borders. Federal Implementation Plans to Reduce Interstate Transport of Fine Particulate Matter and Ozone, 75 Fed. Reg. 45,209, 45,351 (Aug. 2, 2010).

have emphasized a quantified global effect. For example, when estimating the risk of death from debris from the international space station, NASA focused on the risk to the global population.[201]

Opponents Present a Grossly Misleading Parade of Horribles

Using a global SCC or SCM would not alter policy in any other, non-climate context. Gayer and Viscusi make the extravagant claim that using the global SCC will require dramatic shifts in U.S. policy and the allocation of resources, including requiring fully porous borders for immigration into the United States; transferring wealth to low-income, non-U.S. citizens and to eradicate all famine and disease in Africa; and redeploying our military to protect anyone, anywhere.[202] This parade of horribles would never flow automatically from the strategic selection to use the global SCC or SCM in setting U.S. climate policy. If the United States ever adopted a purely utilitarian decisionmaking framework and granted everyone on the planet equal economic standing, then, yes, reallocation of resources to poorer countries would be required. But selecting the global SCC or SCM in no way commits the United States to a purely utilitarian or cosmopolitan framework.

U.S. climate policies and negotiation strategies are about correcting a global externality for which the United States, along with other global actors, is directly responsible, and which also directly harms the United States. Though the United States is now only the second-largest greenhouse gas emitter (after China), some studies estimate that, overall, no country comes close to matching the total, historic U.S. contribution to climate change.[203] Taking responsibility for our own significant role in causing climate change does not mean the United States must give all its money to alleviate poverty that it had no role in causing. Gayer and Viscusi have conflated two very different things.

Using the global SCC or SCM may require consideration of some, but certainly not all, global costs and consequences. Gayer and Viscusi argue that the principle of symmetrical analysis requires that, if the global SCC is used to measure benefits, then U.S. regulatory analysis must account for all global costs as well.[204] Gayer and Viscusi do not define which global costs they have in mind, but the petitioners challenging the use of the global SCC in EPA' Clean Power Plan analysis seemed most concerned about emissions leakage. As explained in their brief, petitioners felt EPA's economic analysis "overstates emissions reductions by ignoring that industries respond to energy price increases by shifting production abroad. This depresses benefits because those businesses do not reduce—and may increase—emissions."[205] In short, if a U.S. regulation causes industry to shift production to countries with no or lax emissions controls, the result may be a costly increase of emissions, also called "emission leakage."

Emissions leakage and other important negative global effects should be included in the analysis of federal climate policies, to the extent feasible and to the extent such negative effects exist. Yet the appropriate response to leakage certainly is not to abandon use of the global SCC or SCM; in fact, since using the global SCC and SCM can induce international cooperation on climate change, it actually addresses the problem of leakage. Leakage costs should be modeled when applying the global SCC or SCM. In the case of EPA's Clean Power Plan, for example, the agency analyzed the issue and concluded that it did "not see evidence" of likely "emissions leakage" due to "the relatively

[201] NASA, Final Tier 2 Environmental Impact Statement for International Space Station, 3-1, 3-7, 4-30 (1996) (NASA did calculate the domestic risk separately, but most of the report emphasized the global risk).

[202] Gayer & Viscusi, *supra* note 185, at 21-22.

[203] Datablog, *A History of CO_2 Emissions*, THE GUARDIAN (Sept. 2, 2009) (from 1900-2004, the United States emitted 314,772.1 million metric tons of carbon dioxide; Russia and China follow, with only around 89,000 million metric tons each).

[204] Gayer & Viscusi, *supra* note 185, at 22.

[205] Opening Brief of Petitioners on Procedural Issues, D.C. Cir. case 15-1363, at 71 (filed Feb. 19, 2016).

modest changes in electricity prices."[206] Nevertheless, EPA qualitatively assesses how rising electricity prices may lead to substitution of goods. While some substitutes could be imports from countries with higher emissions per production-unit, resulting in foreign emissions increases, other substitutes would be to alternate domestic goods or even to imports from countries with less-intensive emissions.[207] EPA also discussed how U.S. regulation could motivate foreign countries to adopt their own climate policies, mitigating the risk of leakage. To the extent there is some remaining chance of unquantified leakage costs, note that regulatory actions like the Clean Power Plan also generate many unquantified benefits.[208]

Other climate regulations may not raise much concern of leakage. For example, the majority of regulatory actions that have used the SCC or SCM to date are energy efficiency standards, many of which will deliver private savings on electricity bills as well as social benefits. Regulation of energy efficiency for passenger cars and residential appliances, for example, should not pose significant risks of foreign leakage: making U.S. home refrigerators more efficient has no effect on foreign emissions.

Some other global "costs" of regulation may really have only distributional effects. For example, when U.S. regulations increase the fuel economy of mobile vehicles, U.S. demand for gasoline drops, and because of role that U.S. consumers play in the global oil market, worldwide gasoline prices will dip as well. The lower prices result in a "monopsony benefit" to U.S. consumers, but also result in an offsetting loss in revenue to foreign oil producers. In recent fuel economy rules, EPA and the Department of Transportation have not counted the monopsony benefit (or, put another way, they have counted the offsetting global costs to foreign producers, which zeroed out any domestic monopsony benefits), because they felt using a global SCC necessitated a global perspective on certain costs as well.[209] However, the monopsony effects are really distributional in nature, involving simply the transfer of money between domestic consumers and foreign producers, and do not implicate the economic efficiency of the climate regulation. Consequently, U.S. agencies arguably could be justified in taking a domestic perspective on purely distributional effects even while using the global SCC or SCM.[210]

Finally, compliance cost estimates should always, to the extent practical, factor in the potential for cost-saving innovation, learning, and adaptation. For example, by forging the path and uncovering the most cost-effective tools for greenhouse gas abatement, the United States can transfer technology and knowledge to developing countries, enabling them to achieve more ambitious emissions reductions at achievable costs—reductions that, again, will directly benefit the United States. In the context of climate change policy analysis, thinking globally will help the United States to benefit locally.

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[206] Envtl. Prot. Agency, Responses to Public Comments on the EPA's Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units ("Comment Responses"), ch. 8, pt.2, p.77 (2015).

[207] EPA, Regulatory Impact Analysis for the Clean Power Plan Final Rule, 5-5—5-6 (2015).

[208] *Id.* at 4- 46—4-56 (listing qualitative benefits from hazardous pollutant reductions and visibility improvements).

[209] 80 Fed. Reg. 40,137, 40,467 (July 13, 2015).

[210] *See supra* note 148, citing OMB, CIRCULAR A-4, at 38; Comments from the Institute for Policy Integrity, to EPA, on Proposed Rulemaking to Establish Light-Duty Vehicle Greenhouse Gas Emission Standards, at 12-13 (Nov. 27, 2009).

Appendix A: *Regulatory Proceedings that Apply the SCC or SCM (since the interagency working group's interim values were first available)*

Rulemaking [note: convert proposed to finals when possible]	Agencies & Statutory Authorities	Publication Date and Citation	Global vs. Domestic
Energy Conservation Standards for Refrigerated Bottled or Canned Beverage Vending Machines	Dept. of Energy ("DOE"), Energy Policy statutes (hereinafter "EPCA etc.")	8/31/2009 74 FR 44,914 (final rule) RIN 1904-AB58	Global emphasized; 1 domestic estimate presented in tables alongside 5 global estimates in preamble
Light-Duty Vehicle Greenhouse Gas Standards and Corporate Average Fuel Economy Standards	EPA, Clean Air Act ("CAA") & Dept. of Transp. ("DOT"), EPCA etc.	9/28/2009 74 FR 49,454 (proposed rule) 5/7/2010 75 FR 25,323 (final rule) RIN 2127-AK50 RIN 2127-AK90 RIN 2060-AP58	Global emphasized; domestic discussed and presented in sensitivity analysis table
Energy Conservation Standards for Dishwashers, Dehumidifiers, Microwave Ovens, Electric & Gas Kitchen Ranges and Ovens, and Commercial Clothes Washers	DOE, EPCA etc.	11/9/2009 74 FR 57,738 (proposed rule) 1/8/2010 75 FR 1121 (final rule) RIN 1904-AB93	Global emphasized; 1 domestic estimate presented in tables alongside 5 global estimates in preamble
Energy Conservation Standards for Small Electric Motors	DOE, EPCA etc.	11/24/2009 74 FR 61410 (proposed rule) 3/9/2010 75 FR 10874 (final rule) RIN 1904-AB70	Global emphasized; 1 domestic estimate presented in tables alongside 5 global estimates in preamble
Energy Conservation Standards for Residential Water Heaters, Direct Heating Equipment, and Pool Heaters	DOE, EPCA etc.	12/11/2009 74 FR 65,852 (proposed rule) 4/16/2010 75 FR 20,111 (final rule) RIN 1904-AA90	Global emphasized; 1 domestic estimate presented in tables alongside 5 global estimates in preamble

Changes to Renewable Fuel Standard Program	EPA, CAA	3/26/2010 75 FR 14,669 (final rule) RIN 2060-A081	Global only
FIP to Reduce Interstate Transport of Fine Particulate Matter and Ozone	EPA, CAA	8/2/2010 75 FR 45,209 (proposed rule) 8/8/2011 76 FR 48,207 (final rule) RIN 2060-AP50	Global only
Energy Conservation Standards for Residential Refrigerators, Refrigerator-Freezers, and Freezers	DOE, EPCA etc.	9/27/2010 75 FR 59,470 (proposed rule) 9/15/2011 76 FR 57,515 (final rule) RIN 1904-AB79	Global emphasized; domestic range discussed in preamble
NSPS and Emission Guidelines for Sewage Sludge Incineration Units	EPA, CAA	10/14/2010 75 FR 63,260 (proposed rule) 3/21/2011 76 FR 15,372 (final rule) RIN 2060-AP90	Global only, calculating carbon dioxide disbenefits (i.e., costs) calculated in regulatory impact analysis
GHG Emission Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles	EPA, CAA & DOT, EPCA etc.	11/30/2010 75 FR 74,152 (proposed rule) 9/15/2011 76 FR 57,105 (final rule) RIN 2060-AP61 RIN 2127-AK74	Global only
NESHAP: Mercury Emissions from Mercury Cell Chlor-Alkali Plants	EPA, CAA	3/14/2011 76 FR 13,852 (proposed rule) RIN 2060-AN99	Global only

NESHAP: Industrial, Commercial, and Institutional Boilers (Area Sources)	EPA, CAA	3/21/2011 76 FR 15,554 (final rule) RIN 2060-AM44	Global only, valuing disbenefits
NESHAP: Industrial, Commercial, and Institutional Boilers and Process Heaters (Major Sources)	EPA, CAA	3/21/2011 76 FR 15,607 (final rule) RIN 2060-AQ25	Global only, valuing disbenefits in regulatory impact analysis
NSPS and EG: Commercial and Industrial Solid Waste Incineration Units	EPA, CAA	3/21/2011 76 FR 15,704 (final rule) RIN 2060-AO12	Global only, valuing disbenefits
Energy Conservation Standards for Fluorescent Lamp Ballasts	DOE, EPCA etc.	4/11/2011 76 FR 20,090 (proposed rule) 11/14/2011 76 FR 70,547 (final rule) RIN 1904-AB50	Domestic discussed in preamble Separate calculations of domestic and global in regulatory impact analysis, though emphasis on global
Energy Conservation Standards for Residential Clothes Dryers and Room Air Conditioners	DOE, EPCA etc.	4/21/2011 76 FR 22,324 (proposed rule) 4/21/2011 76 FR 22,453 (direct final rule) 5/26/2011 76 FR 22,454 (direct final rule) RIN 1904-AA89	Separate tables of domestic and global in TSD, though emphasis on global
Energy Conservation Standards for Residential Furnaces and Residential Central Air Conditioners and Heat Pumps	DOE, EPCA etc.	6/27/2011 76 FR 37,549 (proposed rule) 6/27/2011 76 FR 37,407 (direct final rule) RIN 1904-AC06	Separate tables of domestic and global in TSD, though emphasis on global

Federal Implementation Plans: Interstate Transport of Fine Particulate Matter and Ozone	EPA, CAA	8/8/2011 76 FR 48,207 (final rule)	Global only
NSPS and NESHAP for Oil and Natural Gas Sector	EPA, CAA	8/23/2011 76 FR 52,738 (proposed rule) 8/16/2012 77 FR 49,489 (final rule) RIN 2060-AP76	Global emphasized, though domestic discussed
2017+ Model Year Light-Duty Vehicle Greenhouse Gas Standards and Corporate Average Fuel Economy Standards & DOT's environmental impact statement	EPA, CAA & DOT, EPCA etc. & National Environmental Policy Act ("NEPA")	12/1/2011 76 FR 74,854 (proposed rule) 10/15/2012 77 FR 62,623 (final rule) RIN 2060-AQ54 RIN 2127-AK79	Global only
Commercial and Industrial Solid Waste Incineration Units	EPA, CAA (in conjunction with the Resources Conservation & Recovery Act)	12/23/2011 76 FR 80,452 (proposed rule) RIN 2050-AG44 RIN 2060-AR15	Global only, calculating carbon dioxide disbenefits (i.e., costs) in the regulatory impact analysis
Energy Conservation Standards and Test Procedures for Commercial Heating, Air-Conditioning, and Water-Heating Equipment	DOE, EPCA etc.	1/17/2012 77 FR 2356 (proposed rule) 5/16/2012 77 FR 28,927 (final rule) RIN 1904-AC47	Domestic discussed in preamble Separate tables of domestic and global in TSD, though emphasis on global
Energy Conservation Standards for Distribution Transformers	DOE, EPCA etc.	2/10/2012 77 FR 7281 (proposed rule) 4/18/2013 78 FR 23,335 (final rule) RIN 1094-AC04	Domestic discussed in preamble Separate tables of domestic and global in TSD, though emphasis on global

Energy Conservation Standards for Standby Mode and Off Mode for Microwave Ovens	DOE, EPCA etc.	2/14/2012 77 FR 8526 (proposed rule) 6/17/2013 78 FR 36,316 (final rule) RIN 1904-AC07	Domestic discussed in preamble Separate tables of domestic and global in TSD, though emphasis on global
NESHAP from Coal- and Oil-Fired Electric Utility Steam Generation Units and Standards of Performance for Fossil-Fuel-Fired Electric Utility, Industrial-Commercial-Institutional, and Small Industrial-Commercial-Institutional Steam Generating Units	EPA, CAA etc.	2/16/2012 77 FR 9303 (final rule) RIN 2060-AP52 RIN 2060-AR31	Global only
Energy Conservation Standards for Battery Chargers and External Power Supplies	DOE, EPCA etc.	3/27/2012 77 FR 18,477 (proposed rule) 2/10/2014 79 FR 7845 (final rule) RIN 1904-AB57	Domestic discussed in preamble Separate tables of domestic and global in TSD, though emphasis on global
Energy Conservation Standards for Residential Dishwashers	DOE, EPCA etc.	5/30/2012 77 FR 31,964 (proposed rule) 5/30/2012 77 FR 31,917 (direct final rule) 10/1/2012 77 FR 59,712 (direct final rule) RIN 1904-AC64	Domestic discussed in preamble Separate tables of domestic and global in TSD, though emphasis on global

Energy Conservation Standards for Residential Clothes Washers	DOE, EPCA etc.	5/31/2012 77 FR 32,381 (proposed rule) 5/31/2012 77 FR 32,307 (direct final rule) RIN 1904-AB90	Domestic discussed in preamble Separate tables of domestic and global in TSD, though emphasis on global
Performance Standards for Petroleum Refineries	EPA, CAA	9/12/2012 77 FR 56,422 (final rule) RIN 2060-AN72	Global only
NESHAP for Industrial, Commercial, and Institutional Boilers and Process Heaters (Major Sources)	EPA, CAA	1/31/2013 78 FR 7138 (final rule) RIN 2060-AR13	Global only, calculating carbon dioxide disbenefits in the regulatory impact analysis
Energy Conservation Standards for Distribution Transformers	DOE, EPCA etc.	4/18/2013 78 FR 23,335 (final rule) RIN 1904-AC04	Domestic discussed in preamble Separate tables of domestic and global in TSD, though emphasis on global
Effluent Limitation Guidelines and Standards for the Steam Electric Power Generating Point Source Category	EPA, Clean Water Act ("CWA")	6/7/2013 78 FR 34,431 (proposed rule) 11/3/2015 80 FR 67,837 (final rule) RIN 2040-AF14	Global only
Environmental Assessment of Montana Oil and Gas Lease Sales	Dept. of Interior, NEPA	7/24/2013[211]	Global only

[211] *Available at* http://www.blm.gov/style/medialib/blm/mt/blm_programs/energy/oil_and_gas/leasing/lease_sales/2013/october/7-24-13_post_docs.Par.9918.File.dat/Finial_Billings_EA.pdf.

Energy Conservation Standards for Metal Halide Lamp Fixtures	DOE, EPCA etc.	8/20/2013 78 FR 51,463 (proposed rule) 2/10/2014 79 FR 7745 (final rule) RIN 1904-AC00	Domestic discussed in preamble Separate tables of domestic and global in TSD, though emphasis on global
Energy Conservation Standards for Walk-In Coolers and Freezers	DOE, EPCA etc.	9/11/2013 78 FR 55,781 (proposed rule) 6/3/2014 79 FR 32,049 (final rule) RIN 1904-AB86	Domestic discussed in preamble Separate tables of domestic and global in TSD, though emphasis on global
Energy Conservation Standards for Commercial Refrigeration Equipment	DOE, EPCA etc.	9/11/2013 78 FR 55,889 (proposed rule) 3/28/2014 79 FR 17,725 (final rule) RIN 1904-AC19	Domestic discussed in preamble Separate tables of domestic and global in TSD, though emphasis on global
Energy Conservation Standards for Residential Furnace Fans	DOE, EPCA etc.	10/25/2013 78 FR 64,067 (proposed rule) 7/3/2014 79 FR 38,129 (final rule) RIN 1904-AC22	Domestic discussed in preamble Separate tables of domestic and global in TSD, though emphasis on global
Energy Conservation Standards for Commercial and Industrial Electric Motors	DOE, EPCA etc.	12/06/2013 78 FR 73,589 (proposed rule) 5/29/2014 79 FR 30,933 (final rule) RIN 1904-AC28	Domestic discussed in preamble Separate tables of domestic and global in TSD, though emphasis on global

Standards of Performance for Greenhouse Gas Emissions from New, Modified, and Reconstructed Stationary Sources: Electric Utility Generating Units	EPA, CAA	1/8/2014 79 FR 1429 (proposed rule) 10/23/2015 80 FR 64,509 (final rule) RIN 2060-AQ91	Global only, in regulatory impact analysis
Energy Conservation Standards for Commercial Clothes Washers	DOE, EPCA etc.	3/4/2014 79 FR 12,301 (proposed rule) 12/15/2014 79 FR 74,491 (final rule) RIN 1904-AC77	Domestic discussed in preamble Separate tables of domestic and global in TSD, though emphasis on global
Energy Conservation Standards for Automatic Commercial Ice Makers	DOE, EPCA etc.	3/17/2014 79 FR 14,845 (proposed rule) 1/28/2015 80 FR 4645 (final rule) RIN 1904-AC39	Domestic discussed in preamble Separate tables of domestic and global in TSD, though emphasis on global
Affordability Determination—Energy Efficiency Standards	Dept. of Housing and Urban Dev. & Dept. of Agriculture (USDA), Energy Independence and Security Act ("EISA")	4/15/2014 79 FR 21,259 (notice of preliminary determination) 5/6/2015 80 FR 25,901 (final determination) RIN 2501-ZA01	Global only
Energy Conservation Standards for General Service Fluorescent Lamps and Incandescent Reflector Lamps	DOE, EPCA etc.	4/29/2014 79 FR 24,067 (proposed rule) 1/26/2015 80 FR 4041 (final rule) RIN 1904-AC43	Domestic discussed in preamble Separate tables of domestic and global in TSD, though emphasis on global

Environmental Assessment for the Miles City Oil and Gas Lease Sale	Dept. of Interior, NEPA	5/2014[212]	Global only
Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units	EPA, CAA	6/18/2014 79 FR 34,829 (proposed rule) 10/23/2015 80 FR 64,661 (final rule) RIN 2060-AR33	Global only
National Pollutant Discharge Elimination System: Cooling Water Intake Structures at Existing Facilities	EPA, CWA	8/15/2014 79 FR 48,300 (final rule) RIN 2040-AE95	Global only
Energy Conservation Standards for Packaged Terminal Air Conditioners and Packaged Terminal Heat Pumps	DOE, EPCA etc.	9/16/2014 79 FR 55,537 (proposed rule) 7/21/2015 80 FR 43,161 (final rule) RIN 1904-AC82	Domestic discussed in preamble Separate tables of domestic and global in TSD, though emphasis on global
Energy Conservation Standards for Small, Large, and Very Large Air-Cooled Commercial Package Air Conditioning and Heating Equipment	DOE, EPCA etc.	9/30/2014 79 FR 58947 (proposed rule) 1/15/2016 81 FR 2419 (direct final rule) RIN 1904-AC95 RIN 1904-AD11	Domestic discussed in preamble Separate tables of domestic and global in TSD, though emphasis on global
Fossil Fuel-Generated Energy Consumption Reduction for New Federal Buildings and Major Renovations of Federal Buildings	DOE, EPCA etc.	10/14/2014 79 FR 61,693 (proposed rule) RIN 1904-AB96	Global only

[212] Bureau of Land Management, Environmental Assessment DOI-BLM-MT-C020-2014-0091-EA, 76 (May 2014), *available at* http://www.tonguerivereis.com/documents/deis_comments_organizations/FD-30186-000317-51597.pdf

Carbon Pollution Emission Guidelines for Existing Stationary Sources: EGUs in Indian Country and U.S. Territories	EPA, CAA	11/4/2014 79 FR 65,481 (proposed rule) RIN 2060-AR33	Global only
Energy Conservation Standards for Residential Dishwashers	DOE, EPCA etc.	12/19/2014 79 FR 76,141 (proposed rule) RIN 1904-AD2	Domestic discussed in preamble Separate tables of domestic and global in TSD, though emphasis on global
Energy Conservation Standards for Single Package Vertical Air Conditioners and Heat Pumps	DOE, EPCA etc.	12/30/2014 79 FR 78,613 (proposed rule) 9/23/2015 80 FR 57,437 (final rule) RIN 1904-AC85	Domestic discussed in preamble Separate tables of domestic and global in TSD, though emphasis on global
Energy Conservation Standards for Commercial Heating, Air-Conditioning, and Water-Heating Equipment	DOE, EPCA etc.	1/8/2015 80 FR 1171 (proposed rule) 7/17/2015 80 FR 42,613 (final rule) RIN 1904-AD23	Domestic discussed in preamble Separate tables of domestic and global in TSD, though emphasis on global
Energy Conservation Standards for Commercial Warm Air Furnaces	DOE, EPCA etc.	2/4/2015 80 FR 6181 (proposed rule) RIN 1904-AD11	Domestic discussed in preamble Separate tables of domestic and global in TSD, though emphasis on global
Energy Conservation Standards for Hearth Products	DOE, EPCA etc.	2/9/2015 80 FR 7081 (proposed rule) RIN 1904-AD35	Domestic discussed in preamble Separate tables of domestic and global in TSD, though emphasis on global
Environmental Assessment of Little Willow Creek Protective Oil and Gas Leasing	Dept. of Interior, NEPA	2/10/2015[213]	Global only

[213] *Available at* https://eplanning.blm.gov/epl-front-office/projects/nepa/39064/55133/59825/DOI-BLM-ID-B010-2014-0036-EA_UPDATED_02272015.pdf

Energy Conservation Standards for Residential Furnaces	DOE, EPCA etc.	3/12/2015 80 FR 13,119 (proposed rule) RIN 1904-AD20	Domestic discussed in preamble Separate tables of domestic and global in TSD, though emphasis on global
Energy Conservation Standards for Residential Boilers	DOE, EPCA etc.	3/31/2015 80 FR 17,221 (proposed rule) 1/15/2016 81 FR 2319 (final rule) RIN 1904-AC88	Domestic discussed in preamble Separate tables of domestic and global in TSD, though emphasis on global
Energy Conservation Standards for Pumps	DOE, EPCA etc.	4/2/2015 80 FR 17,825 (proposed rule) 1/26/2016 81 FR 4367 (final rule) RIN 1904-AC54	Domestic discussed in preamble Separate tables of domestic and global in TSD, though emphasis on global
Final Environmental Impact Statement for Four Corners Power Plant and Navajo Mine Energy Project	Dept. of Interior, NEPA	5/2015[214]	Global only
Energy Conservation Standards for Residential Dehumidifiers	DOE, EPCA etc.	6/3/2015 80 FR 31,645 (proposed rule) 6/13/2016 81 FR 38,337 (final rule) RIN 1904-AC81	Domestic discussed in preamble Separate tables of domestic and global in TSD, though emphasis on global
Energy Conservation Standards for Residential Conventional Ovens	DOE, EPCA etc.	6/10/2015 80 FR 33,029 (proposed rule) RIN 1904-AD15	Domestic discussed in preamble Separate tables of domestic and global in TSD, though emphasis on global

[214] *Available at* http://www.wrcc.osmre.gov/initiatives/fourCorners/documents/FinalEIS/Section%204.2%20-%20Climate%20Change.pdf

Energy Conservation Standards for Commercial Prerinse Spray Valves	DOE, EPCA etc.	7/9/2015 80 FR 39485 (proposed rule) 1/27/2016 81 FR 4747 (final rule) RIN 1904-AD31	Domestic discussed in preamble Separate tables of domestic and global in TSD, though emphasis on global
GHG and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles, Phase 2 & DOT's environmental impact statement	EPA, CAA DOT, EPCA etc. & NEPA	7/13/2015 80 FR 40,137 (proposed rule) RIN 2060-AS16 RIN 2127-AL52	Global only
Pipeline Safety: Expanding the Use of Excess Flow Valves in Gas Distribution Systems to Applications Other than Single-Family Residences	DOT, Natural Gas Pipeline Safety Act, amended by Pipeline Safety, Job Creation, and Regulatory Certainty Act	7/15/2015 80 FR 41,460 (proposed rule) RIN 2137-AE71	Global only, in the regulatory impact analysis's sensitivity analysis
Energy Conservation Standards for Ceiling Fan Light Kits	DOE, EPCA etc.	8/13/2015 80 FR 48,623 (proposed rule) 1/6/2016 81 FR 579 (final rule) RIN 1904-AC87	Domestic discussed in preamble Separate tables of domestic and global in TSD, though emphasis on global
Energy Conservation Standards for Refrigerated Bottled or Canned Beverage Vending Machines	DOE, EPCA etc.	8/19/2015 80 FR 50,461 (proposed rule) 1/8/2016 81 FR 1027 (final rule) RIN 1904-AD00	Domestic discussed in preamble Separate tables of domestic and global in TSD, though emphasis on global
Emission Guidelines and Compliance Times for Municipal Solid Waste Landfills	EPA, CAA	8/27/2015 80 FR 52099 (proposed rule) RIN 2060-AS23	Global only

NSPS for Municipal Solid Waste Landfills	EPA, CAA	8/27/2015 80 FR 52,162 (proposed rule) RIN 2060-AM08	Global only
Energy Conservation Standards for Battery Chargers	DOE, EPCA etc.	9/1/2015 80 FR 52849 (proposed rule) 6/13/2016 81 FR 38265 (final rule) RIN 1904-AB57	Domestic discussed in preamble Separate tables of domestic and global in TSD, though emphasis on global
NSPS for Oil and Natural Gas Sector	EPA, CAA	9/18/2015 80 FR 56,593 (proposed rule) 6/3/2016 81 FR 35,823 (final rule) RIN 2060-AS30	Global only
Federal Plan for GHG from EGUs	EPA, CAA	10/23/2015 80 FR 64,965 (proposed rule) RIN 2060-AS47	Global only
Roadless Area Conservation in Colorado & the Supplemental Environmental Impact Statement	Dept. of Agriculture (Forest Service), NEPA	11/20/2015 80 FR 72,665 (proposed rule) RIN 0596-AD26	Domestic and global disbenefits presented equally, along with forest-boundary estimate, with decision seemingly made on the basis of the domestic estimate
Cross-State Air Pollution Rule Update for the 2008 Ozone NAAQS	EPA, CAA	12/3/2015 80 FR 75,705 (proposed rule) RIN 2060-AS05	Global only
Energy Conservation Standards for Ceiling Fans	DOE, EPCA etc.	1/13/2016 81 FR 1687 (proposed rule) RIN 1904-AD28	Domestic discussed in preamble Separate tables of domestic and global in TSD, though emphasis on global

Waste Prevention, Production Subject to Royalties, and Resource Conservation & accompanying regulatory impact analysis and environmental assessment	Dept. of Interior, Mineral Leasing Act, Federal Land Policy and Mgmt. Act, etc. & NEPA	2/8/2016 81 FR 6615 (proposed rule) RIN 1004-AE14	Global only
Energy Conservation Standards for General Service Lamps	DOE, EPCA etc.	3/17/2016 81 FR 14,527 (proposed rule) RIN 1904-AD09	Domestic discussed in preamble, and Separate tables of domestic and global in TSD, though emphasis on global
Energy Conservation Standards for Commercial Packaged Boilers	DOE, EPCA etc.	3/24/2016 81 FR 15,835 RIN 1904-AD01	Domestic discussed in preamble, and Separate tables of domestic and global in TSD, though emphasis on global
Pipeline Safety: Safety of Gas Transmission and Gathering Pipelines	DOT, Natural Gas Pipeline Safety Act	4/8/2016 81 FR 20,722 (proposed rule) RIN 2137-AE72	Global only, in regulatory impact analysis
Energy Conservation Standards for Compressors	DOE, EPCA etc.	5/19/2016 81 FR 31,679 (proposed rule) RIN 1904-AC83	Domestic discussed in preamble, and Separate tables of domestic and global in TSD, though emphasis on global
Energy Conservation Standards for Commercial Water Heating Equipment	DOE, EPCA etc.	5/31/2016 81 FR 34,439 (proposed rule) RIN 1904-AD34	Domestic discussed in preamble, and Separate tables of domestic and global in TSD, though emphasis on global
Energy Conservation Standards for Portable Air Conditioners	DOE, EPCA etc.	6/13/2016 81 FR 38,397 (proposed rule) RIN 1904-AD02	Domestic discussed in preamble, and Separate tables of domestic and global in TSD, though emphasis on global
Energy Conservation Standards for Manufactured Housing	DOE, EPCA etc.	6/17/2016 81 FR 39,755 (proposed rule) RIN 1904-AC11	Domestic discussed in preamble, and Separate tables of domestic and global in TSD, though emphasis on global

Appendix B: Carbon Valuations Around the World

Jurisdiction/Entity	**Valuation Label** (green=analytic metric, red=tax, blue=allowance price)	**Source/Year Adopted**	**Value per tCO_2e (in 2016 US$)** [note: taxes and trading systems may not cover all economic sectors]	**Is Value > Domestic-Only SCC** (Country's % World GDP[215] * U.S. SCC)**?**
Sweden (also has carbon tax and part of EU-ETS)	"Valuation of carbon dioxide"[216]	Swedish Transport Admin.'s *Economic Principles and Estimates for the Transportation Section* (2012)[217]	**$168**, central value for emissions from long-term investments[218]	Yes (0.41% of $59 =$0.24)
Germany (also part of EU-ETS)	"Climate Cost"	Recommendations by the Federal Environment Agency on *Environmental Costs in the Energy and Transport Sectors* (2014)[219]	**$167**, average value for 2030 emissions[220]	Yes (3.45% of $59=$2)
Sweden (also part of EU-ETS and has analytic metric)	Carbon tax	Adopted 1991	**$130**[221]	Yes (0.41% of $43=$0.17)
United Kingdom (also has carbon tax and part of EU-ETS[222])	"Shadow price of carbon"[223]	*Carbon Valuation in UK Policy Appraisal*, Dept. of Energy and Climate Change (2009, 2015)[224]	**$115**, central value for 2030 non-traded emissions[225]	Yes (2.36% of $59=$1.4)

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[215] *GDP as Share of World GDP at PPP by Country,* QUANDL, https://www.quandl.com/collections/economics/gdp-as-share-of-world-gdp-at-ppp-by-country (last updated 2015); *Gross Domestic Product 2015, PPP,* WORLD DEVELOPMENT INDICATORS DATABASE, WORLD BANK (July 22, 2016), http://databank.worldbank.org/data/download/GDP_PPP.pdf.

[216] SIKA, *Summary of ASEK Estimates*, SIKA Report 2000:3 13 (2000), http://trafa.se/globalassets/sika/sika-rapport/sr_2000_3en.pdf.

[217] Cited in *Cost-Benefit Analysis*, Official Norwegian Reports NOU 2012:16 at 145 (2012), https://www.regjeringen.no/contentassets/5fce956d51364811b8547eebdbcde52c/en-gb/pdfs/nou201220120016000en_pdfs.pdf.

[218] Value reported for long-term investments as SEK 1450 (for sensitivity analysis, a SEK 3500 value is recommended), presumably in 2012 SEK, based on the publication date of the transportation sector guidelines. Inflating to 2016 SEK, based on Statistics Sweden inflation index, gives SEK 1450.81. Converting that to March 2016 US$, using Google Finance, gives $168.13, which we round to $168. *See also* SIKA Report 2000:3, *supra* note 216, at page 13, a 2000 report that suggests a value of SEK 1.5 per kilogram of carbon dioxide, which would equal about SEK 1361 per ton of carbon dioxide.

[219] Umweltbundesamt, *Environmental Costs in the Energy and Transport Sectors: Recommendations by the Federal Environment Agency*, tbl 1 (2013), http://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/hgp_umweltkosten_en.pdf.

[220] Minimum (€70), average (€145), and maximum (€215) values are given for 2030 emissions, in 2010€. Inflating the average value to 2016€, using the Eurostat index, gives €153.7. Converting that to March 2016 US$, based on Google Finance, gives $166.58, which we round to $167.

[221] Alexandre Kossoy et. al., World Bank Group & Ecofys, *State and Trends of Carbon Pricing* (2015), http://www.worldbank.org/content/dam/Worldbank/document/Climate/State-and-Trend-Report-2015.pdf; Svebio, *Carbon Tax – Key Instrument for Energy Transition,* https://www.svebio.se/sites/default/files/Carbon%20tax%20paper_COP21.pdf

[222] UK participation in the EU-ETS may depend on the Brexit negotiations.

[223] *Carbon Valuation,* GOV.UK, https://www.gov.uk/government/collections/carbon-valuation--2#shadow-price-of-carbon (last updated Nov. 18, 2015).

[224] Cited in Dept. of Energy & Climate Change, *A Brief Guide to the Carbon Valuation Methodology for UK Policy Appraisal* Table 1 (2011),

Jurisdiction/Entity	Valuation Label (green=analytic metric, red=tax, blue=allowance price)	Source/Year Adopted	Value per tCO_2e (in 2016 US$) [note: taxes and trading systems may not cover all economic sectors]	Is Value > Domestic-Only SCC (Country's % World GDP[215] * U.S. SCC)?
France (also part of EU-ETS)	Carbon tax	Adopted 2014	**$110** for 2030 emissions (currently $24)[226]	Yes (2.39% of $59=$1.4)
Norway (also part of EU-ETS and has carbon tax)	"Global marginal social cost of carbon"	Recommendations of Ministry of Finance on *Cost-Benefit Analysis* (2012), citing to the carbon price used in cost-benefit analyses by Norwegian Public Roads Admin.[227]	**$104** for 2030 non-traded emissions[228]	Yes (0.32% of $59=$0.19)
Switzerland (also has Emissions Trading System)	Carbon tax	Adopted 2008	**$87** currently, rising to maximum of $125, based on emissions trajectory[229]	Yes (0.44% of $43=$0.19)
United States—Washington State	Social Cost of Carbon	Washington State Energy Office *Recommendation for Standardizing the Social Cost of Carbon when Used for Public Decision-Making Processes* (2014)	**$86** central value for 2030 emissions (follow federal SCC, but focus on 2.5% discount rate values, rather than 3% discount rate)[230]	n/a

https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48184/3136-guide-carbon-valuation-methodology.pdf; see 2015 update for traded: Dept. of Energy & Climate Change, *Updated Short-Term Traded Carbon Values Used for UK Public Policy Appraisal* Table 1 (2015), https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/477540/Updated_short-term_traded_carbon_values_used_for_UK_policy_appraisal__2015_.pdf

225 2030 emission values are given for both emissions covered and emissions not covered by ETS: £37 (low), £74 (central), £111 (high), in 2011£. Inflating the central, non-traded value to 2016£, using the U.K. Office for National Statistics Index, gives £81.66. Converting that to March 2016 US$, based on Google Finance, gives $114.85, which we round to $115.

226 *State and Trends of Carbon Pricing, supra* note 221.

227 *Cost-Benefit Analysis, supra* note 217, at 141, 145, 148.

228 NOK 800 is the fixed unit price given for emissions starting in the year 2030. We assume that value is given in 2009NOK, based on the 2009 publication date of the Climate Cure assessment of future allowance prices. Inflating from 2009NOK to 2016NOK, using Statistics Norway inflation index, gives NOK 899.92. Converting that to March 2016 US$, using Google Finance, gives $103.54, which we round to $104.

229 *State and Trends of Carbon Pricing, supra* note 221.

230 $75, inflated from 2007 US$ to 2016 US$. Washington State Energy Office, *Recommendations for Standardizing the Social Cost of Carbon When Used for Public Decision-Making Processes* 3 (2014) (explaining "why we recommend using a 2.5% discount rate").

Jurisdiction/Entity	**Valuation Label** (green=analytic metric, red=tax, blue=allowance price)	**Source/Year Adopted**	**Value per tCO_2e (in 2016 US$)** [note: taxes and trading systems may not cover all economic sectors]	**Is Value > Domestic-Only SCC** (Country's % World GDP[215] * U.S. SCC)**?**
Various Corporations	Internal shadow prices	See CDP report[231]	As high as **$80** (Exxon) and as low as $6 (Microsoft)	n/a
Finland (also part of EU-ETS)	Carbon tax	Adopted 1990	**$64** for transport fuels, $48 for heating fuels[232]	Yes (0.2% of $43=$0.9)
United States (also has sub-national SCC use and cap-and-trade systems)	Social Cost of Carbon	Interagency Working Group *Technical Support Document on the Social Cost of Carbon* (2013)[233]	**$59**, central value for 2030 emissions[234] ($43 for 2015 emissions, $49 for 2020 emissions, and $55 for 2025 emissions)	Yes (16.14% of $59=$9.5)
United States—Minnesota	Social cost of carbon	Minnesota Public Utilities Commission recommendation for use in solar valuation	**$59**, central value for 2030 emissions (copied the federal SCC)	n/a
United States—Maine	Social cost of carbon	Maine Public Utilities Commission recommendation for use in solar valuation[235]	**$59**, central value for 2030 emissions (copied the federal SCC)	n/a
United States—New York	Social cost of carbon	New York Public Services Commission[236]	**$59**	n/a
Canada (also has sub-national taxes and cap-and-trade systems, and Prime Minister recently pledged future national carbon tax[237])	Social cost of carbon	Pledged to "align" SCC with United States;[238] history of using the U.S. interagency working group numbers[239]	**$59**, central value for 2030 emissions[240]	Yes (1.48% of $59=$0.9)

[231] CDP, *Global Corporate Use of Carbon Pricing: Disclosures to Investors* (2014); *see also State and Trends of Carbon Pricing, supra* note 221.

[232] *Id.*

[233] Interagency Working Group on Social Cost of Carbon, *Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis – Under Executive Order 12866* (2013), https://www.whitehouse.gov/sites/default/files/omb/inforeg/social_cost_of_carbon_for_ria_2013_update.pdf.

[234] *Id.* 3% discount rate value for 2030 emissions, inflated from 2007$ to 2016$ using BLS's inflation index.

[235] Maine Public Utilities Comm'n, *Main Distributed Solar Valuation Study* (2015), http://www.nrcm.org/wp-content/uploads/2015/03/MPUCValueofSolarReport.pdf.

[236] NY Pub. Serv. Comm'n, Order Adopting a Clean Energy Standard, Aug. 1, 2016, *available at* http://on.ny.gov/2amOKZI

[237] Jean Chemnick, Canada to impose a national carbon price, E&E, July 21, 2016.

[238] White House Press Secretary, U.S.-Canada Joint Statement on Climate, Energy, and Arctic Leadership, Mar. 10, 2016, https://www.whitehouse.gov/the-press-office/2016/03/10/us-canada-joint-statement-climate-energy-and-arctic-leadership ("align approaches, reflecting the best available science for accounting for the broad costs to society of the GHG emissions that will be avoided by mitigation measures, including using similar values for the social cost of carbon and other GHGs for assessing the benefits of regulatory measures.").

Jurisdiction/Entity	**Valuation Label** (green=analytic metric, red=tax, blue=allowance price)	**Source/Year Adopted**	**Value per tCO_2e (in 2016 US$)** [note: taxes and trading systems may not cover all economic sectors]	**Is Value > Domestic-Only SCC** (Country's % World GDP[215] * U.S. SCC)**?**
Mexico	Social cost of carbon	Pledged to "align" SCC with United States[241]	**$59**, presumed central value for 2030 emissions	Yes (1.98% of $59=$1.17
European Union—European Investment Bank	"Value of carbon"	*Economic Appraisal of Investment Projects at the EIB* (2013)[242]	**$57**, central value for 2030 emissions[243]	Yes (17% of $59=$10)
European Union—HEATCO Project	"Shadow Prices"	*Developing Harmonised European Approaches for Transport Costing and Project Assessment* (2006)[244]	**$55**, central value for 2030 emissions[245]	Yes (17% of $59=$10)
European Union—European Commission (also manages EU-ETS)	"Social cost of carbon"[246]	EU-ETS Impact Assessment (2008)[247]	**$52** for 2020 emissions[248]	Yes (17% of $59=$10)

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[239] *See* Order Declaring that the Reductions of Carbon Dioxide Emissions from Coal-Fired Generation of Electricity Regulations Do Not Apply in Nova Scotia, 148 Canada Gazette Part I, 1719, 1735 (June 28, 2014).

[240] Canada has used the U.S. Interagency Working Group estimates from the 2010 Technical Support Document, focusing on the 3% discount rate value, though also considering the 95th percentile value for sensitivity. *See id.* Inflating the 2010 Technical Support Document values to 2016$, based on the Bureau of Labor Statistic's inflation index, gives a central estimate for 2030 emissions of $37.48, which we round to $37.

[241] Jason Furman & Brian Deese, *The Economic Benefits of a 50 Percent Target for Clean Energy Generation by 2025*, White House Blog, June 29, 2016 (summarizing the North American Leader's Summit announcement that U.S., Canada, and Mexico would "align" their SCC estimates), https://www.whitehouse.gov/blog/2016/06/29/economic-benefits-50-percent-target-clean-energy-generation-2025.

[242] European Investment Bank, *The Economic Appraisal of Investment Projects at the EIB* Table 4.1 (2013), http://www.eib.org/attachments/thematic/economic_appraisal_of_investment_projects_en.pdf.

[243] Values are given for 2010 emissions, with annual adders. 2030 emissions are valued at €20 (low), €45 (central), €80 (high) per tCO2e, in 2006€. Inflating the central value to 2016€, using the Eurostat index, gives €52.5. Converting that to March 2016 US$, based on Google Finance, gives $56.87, which we round to $57.

[244] Peter Bickel et. al., *HEATCO Deliverable 5, Proposal for Harmonised Guidelines* (2006), http://heatco.ier.uni-stuttgart.de/HEATCO_D5_summary.pdf.

[245] Values are given for 2030 emissions: €26 (low), €40 (central), €103 (upper), in 2002€. Inflating the central value to 2016€, using the Eurostat index, gives €50.92. Converting that to March 2016 US$, based on Google Finance, gives $55.24, which we round to $55.

[246] European Comm'n DG Environment News Alert Service, *Science for Environment Policy: The Economic Benefits of Carbon Storage in the Mediterranean Sea* (23 July 2015), http://ec.europa.eu/environment/integration/research/newsalert/pdf/economic_benefits_carbon_storage_in_mediterranean_sea_422na3_en.pdf (referring to "European Commission estimates of the social cost of carbon emissions").

[247] *See* Dept. of Energy & Climate Change, *Carbon Valuation in UK Policy Appraisal: A Revised Approach* 42 (2009), https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/245334/1_20090715105804_e____carbonvaluationinukpolicyappraisal.pdf; *see also* European Commission, Impact Assessment Accompanying the Package of Implementation Measures for the EU's Objectives on Climate Change and Renewable Energy for 2020, SEC (2008), 85, at 24, http://ec.europa.eu/transparency/regdoc/rep/2/2008/EN/2-2008-85-EN-1-0.Pdf, (listing 39 euro/tCO2 as carbon price for both ETS and non-ETS).

[248] €40 value is given for 2020 emissions, in 2005€. Inflating to 2016€, using the Eurostat index, gives €47.71. Converting that to March 2016 US$, based on Google Finance, gives $51.70, which we round to $52.

Jurisdiction/Entity	**Valuation Label** (green=analytic metric, red=tax, blue=allowance price)	**Source/Year Adopted**	**Value per tCO_2e (in 2016 US$)** [note: taxes and trading systems may not cover all economic sectors]	**Is Value > Domestic-Only SCC** (Country's % World GDP[215] * U.S. SCC)**?**
Norway (also part of EU-ETS and has analytic metric)	Carbon tax	Adopted 1991	**$52** for natural gas and petrol; as low as $3 for some fuels[249]	Yes (0.32% of $43=$0.14)
United Kingdom (also part of EU-ETS and has analytic metric)	"Carbon price floor" (a tax)	Adopted 2013	**$50**, projected price for 2020 emissions[250] (currently $28[251])	Yes (2.36% of $49=$1.16)
Japan—Tokyo (Japan also has a carbon tax)	Cap and trade	Adopted 2010	**$36** (price as of 2015)[252]	Yes (4.4%* of $43=$1.9) [*Japan's GDP share]
International Monetary Fund	"Damages from global warming"	Recommendation for corrective carbon tax (2013), based on U.S. Interagency Working Group's 2010 Technical Support Document[253]	**$27**, value given without emissions year[254]	n/a
Canada—Alberta	Carbon tax	Adopted 2015[255]	**$28** for 2030 emissions[256]	n/a
Denmark (also part of EU-ETS)	Carbon tax	Adopted 1992	**$25**[257]	Yes (0.23% of $43=$0.1)

[249] *State and Trends of Carbon Pricing, supra* note 221 *see also* Statistics Norway, *Pricing of CO2 Emissions in Norway* (2009), https://www.ssb.no/a/english/publikasjoner/pdf/doc_200916_en/doc_200916_en.pdf.

[250] £30 in 2009 prices for year 2020; inflates to £35.32. Converts to $49.71, round to $50. *UK Carbon Price Floor and Carbon Price Support Mechanism*, SCOTTISH GOV'T, http://www.gov.scot/Topics/Environment/climatechange/ukandeuclimatechange/Carbon-Price-Floor (last updated Apr. 15, 2015); Dept. of Energy & Climate Change, *Overview of UK Carbon Pricing Policies* (2015),http://www.gov.scot/Topics/Environment/climatechange/ukandeuclimatechange/Carbon-Price-Floor; https://www.thepmr.org/system/files/documents/United%20Kingdom-%20Overview%20of%20Domestic%20Carbon%20Pricing%20Policies.pdf.

[251] *State and Trends of Carbon Pricing, supra* note 221.

[252] *State and Trends of Carbon Pricing, supra* note 221.

[253] Int'l Monetary Fund, *Energy Subsidy Reform: Lessons and Implications* 45 (Jan. 28, 2013), http://www.imf.org/external/np/pp/eng/2013/012813.pdf.

[254] $25 value given in 2010 US$, claiming to follow the U.S. Interagency Working Group's 2010 Technical Support Document. Inflated to 2016 US$ using BLS inflation index.

[255] *Carbon Levy and Rebates,* ALBERTA GOV'T, http://www.alberta.ca/climate-carbon-pricing.cfm.

[256] Tax set at 30$(Can) for 2018 emission, rising at inflation plus 2 percent after that. Trevor Tombe, *Here's What We Know – And Don't Know – About Alberta's Carbon Tax,* MACLEAN'S (Nov. 23, 2015), http://www.macleans.ca/economy/economicanalysis/heres-what-we-know-and-dont-know-about-albertas-carbon-tax/; *Carbon Levy and Rebates, supra* note 255. Ignoring the inflation adjuster, a 2 percent increase per year would price 2030 emissions at 38$(Can). Converting to March 2016 US$, based on Google Finance, gives $28.28, which we round to $28.

[257] *State and Trends of Carbon Pricing, supra* note 221.

Jurisdiction/Entity	Valuation Label (green=analytic metric, red=tax, blue=allowance price)	Source/Year Adopted	Value per tCO_2e (in 2016 US$) [note: taxes and trading systems may not cover all economic sectors]	Is Value > Domestic-Only SCC (Country's % World GDP[215] * U.S. SCC)?
Canada—British Columbia	Carbon tax	Adopted 2008[258]	**$23** currently[259]	n/a
Ireland (also part of EU-ETS)	Carbon tax	Adopted 2010	**$22**[260]	Yes (0.21% of $43=$0.09)
Slovenia	Carbon tax	Adopted 1996	**$19**[261]	Yes (0.06% of $43=$0.03)
Costa Rica	Fossil fuel tax (3.5% of market value)	Adopted 1997[262]	Equivalent of about $1 to **$14** per tCO2e	Yes (0.07% of $43=$0.03)
Canada—Quebec	Cap and trade	Implemented 2013	**$13** (price as of 2015)[263]	n/a
United States—California	Cap and trade	Assembly Bill (AB) 32, implemented 2013[264]	**$13** (average price as of May 2016[265])	n/a
New Zealand	Emissions Trading System	Adopted 2008	**$12.5** (price as of June 2016)[266]	Yes (0.15% of $43=$0.06)
Switzerland (also has carbon tax)	Emissions trading system	Adopted 2008[267]	**$12** (price as of 2015)[268]	Yes (0.44% of $43=$0.19)
European Union (various members have taxes; EU also uses SCC estimates)	Emissions Trading System	Implemented in 2005[269]	**$9** (price as of August 2015)[270]	Yes (17% of $43=$7.3)

[258] *See* The World Bank, *Putting a Price on Carbon with a Tax* (2014), See http://www.worldbank.org/content/dam/Worldbank/document/SDN/background-note_carbon-tax.pdf.

[259] *State and Trends of Carbon Pricing, supra* note 221; *How the Carbon Tax Works,* BRITISH COLUMBIA, http://www.fin.gov.bc.ca/tbs/tp/climate/A4.htm.

[260] *Id.*

[261] *State and Trends of Carbon Pricing, supra* note 221.

[262] Sightline Institute, *Carbon Pricing as of 2014,* http://sightline.wpengine.netdna-cdn.com/wp-content/uploads/2014/11/global-carbon-programs-map-still-111714.png; http://www.worldbank.org/content/dam/Worldbank/document/Climate/background-note_carbon-tax.pdf.

[263] *State and Trends of Carbon Pricing, supra* note 221; *see also* Québec Ministry of Sustainable Development, Environment and the Fight Against Climate Change (MDDELCC), *The Québec Cap-and-Trade System for Greenhouse Gas Emission Allowances: Frequently Asked Questions* (2014), http://www.mddelcc.gouv.qc.ca/changements/carbone/documents-spede/q&a.pdf (noting a $10 floor in 2012, with floor rising 5% per year); *see also*

[264] http://www.arb.ca.gov/cc/capandtrade/guidance/cap_trade_overview.pdf.

[265] California Air Resources Board, May 2016 Joint Auction #7 Summary Results Report 4 (2016), http://www.arb.ca.gov/cc/capandtrade/auction/may-2016/summary_results_report.pdf.

[266] ICAP, New Zealand Emissions Trading Scheme 2 (2016), https://icapcarbonaction.com/en/?option=com_etsmap&task=export&format=pdf&layout=list&systems%5B%5D=48.

[267] http://www.worldbank.org/content/dam/Worldbank/document/Climate/background-note_carbon-tax.pdf

[268] *State and Trends of Carbon Pricing, supra* note 221.

[269] European Commission, The EU Emissions Trading System (2013), http://ec.europa.eu/clima/publications/docs/factsheet_ets_en.pdf.

Jurisdiction/Entity	**Valuation Label** (green=analytic metric, red=tax, blue=allowance price)	**Source/Year Adopted**	**Value per tCO_2e (in 2016 US$)** [note: taxes and trading systems may not cover all economic sectors]	**Is Value > Domestic-Only SCC** (Country's % World GDP[215] * U.S. SCC)**?**
South Korea	Emissions Trading System	Adopted 2015	**$9** (price as of 2015)[271]	Yes (1.65% of $43=$0.7)
Iceland (also part of EU-ETS)	Carbon tax	Adopted 2010	**$8**[272]	Yes (0.01% of $43=$0.004)
South Africa	Carbon tax	Anticipated to Take Effect in January 2017[273]	**$8** (R120)	Yes (0.65% of $43=$0.28)
United States—RGGI States	Cap and trade	Implemented 2009[274]	**$8** clearing price as of December 2015[275]	n/a
United States—Boulder, Colorado	Carbon tax	Adopted 2007	Approximately **$7**[276] (up to 0.5cents per kilowatt-hour[277])	n/a
China—Beijing, Shenzhen, Hubei, Guangdong, Chongqing, Tianjin	Pilot Emissions Trading System	Adopted 2013	$2 to **$7** (prices vary across cities)[278]	No (16.32%* of $43=$7) [*China's GDP share]
Chile	Carbon tax	Effective 2018	**$5**[279]	Yes (0.38% of $49=$0.19)
Portugal (also part of EU-ETS)	Carbon tax	Adopted 2015	**$5**[280]	Yes (0.26% of $43=$0.11)
Latvia (also part of EU-ETS)	Carbon tax	Adopted 1995	**$4**[281]	Yes (0.04% of $43=$0.02)

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[270] *Id.*

[271] *Id.*

[272] *Id.*

[273] http://carbon-pulse.com/16167/

[274] RGGI Fact Sheet, https://www.rggi.org/docs/Documents/RGGI_Fact_Sheet.pdf.

[275] $7.5 per short ton clearing price for Auction 30, 12/2/2015, *Auction Results*, REGIONAL GREENHOUSE GAS INITIATIVE, https://www.rggi.org/market/co2_auctions/results,https://www.rggi.org/market/co2_auctions/results, which converts to $8.3 per metric ton, which we round to $8. *State and Trends of Carbon Pricing, supra* note 221.

[276] *Where Carbon is Taxed,* CARBON TAX CENTER, http://www.carbontax.org/states/#Boulder (Colorado).

[277] *Climate Action Tax*, CITY OF BOULDER COLORADO, https://bouldercolorado.gov/climate/climate-action-plan-cap-tax.

[278] *State and Trends of Carbon Pricing, supra* note 221.

[279] Id. http://www.worldbank.org/content/dam/Worldbank/document/Climate/State-and-Trend-Report-2015.pdf

[280] *Id.*

[281] *Id.*

Jurisdiction/Entity	Valuation Label (green=analytic metric, red=tax, blue=allowance price)	Source/Year Adopted	Value per tCO_2e (in 2016 US$) [note: taxes and trading systems may not cover all economic sectors]	Is Value > Domestic-Only SCC (Country's % World GDP[215] * U.S. SCC)?
Japan (also has sub-national cap-and-trade systems)	Carbon tax	Adopted 2012	**$3**[282]	Not significantly greater (4.4% of $49=$2.2)
Mexico (also calculates global benefits in regulatory impact analyses)	Carbon tax	Adopted 2012	$1 to **$3**, depending on fuel type[283]	Yes (1.98% of $43=$0.85)
Kazakhstan	Emissions Trading System	Adopted 2013	**$2** (average price as of 2014)[284]	Yes (0.39% of $43=$0.17)
Estonia (also part of EU-ETS)	Carbon tax	Adopted 2000	**$2**	Yes (0.03% of $43=$0.01)
India	Coal tax (INR 50 per ton of coal)	Adopted 2010	About **$2** per tCO2 (also claims an implicit carbon tax on petrol of $140 per tCO2)[285]	No (6.83% of $43=$2.7)
Poland (also part of EU-ETS)	Carbon tax	Adopted 1990	<$1[286]	Uncertain (0.88% of $43=$0.38)
Thailand	Vehicle tax based on CO_2 emissions[287]	Effective 2016[288]	>$0 (tax based on car price, difficult to convert to price per tCO2e)	Uncertain

[282] *Japan Introduces New Tax on Carbon Emissions,* JAPAN FOR SUSTAINABILITY (Jan. 4, 2013), http://www.japanfs.org/en/news/archives/news_id032490.html (289 yen);).*State and Trends of Carbon Pricing, supra* note 221; http://www.iea.org/policiesandmeasures/pams/japan/name-139284-en.php.

[283] Mike Szabo, *Mexico to Launch Carbon Offset Trading in 2017, Will Pursue Link to WCI Markets,* CARBON PULSE (July 9, 2015), http://carbon-pulse.com/6143/; *State and Trends of Carbon Pricing, supra* note 221.

[284] *State and Trends of Carbon Pricing, supra* note 221.

[285] India, Intended Nationally Determined Contribution, Submission to UNFCCC, at 27 (2015), http://www4.unfccc.int/submissions/INDC/Published%20Documents/India/1/INDIA%20INDC%20TO%20UNFCCC.pdf.

[286] *State and Trends of Carbon Pricing, supra* note 221.

[287] Excise Dept., *Thailand's Automotive Excise Tax Reform* (2014), http://transportandclimatechange.org/wp-content/uploads/2015/01/Thailands-Automotive-Excise-Tax-Reform.pdf.

[288] Thailand Intended Nationally Determined Contribution, Submission to UNFCCC (2015), http://www4.unfccc.int/submissions/INDC/Published%20Documents/Thailand/1/Thailand_INDC.pdf.