EDF'S
EXHIBIT GGG

Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide Interim Estimates under Executive Order 13990

Interagency Working Group on Social Cost of Greenhouse Gases, United States Government

With participation by

Council of Economic Advisers
Council on Environmental Quality
Department of Agriculture
Department of Commerce
Department of Energy
Department of Health and Human Services
Department of the Interior
Department of Transportation
Department of the Treasury
Environmental Protection Agency
National Climate Advisor
National Economic Council
Office of Management and Budget
Office of Science and Technology Policy

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Preface

The Interagency Working Group (IWG) on the Social Cost of Greenhouse Gases is committed to ensuring that the estimates agencies use when monetizing the value of changes in greenhouse gas emissions resulting from regulations and other relevant agency actions continue to reflect the best available science and methodologies. This Technical Support Document (TSD) presents interim estimates of the social cost of carbon, methane, and nitrous oxide developed under Executive Order 13990. These interim values are the same as those developed by the IWG in 2013 and 2016. The current IWG will take comment on recent developments in the science and economics for use in a more comprehensive update, to be issued by January 2022, which will more fully address the recommendations of the National Academies of Sciences, Engineering, and Medicine as reported in Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide (2017) and other pertinent scientific literature. As a part of that request for comment, the IWG will seek comment on the discussion of advances in science and methodology included in this TSD and how those advances can best be incorporated into the revised final estimates.

Executive Summary

A robust and scientifically founded assessment of the positive and negative impacts that an action can be expected to have on society provides important insights in the policy-making process. The estimates of the social cost of carbon (SC-CO_2), social cost of methane (SC-CH_4), and social cost of nitrous oxide (SC-N_2O) presented here allow agencies to understand the social benefits of reducing emissions of each of these greenhouse gases, or the social costs of increasing such emissions, in the policy making process. Collectively, these values are referenced as the "social cost of greenhouse gases" (SC-GHG) in this document. The SC-GHG is the monetary value of the net harm to society associated with adding a small amount of that GHG to the atmosphere in a given year. In principle, it includes the value of all climate change impacts, including (but not limited to) changes in net agricultural productivity, human health effects, property damage from increased flood risk natural disasters, disruption of energy systems, risk of conflict, environmental migration, and the value of ecosystem services. The SC-GHG, therefore, should reflect the societal value of reducing emissions of the gas in question by one metric ton. The marginal estimate of social costs will differ by the type of greenhouse gas (such as carbon dioxide, methane, and nitrous oxide) and by the year in which the emissions change occurs. The SC-GHGs are the theoretically appropriate values to use in conducting benefit-cost analyses of policies that affect GHG emissions.

Federal agencies began regularly incorporating social cost of carbon (SC-CO_2) estimates in benefit-cost analyses conducted under Executive Order (E.O.) 12866[1] in 2008, following a court ruling in which an agency was ordered to consider the value of reducing CO_2 emissions in a rulemaking process. The U.S. Ninth Circuit Court of Appeals remanded a fuel economy rule to DOT for failing to monetize CO_2 emission reductions, stating that "while the record shows that there is a range of values, the value of carbon emissions reduction is certainly not zero."[2] In 2009, an interagency working group (IWG) was established to ensure that agencies were using the best available science and to promote consistency in the values used across agencies. The IWG published SC-CO_2 estimates in 2010 that were developed from an ensemble of three widely cited integrated assessment models (IAMs) that estimate global climate damages using highly aggregated representations of climate processes and the global economy combined into a single modeling framework. The three IAMs were run using a common set of input assumptions in each model for future population, economic, and GHG emissions growth, as well as equilibrium climate sensitivity (ECS) – a measure of the globally averaged temperature response to increased atmospheric CO_2 concentrations. These estimates were updated in 2013 based on new versions of each IAM. In August 2016 the IWG published estimates of the social cost of methane (SC-CH_4) and nitrous oxide (SC-N_2O) using methodologies that are consistent with the methodology underlying the SC-CO_2 estimates. In January 2017, the National Academies of Sciences, Engineering, and Medicine issued recommendations for an updating process to ensure the estimates continue to reflect the best available science. In March 2017, Executive Order 13783 disbanded the IWG and instructed agencies when monetizing the value of changes

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[1] Under E.O. 12866, agencies are required, to the extent permitted by law and where applicable, "to assess both the costs and the benefits of the intended regulation and, recognizing that some costs and benefits are difficult to quantify, propose or adopt a regulation only upon a reasoned determination that the benefits of the intended regulation justify its costs." As indicated in the discussion above, many statutes also require agencies to conduct at least some of the same analyses required under E.O. 12866, such as the Energy Policy and Conservation Act which mandates the setting of fuel economy regulations.

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

in greenhouse gas emissions resulting from regulations to follow the Office of Management and Budget's (OMB) Circular A-4.

On January 20, 2021, President Biden issued E.O. 13990 which re-established the IWG and directed it to ensure that SC-GHG estimates used by the U.S. Government (USG) reflect the best available science and the recommendations of the National Academies (2017) and work towards approaches that take account of climate risk, environmental justice, and intergenerational equity. The IWG was tasked with first reviewing the SC-GHG estimates currently used by the USG and publishing interim estimates within 30 days of the E.O. that reflect the full impact of GHG emissions, including taking global damages into account. In this initial review, the IWG finds that the SC-GHG estimates used since E.O. 13783 fail to reflect the full impact of GHG emissions in multiple ways. First, the IWG found previously and is restating here that a global perspective is essential for SC-GHG estimates because climate impacts occurring outside U.S. borders can directly and indirectly affect the welfare of U.S. citizens and residents. Thus, U.S. interests are affected by the climate impacts that occur outside U.S. borders. Examples of affected interests include: direct effects on U.S. citizens and assets located abroad, international trade, tourism, and spillover pathways such as economic and political destabilization and global migration. In addition, assessing the benefits of U.S. GHG mitigation activities requires consideration of how those actions may affect mitigation activities by other countries, as those international mitigation actions will provide a benefit to U.S. citizens and residents by mitigating climate impacts that affect U.S. citizens and residents. Second, the IWG found previously and is restating here that the use of the social rate of return on capital to discount the future benefits of reducing GHG emissions inappropriately underestimates the impacts of climate change for the purposes of estimating the SC-GHG (see Section 3.1). Consistent with the findings of the National Academies (2017) and the economic literature, the IWG continues to conclude that the consumption rate of interest is the theoretically appropriate discount rate in an intergenerational context (IWG 2010, 2013, 2016). The IWG recommends that discount rate uncertainty and relevant aspects of intergenerational ethical considerations be accounted for in selecting future discount rates.

While the IWG works to assess how best to incorporate the latest, peer reviewed science to develop an updated set of SC-GHG estimates, it is setting interim estimates to be the most recent estimates developed by the IWG prior to the group being disbanded in 2017. The IWG concludes that these interim estimates represent the most appropriate estimate of the SC-GHG until the revised estimates have been developed. This update reflects the immediate need to have an operational SC-GHG for use in regulatory benefit-cost analyses and other applications that was developed using a transparent process, peer-reviewed methodologies, and the science available at the time of that process. Those estimates were subject to public comment in the context of dozens of proposed rulemakings as well as in a dedicated public comment period in 2013.

At the same time, consistent with its continuing commitment to a transparent process and a desire to move quickly to update SC-GHG estimates to better reflect the recent science, the IWG will be taking comment on how to incorporate the recommendations of the National Academies (2017) and other recent science , including the advances discussed in this Technical Support Document (TSD), both during the development of the fully updated SC-GHG estimates to be released by January of 2022 and in subsequent updates. The IWG will soon issue a Federal Register notice with a detailed set of requests for public comments on the new information presented in this TSD, as well as other topics and issues the IWG will address as we develop the next set of updates.

This TSD presents the IWG's interim findings and provides interim estimates of the SC-CO_2, SC-CH_4, and SC-N_2O that should be used by agencies until a comprehensive review and update is developed in line with the requirements in E.O. 13990. The TSD maintains the same methodological approach as has been used for global USG SC-GHG estimation to date. The estimates rely on the same models and harmonized inputs and are calculated using a range of discount rates. At this time, the IWG has determined that it is appropriate for agencies to revert to the same set of four values drawn from the SC-GHG distributions based on three discount rates (2.5 percent, 3 percent, and 5 percent) as were used in regulatory analyses between 2010 and 2016 and subject to public comment. However, as described below, based on the IWG's initial review, new data and evidence strongly suggests that the discount rate regarded as appropriate for intergenerational analysis is lower.

Tables ES-1, ES-2, and ES-3 summarize the interim SC-CO_2, SC-CH_4, and SC-N_2O estimates, respectively, for the years 2020 through 2050. These estimates are reported in 2020 dollars but are otherwise identical to those presented in the previous version of the TSD and its Addendum, released in August 2016. For purposes of capturing uncertainty around the SC-GHG estimates in analyses, the IWG emphasized previously and reemphasizes here the importance of considering all four of the SC-GHG values. In particular, this TSD discusses how the understanding of discounting approaches suggests discount rates appropriate for intergenerational analysis in the context of climate change that are lower than 3 percent. Consistent with the guidance in E.O. 13990 for the IWG to ensure that the SC-GHG reflect the interests of future generations, the latest scientific and economic understanding of discount rates discussed in this TSD, and the recommendation from OMB's Circular A-4 to include sensitivity analysis with lower discount rates when a rule has important intergenerational benefits or costs, agencies may consider conducting additional sensitivity analysis using discount rates below 2.5 percent. Furthermore, the IAMs used to produce these interim estimates do not include all of the important physical, ecological, and economic impacts of climate change recognized in the climate change literature. For these same impacts, the science underlying their "damage functions" – i.e., the core parts of the IAMs that map global mean temperature changes and other physical impacts of climate change into economic (both market and nonmarket) damages – lags behind the most recent research. Likewise, the assumptions regarding equilibrium climate sensitivity and socioeconomic and emissions scenarios used as inputs to the model runs in this TSD will need to be updated. It is the IWG's judgment that, taken together, these limitations suggest that the range of four interim SC-GHG estimates presented in this TSD likely underestimate societal damages from GHG emissions.

Table ES-1: Social Cost of CO_2, 2020 – 2050 (in 2020 dollars per metric ton of CO_2)[3]

Emissions Year	Discount Rate and Statistic			
	5% Average	3% Average	2.5% Average	3% 95th Percentile
2020	14	51	76	152
2025	17	56	83	169
2030	19	62	89	187
2035	22	67	96	206
2040	25	73	103	225
2045	28	79	110	242
2050	32	85	116	260

Table ES-2: Social Cost of CH_4, 2020 – 2050 (in 2020 dollars per metric ton of CH_4)

Emissions Year	Discount Rate and Statistic			
	5% Average	3% Average	2.5% Average	3% 95th Percentile
2020	670	1500	2000	3900
2025	800	1700	2200	4500
2030	940	2000	2500	5200
2035	1100	2200	2800	6000
2040	1300	2500	3100	6700
2045	1500	2800	3500	7500
2050	1700	3100	3800	8200

[3] The values reported in this TSD are identical to those reported in the 2016 TSD adjusted for inflation to 2020 dollars using the annual GDP Implicit Price Deflator values in the U.S. Bureau of Economic Analysis' (BEA) NIPA Table 1.1.9: 113.626 (2020)/ 92.486 (2007) = 1.228575 (U.S. BEA 2021). Values are the average across models and socioeconomic emissions scenarios for each of three discount rates (2.5%, 3%, and 5%), plus a fourth value, selected as the 95th percentile of estimates based on a 3 percent discount rate. Values of SC-CO_2 are rounded to the nearest dollar; SC-CH_4 and SC-N_2O are rounded to two significant figures. The annual unrounded estimates are available on OMB's website for use in regulatory and other analyses: https://www.whitehouse.gov/omb/information-regulatory-affairs/regulatory-matters/#scghgs

Table ES-3: Social Cost of N_2O, 2020 – 2050 (in 2020 dollars per metric ton of N_2O)

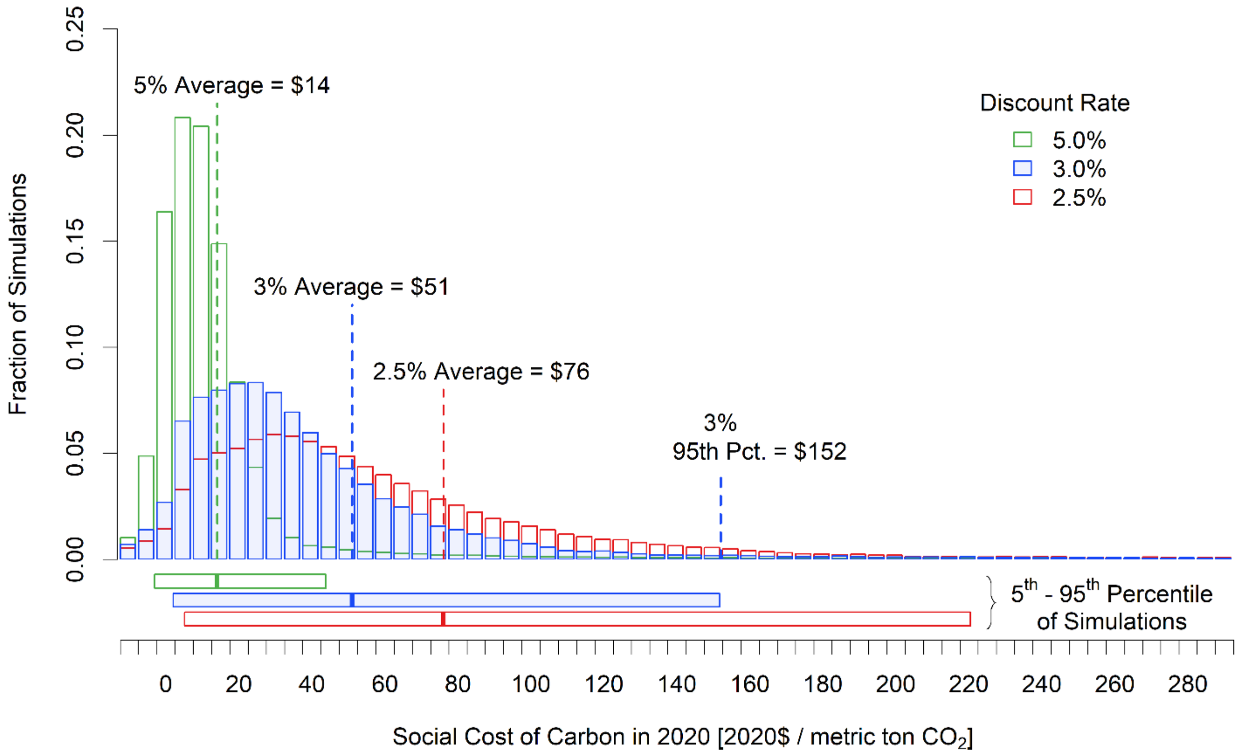
Emissions Year	Discount Rate and Statistic			
	5% Average	3% Average	2.5% Average	3% 95th Percentile
2020	5800	18000	27000	48000
2025	6800	21000	30000	54000
2030	7800	23000	33000	60000
2035	9000	25000	36000	67000
2040	10000	28000	39000	74000
2045	12000	30000	42000	81000
2050	13000	33000	45000	88000

While point estimates are important for providing analysts with a tractable approach for regulatory analysis, they do not fully quantify uncertainty associated with the SC-GHG estimates. Figures ES-1 through ES-3 present the quantified sources of uncertainty in the form of frequency distributions for the SC-GHG estimates for emissions in 2020. The distributions of SC-GHG estimates reflect uncertainty in key model parameters chosen by the IWG such as the equilibrium climate sensitivity, as well as uncertainty in other parameters set by the original model developers. To highlight the difference between the impact of the discount rate and other quantified sources of uncertainty, the bars below the frequency distributions provide a symmetric representation of quantified variability in the SC-GHG estimates for each discount rate. There are other sources of uncertainty that have not yet been quantified and are thus not reflected in these estimates. When an agency determines that it is appropriate to conduct additional quantitative uncertainty analysis, it should follow best practices for probabilistic analysis.[4] The full set of information that underlies the frequency distributions in Figures ES-1 through ES-3 is available on OMB's website[5].

See e.g. OMB's Circular A-4, section on *Treatment of Uncertainty*. Available at: https://www.whitehouse.gov/sites/whitehouse.gov/files/omb/circulars/A4/a-4.pdf.

[5] Available at https://www.whitehouse.gov/omb/information-regulatory-affairs/regulatory-matters/#scghgs

Figure ES-1: Frequency Distribution of $SC\text{-}CO_2$ Estimates for 2020[6]



[6] Although the distributions and numbers in Figures ES-1, ES-2, and ES-3 are based on the full set of model results (150,000 estimates for each discount rate and gas), for display purposes the horizontal axis is truncated with 0.02 to 0.68 percent of the estimates falling below the lowest bin displayed and 0.12 to 3.11 percent of the estimates falling above the highest bin displayed, depending on the discount rate and GHG.

Figure ES-2: Frequency Distribution of SC-CH₄ Estimates for 2020

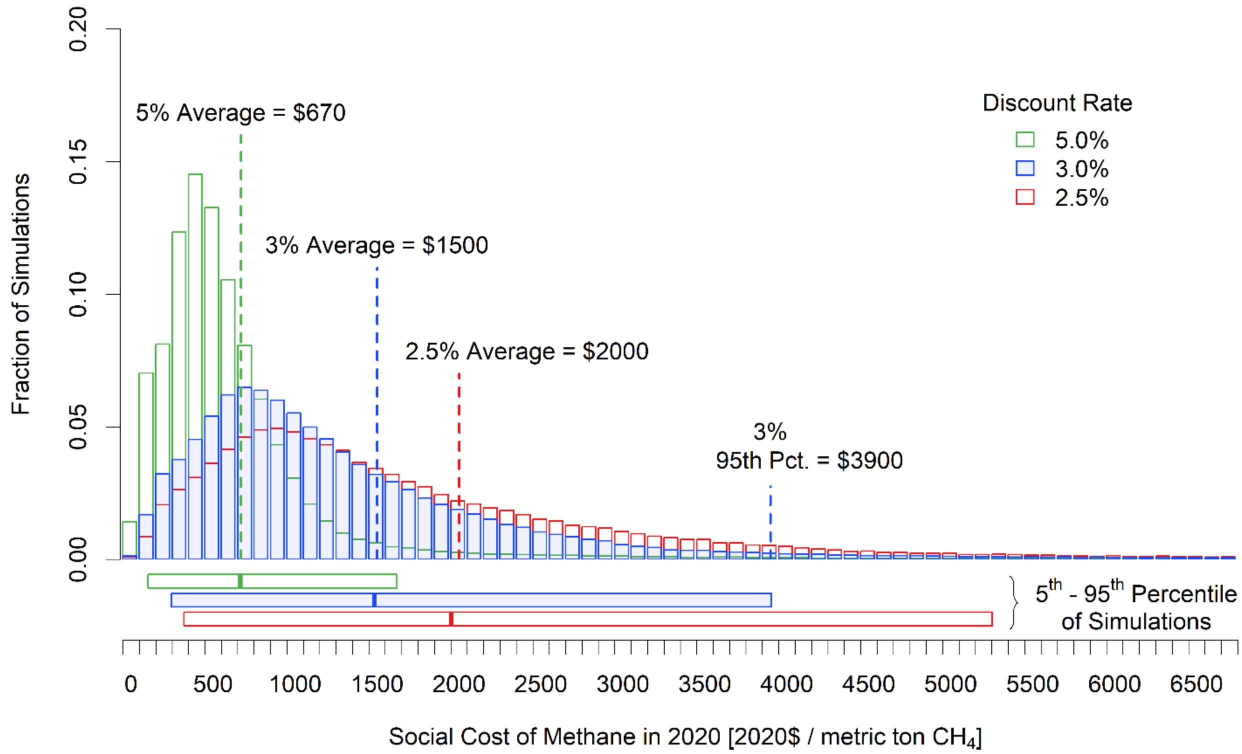
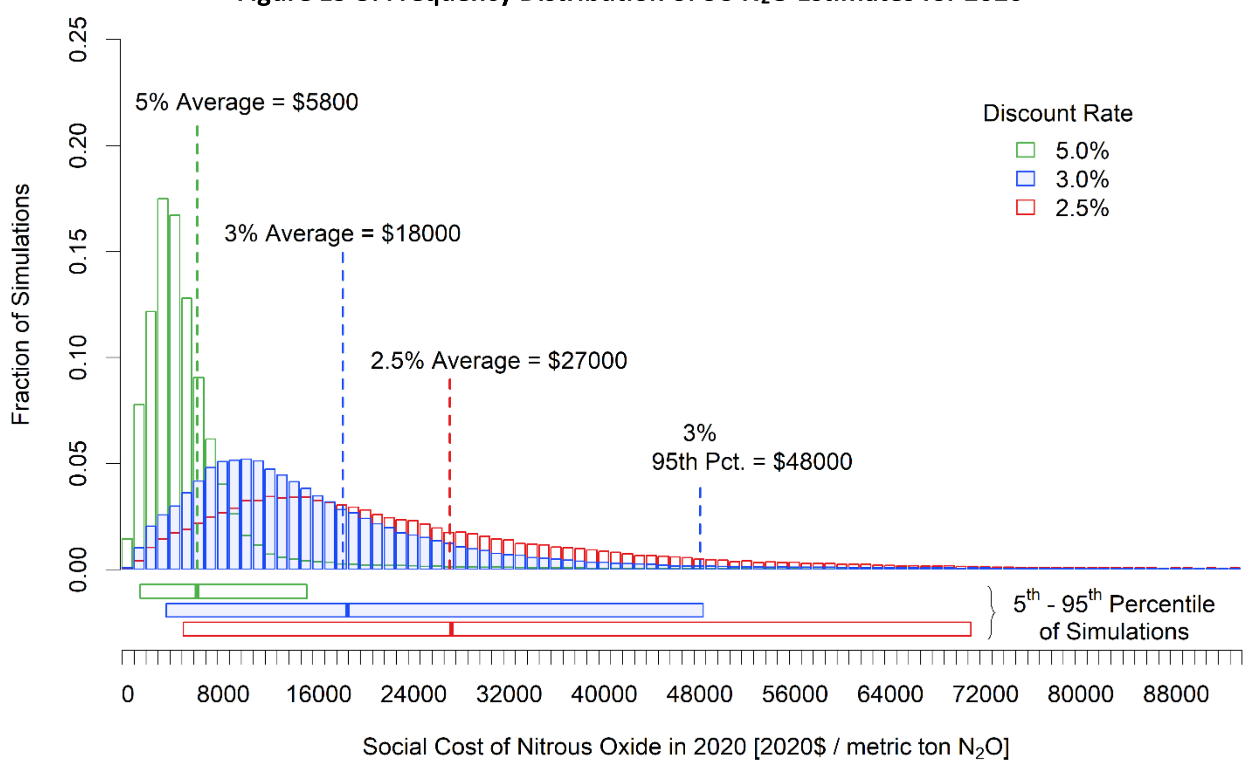


Figure ES-3: Frequency Distribution of SC-N_2O Estimates for 2020



1 Background

The estimates of the social cost of carbon (SC-CO_2), social cost of methane (SC-CH_4), and social cost of nitrous oxide (SC-N_2O) presented here allow agencies to incorporate the social benefits of reducing emissions of each of these greenhouse gases, or the social costs of increasing such emissions, in decision making. Collectively, these values are referenced as the "social cost of greenhouse gases" (SC-GHG) in this document. The SC-GHG is the monetary value of the net harm to society associated with adding a small amount of that GHG to the atmosphere in a given year. In principle, it includes the value of all climate change impacts, including (but not limited to) changes in net agricultural productivity, human health effects, property damage from increased flood risk natural disasters, disruption of energy systems, risk of conflict, environmental migration, and the value of ecosystem services. The SC-GHG, therefore, should reflect the societal value of reducing emissions of the gas in question by one ton. The marginal estimate of social costs will differ by the type of greenhouse gas (such as carbon dioxide, methane, and nitrous oxide) and by the year in which the emissions change occurs. The SC-GHGs are calculated along a baseline path and provide a measure of the marginal benefit of GHG abatement. Thus, they are the theoretically appropriate values to use when conducting benefit-cost analyses of policies that affect GHG emissions.[7]

1.1 Overview of U.S. Government SC-GHG Estimates to Date

Estimates of the social cost of carbon and other greenhouse gases have been published in the academic literature for many years. Meta-reviews of SC-CO_2 estimates were available as early as 2002 (Clarkson and Deyes 2002). Federal agencies began regularly incorporating SC-CO_2 estimates in regulatory impact analyses in 2008, following a court ruling in which an agency was ordered to consider the SC-CO_2 in the rulemaking process. The U.S. Ninth Circuit Court of Appeals remanded a fuel economy rule to the Department of Transportation (DOT) for failing to consider the value of reducing CO_2 emissions, stating that "while the record shows that there is a range of values, the value of carbon emissions reduction is certainly not zero."[8]

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[7] These estimates of social damages should not be confused with estimates of the costs of attaining a specific emissions or warming limit. Specifically, there is another strand of research that investigates the costs of setting a specific climate target (e.g., capping emissions or temperature increases to a certain level). If total emissions are capped, IAM models can estimate the costs of limiting emissions or temperature increase to that cap. Similarly, other models simulate market trading in a cap and trade system. The price of a permit to emit one ton of carbon provides a measure of the marginal cost of GHG abatement, which can be useful in evaluating policy cost-effectiveness but is not an alternative way to value damages from GHG emissions in benefit-cost analysis. Moreover, a policy that specifies an environmental target implicitly requires a valuation of damages when setting the constraint even though it is not explicitly modeled or estimated. For example, a target set to keep temperature increases below a certain threshold implicitly places value on damages incurred beyond that threshold. For more on how these concepts (e.g., a predetermined target-based approach and a damage (SC-GHG) based approach) can be used when designing climate policy see, for example, Hansel et al. (2020) and Stern and Stiglitz (2021).

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

In 2009, an interagency process was launched, under the leadership of the Office of Management and Budget (OMB) and the Council of Economic Advisers (CEA), that sought to harmonize a range of different SC-CO_2 values being used across multiple Federal agencies. The purpose of this process was to ensure that agencies were using the best available information and to promote consistency in the way agencies quantify the benefits of reducing CO_2 emissions in regulatory impact analyses. This included the establishment of an IWG which represented perspectives and technical expertise from many federal agencies and a commitment to following the peer-reviewed literature. In 2010, the IWG finalized a set of four SC-CO_2 values for use in regulatory analyses and presented them in a TSD that also provided guidance for agencies on using the estimates (IWG 2010). Three of these values were based on the average SC-CO_2 from three widely cited integrated assessment models (IAMs) in the peer-reviewed literature – DICE, PAGE, and FUND[9] – at discount rates of 2.5, 3, and 5 percent. The fourth value was included to represent higher-than-expected economic impacts from climate change further out in the tails of the SC-CO_2 distribution. For this purpose, it used the SC-CO_2 value for the 95th percentile at a 3 percent discount rate.

In May of 2013, the IWG provided an update of the SC-CO_2 estimates to incorporate new versions of the IAMs used in the peer-reviewed literature (IWG 2013). The 2013 update did not revisit other IWG modeling decisions (i.e., the discount rates or harmonized inputs for socioeconomic and emission scenarios and equilibrium climate sensitivity). Improvements in the way damages are modeled were confined to those that had been incorporated into the latest versions of the models by the developers themselves in the peer-reviewed literature.[10] In August of 2016, the IWG published estimates of the social cost of methane (SC-CH_4) and nitrous oxide (SC-N_2O) that are consistent with the methodology underlying the SC-CO_2 estimates (IWG 2016a, 2016b).

Over the course of developing and updating the USG SC-GHG, through both the IWG and individual agencies, there were extensive opportunities for public input on the estimates and underlying methodologies. There was a public comment process associated with each proposed rulemaking that used the estimates, and OMB initiated a separate comment process on the IWG TSD in 2013. Commenters offered a wide range of perspectives on all aspects of process, methodology, and final estimates and diverse suggestions for improvements. The U.S. Government Accountability Office (GAO) also reviewed the development of the USG SC-CO_2 estimates and concluded that the IWG processes and methods reflected three principles: consensus-based decision making, reliance on existing academic literature and models, and disclosure of limitations and incorporation of new information (U.S. GAO 2014).

[9] The DICE (Dynamic Integrated Climate and Economy) model by William Nordhaus evolved from a series of energy models and was first presented in 1990 (Nordhaus and Boyer 2000, Nordhaus 2008). The PAGE (Policy Analysis of the Greenhouse Effect) model was developed by Chris Hope in 1991 for use by European decision-makers in assessing the marginal impact of carbon emissions (Hope 2006, Hope 2008). The FUND (Climate Framework for Uncertainty, Negotiation, and Distribution) model, developed by Richard Tol in the early 1990s, originally to study international capital transfers in climate policy was widely used to study climate impacts (e.g., Tol 2002a, Tol 2002b, Anthoff et al. 2009, Tol 2009).

[10] The IWG subsequently provided additional minor technical revisions in November of 2013 and July of 2015, as explained in Appendix B of the 2016 TSD (IWG 2016a).

In 2015, as part of the IWG response to the public comments received in the 2013 solicitation, the IWG announced a National Academies of Sciences, Engineering, and Medicine review of the IWG estimates (IWG 2015). Specifically, the IWG asked the National Academies to conduct a multi-discipline, two-phase assessment of the IWG estimates and to offer advice on how to approach future updates to ensure that the estimates continue to reflect the best available science and methodologies. The National Academies' interim (Phase 1) report (National Academies 2016a) recommended against a near term update of the SC-CO_2 estimates within the existing modeling framework. For future revisions, the National Academies recommended the IWG move efforts towards a broader update of the climate system module consistent with the most recent, best available science and offered recommendations for how to enhance the discussion and presentation of uncertainty in the SC-CO_2 estimates. In addition to publishing estimates of SC-CH_4 and SC-N_2O, the IWG's 2016 TSD revision responded to the National Academies' Phase 1 report recommendations regarding presentation of uncertainty. The revisions included: an expanded presentation of the SC-GHG estimates that highlights a symmetric range of uncertainty around estimates for each discount rate; new sections that provide a unified discussion of the methodology used to incorporate sources of uncertainty; detailed explanation of the uncertain parameters in both the FUND and PAGE models; and making the full set of SC-CO_2 estimates easily accessible to the public on OMB's website.

In January 2017, the National Academies released their final report, *Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide*, and recommended specific criteria for future updates to the SC-CO_2 estimates, a modeling framework to satisfy the specified criteria, and both near-term updates and longer-term research needs pertaining to various components of the estimation process (National Academies 2017). A description of the National Academies' recommendations for near-term updates are described in Section 1.2 of this document. Shortly thereafter, in March 2017, President Trump issued Executive Order (E.O.) 13783 which called for the rescission and review of several climate-related Presidential and regulatory actions as well as for a review of the SC-GHG estimates used for regulatory impact analysis. E.O. 13783 disbanded the IWG, withdrew the previous TSDs, and directed agencies to ensure SC-GHG estimates used in regulatory analyses are consistent with the guidance contained in OMB's Circular A-4, "including with respect to the consideration of domestic versus international impacts and the consideration of appropriate discount rates" (E.O. 13783, Section 5(c)). Benefit-cost analyses following E.O. 13783 used SC-GHG estimates that attempted to focus on the domestic impacts of climate change as estimated by the models to occur within U.S. borders and were calculated using two discount rates recommended by OMB's Circular A-4, 3 percent and 7 percent.[11] All other methodological decisions and model versions used in SC-GHG calculations remained the same as those used by the IWG in 2010 and 2013, respectively.

On January 20, 2021, President Biden issued E.O. 13990, which re-established the IWG and directed it to ensure that USG SC-GHG estimates reflect the best available science and the recommendations of the National Academies (2017). The IWG was tasked with first reviewing the SC-GHG estimates currently used by the USG and publishing interim estimates within 30 days of the E.O. that reflect the full impact of GHG emissions, including by taking global damages into account. The E.O. instructs the IWG to develop final SC-GHG estimates by January 2022. Section 1.3 describes requirements established by E.O. 13990 in greater detail. In addition, the E.O. instructs the IWG to provide recommendations to the President by

[11] OMB Circular A-4 (2003) indicates that sensitivity analysis using lower discount rates than 3 percent and 7 percent may be appropriate where intergenerational effects are important. See Section 3 for further discussion.

September 2021, regarding areas of decision-making, budgeting, and procurement by the Federal Government where the SC-GHG should be applied. The SC-GHG has been used previously in non-regulatory Federal analysis, such as in federal procurement,[12] grant programs,[13] and National Environmental Policy Act (NEPA) analysis,[14] as well as in state level applications; the latter is discussed further in Section 5.

1.2 Recommendations from the National Academies of Sciences, Engineering, and Medicine

In 2015, the IWG requested that the National Academies of Sciences, Engineering, and Medicine review and recommend potential approaches for improving its SC-CO_2 estimation methodology. In response, the National Academies convened a multidisciplinary committee, the Committee on Assessing Approaches to Updating the Social Cost of Carbon. In addition to evaluating the IWG's overall approach to SC-CO_2 estimation, the committee reviewed its choices of IAMs and damage functions, climate science assumptions, future baseline socioeconomic and emission projections, presentation of uncertainty, and discount rates.

In its final report (National Academies 2017), the National Academies committee recommended that the IWG pursue an integrated modular approach to the key components of SC-CO_2 estimation to allow for independent updating and review and to draw more readily on expertise from the wide range of scientific disciplines relevant to SC-CO_2 estimation. Under this approach, each step in SC-CO_2 estimation is developed as a module—socioeconomic projections, climate science, economic damages, and discounting—that reflects the state of scientific knowledge in the current, peer-reviewed literature. In the longer-term, it recommended that the IWG also fund research on ways to better capture interactions and feedbacks between these components. In addition, the committee noted that, while the IWG harmonized assumptions across the IAMs for socioeconomic and emission projections, climate sensitivity, and discount rates when estimating the SC-CO_2, using a single climate module in the nearer-term (2-3 years) and eventually transitioning to a single IAM framework will enhance transparency, improve consistency with the underlying science, and allow for more explicit representation of uncertainty. It recommended these three criteria also be used to judge the value of other updates to the methodology. In addition, it recommended that the IWG update SC-CO_2 estimates at regular intervals, suggesting a five-year cycle.

Regarding the key components of the SC-CO_2, the committee recommended the following improvements in the nearer-term:

- Socioeconomic and emissions projections: Use accepted statistical methods and elicit expert judgment to project probability distributions of future annual growth rates of per-capita GDP and

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[12] For example, SC-CO_2 estimates have been used in Domestic Delivery Services contracts for USG parcel shipping (https://westcoastclimateforum.com/sites/westcoastclimateforum/files/related_documents/FedGSA_DDS3_green_features_fact_sheet.pdf).

[13] For example, in 2016 DOT's Transportation Investment Generating Economic Recovery (TIGER) discretionary grant program required a demonstration that benefits justify costs for proposed projects, and the guidance DOT provides to applicants for how to conduct such an analysis specified that they should use the USG SC-CO_2 estimates (https://www.transportation.gov/sites/dot.gov/files/docs/BCARG2016March.pdf).

[14] See Howard and Schwartz (2019) for examples of the use of SC-CO_2 estimates in NEPA analyses.

population, bearing in mind potential correlation between economic and population projections. Then using expert elicitation, guided by information on historical trends and emissions consistent with different climate outcomes, project emissions for each forcing agent of interest conditional on population and income scenarios. Additional recommendations were offered for improving the socioeconomic module centered on four broad criteria: time horizon, future policies, disaggregation, and feedbacks.

- Climate science: Adopt or develop a simple Earth system model (such as the Finite Amplitude Impulse Response (FaIR) model) to capture relationships between CO_2 emissions, atmospheric CO_2 concentrations, and global mean surface temperature change over time while accounting for non-CO_2 forcing and allowing for the evaluation of uncertainty. It also recommended the IWG adopt or develop a sea level rise component in the climate module that: (1) accounts for uncertainty in the translation of global mean temperature to global mean sea level rise and (2) is consistent with sea level rise projections available in the literature for similar forcing and temperature pathways. It also noted the importance of generating spatially and temporally disaggregated climate information as inputs into damage estimation. It recommended the use of linear pattern scaling (which estimates linear relationships between global mean temperature and local climate variables) to achieve this goal in the near-term.
- Economic damages: Improve and update existing formulations of individual sectoral damage functions when feasible; characterize damage function calibrations quantitatively and transparently; present spatially disaggregated damage projections and discuss how they scale with temperature, income, and population; and recognize any correlations between formulations when multiple damage functions are used.
- Discounting: Account for the relationship between economic growth and discounting; explicitly recognize uncertainty surrounding discount rates over long time horizons using a Ramsey-like approach; select parameters to implement this approach that are consistent with theory and evidence to produce certainty-equivalent discount rates consistent with near-term consumption rates of interest; use three sets of Ramsey parameters to generate a low, central, and high certainty-equivalent near-term discount rate, and three means and ranges of SC-CO_2 estimates; discuss how the SC-CO_2 estimates should be combined with other cost and benefit estimates that may use different discount rates in regulatory analysis.

Additional details on each of these recommendations as well as longer term research needs are provided in the National Academies' final report (National Academies 2017).

1.3 Executive Order 13990

On January 20, 2021, President Biden issued E.O. 13990, "Protecting Public Health and the Environment and Restoring Science to Tackle the Climate Crisis." Echoing one of the general principles of E.O. 12866 that an Agency "shall base its decisions on the best reasonably obtainable scientific, technical, economic, and other information", E.O. 13990 states that it is essential for Agencies to account for the benefits of reducing GHG emissions as accurately as possible. It emphasizes that a full global accounting of the costs of GHG emissions "facilitates sound decision-making, recognizes the breadth of climate impacts, and supports the international leadership of the United States on climate issues" (E.O. 13990 2021). Specifically, E.O. 13990 reinstates the IWG as the Interagency Working Group on the Social Cost of Greenhouse Gases, names the Chair of the CEA, Director of OMB, and Director of the Office of Science and Technology Policy (OSTP) as co-chairs of the IWG, and specifies the membership of the IWG to include the following officials, or their designees: the Secretary of the Treasury; the Secretary of the Interior; the Secretary of Agriculture; the Secretary of Commerce; the Secretary of Health and Human Services; the Secretary of Transportation; the Secretary of Energy; the Chair of the Council on Environmental Quality; the Administrator of the Environmental Protection Agency; the Assistant to the President and National Climate Advisor; and the Assistant to the President for Economic Policy and Director of the National Economic Council.

E.O. 13990 tasks the reinstated IWG with the following:

(1) publish an interim update to the SC-GHG (SC-CO_2, SC-CH_4, and SC-N_2O) estimates by February 19, 2021, for agencies to use when monetizing the value of changes in greenhouse gas emissions resulting from regulations and other relevant agency actions until final values are published;

(2) publish a final update to the SC-GHG estimates by no later than January 2022;

(3) provide recommendations, by no later than September 1, 2021, regarding areas of decision-making, budgeting, and procurement by the Federal Government where the SC-GHG estimates should be applied;

(4) provide recommendations, by no later than June 1, 2022, regarding a process for reviewing and, as appropriate, updating the SC-GHG estimates to ensure that these estimates are based on the best available economics and science; and

(5) provide recommendations, to be published with the interim SC-GHG estimates if feasible and by no later than June 1, 2022, to revise methodologies for SC-GHG calculations to the extent that current methodologies do not adequately take account of climate risk, environmental justice, and intergenerational equity.

Finally, the E.O. specifies that in carrying out its activities, the IWG shall consider the recommendations of the National Academies (2017) and other pertinent scientific literature; solicit public comment; engage with the public and stakeholders; seek the advice of ethics experts; and ensure that the SC-GHG estimates reflect the interests of future generations in avoiding threats posed by climate change.

This TSD presents the interim SC-GHG estimates called for in the first of these tasks. It also provides preliminary discussion of how at least one component of SC-GHG estimation, discounting, warrants reconsideration in the more comprehensive update by January 2022 to reflect the advice of the National Academies (2017) and other recent scientific literature.

2 The Importance of Accounting for Global Damages

Benefit-cost analyses of U.S. Federal regulations have traditionally focused on the benefits and costs that accrue to individuals that reside within the country's national boundaries. This is a natural result of the fact that most regulations have a limited impact on individuals residing outside of the United States and do not reflect any other scientific, legal, or other rationale. According to OMB's Circular A-4 (2003), an "analysis should focus on benefits and costs that accrue to citizens and residents of the United States."[15] While Circular A-4 does not elaborate, this guidance towards a focus on U.S. populations in domestic policy analysis is broadly consistent with the fact that the authority to regulate only extends to a nation's own residents who have consented to adhere to the same set of rules and values for collective decision-making (EPA 2010; Kopp et al. 1997; Whittington and MacRae 1986). However, guidance towards a focus on impacts to U.S. citizens and residents is different than recommending that analysis be limited to the impacts that occur within the borders of the U.S. Furthermore, OMB Circular A-4 states that when a regulation is likely to have international effects that "these effects should be reported" though the guidance recommends this be done separately. There are many reasons, as summarized in this TSD, why it is appropriate for agencies to use the global value of damages in making decisions that affect, or may be affected by, GHG emissions. Courts have upheld the use of global damages in estimating the social cost of GHGs, in part in recognition of the diverse ways in which U.S. interests, businesses, and residents may be impacted by climate change beyond U.S. borders.[16]

Unlike many environmental problems where the causes and impacts are distributed more locally, climate change is a true global challenge making GHG emissions a global externality. GHG emissions contribute to damages around the world regardless of where they are emitted. The global nature of GHGs means that U.S. interests, and therefore the benefits to the U.S. population of GHG mitigation, cannot be defined solely by the climate impacts that occur within U.S. borders. Impacts that occur outside U.S. borders as a result of U.S. actions can directly and indirectly affect the welfare of U.S. citizens and residents through a multitude of pathways. Over 9 million U.S. citizens lived abroad as of 2016[17] and U.S. direct investment positions abroad totaled nearly $6 trillion in 2019.[18] Climate impacts occurring outside of U.S. borders will have a direct impact on these U.S. citizens and the investment returns on those assets owned by U.S. citizens and residents. The U.S. economy is also inextricably linked to the rest of the world. The U.S. exports over $2 trillion worth of goods and services a year and imports around $3 trillion.[19] Climate impacts that occur outside U.S. borders can thus impact the welfare of individuals and firms that reside in the United States through their effect on international markets, trade, tourism, and other activities. Furthermore, additional spillovers can occur through pathways such as economic and political destabilization and global migration that can lead to adverse impacts on U.S. national security, public health, and humanitarian concerns (DoD 2014, CCS 2018). As described by the National Academies (2017), to correctly assess the total damages to U.S. citizens and residents, one must account for these spillover effects on the United States.

As an empirical matter, the development of a domestic SC-GHG is greatly complicated by the relatively few region- or country-specific estimates of the SC-CO_2 in the literature. At present, the only quantitative

[15] OMB's Circular A-4 provides guidance to Federal agencies on the development of regulatory analysis conducted pursuant to Executive Order 12866.

[16] *Zero Zone, Inc. v. Dep't of Energy*, 832 F.3d 654, 678-79 (7th Cir. 2016) (rejecting a petitioner's challenge to DOE's use of a global (rather than domestic) social cost of carbon in setting an efficiency standard under the Energy Policy and Conservation Act, holding that DOE had reasonably identified carbon pollution as "a global externality" and concluding that, because "national energy conservation has global effects, . . . those global effects are an appropriate consideration when looking at a national policy.").

[17] U.S. Department of State's Bureau of Consular Affairs.

[18] BEA Direct Investment by Country and Industry 2019, https://www.bea.gov/data/intl-trade-investment/direct-investment-country-and-industry

[19] BEA National Income and Product Accounts Table 1.1.5.

characterization of domestic damages from GHG emissions, as represented by the domestic SC-GHG, is based on the share of damages arising from climate impacts occurring within U.S. borders as represented in current IAMs. This is both incomplete and an underestimate of the share of total damages that accrue to the citizens and residents of the U.S. because these models do not capture the regional interactions and spillovers discussed above. A 2020 U.S. GAO study observed that "[a]ccording to the National Academies, the integrated assessment models were not premised or calibrated to provide estimates of the social cost of carbon based on domestic damages, and more research would be required to update the models to do so. The National Academies stated it is important to consider what constitutes a domestic impact in the case of a global pollutant that could have international implications that affect the United States" (U.S. GAO 2020).

The global nature of GHGs means that damages caused by a ton of emissions in the U.S. are felt globally and that a ton emitted in any other country harms those in the U.S. Therefore, assessing the benefits of U.S. GHG mitigation activities will require consideration of how those actions may affect mitigation activities by other countries since those international actions will provide a benefit to U.S. citizens and residents. A wide range of scientific and economic experts have emphasized the issue of reciprocity as support for considering global damages of GHG emissions (e.g., Kopp and Mignone 2013, Pizer et al. 2014, Howard and Schwartz 2019, Pindyck 2017, Revesz et al. 2017, Carleton and Greenstone 2021). Carleton and Greenstone (2021) discuss examples of how historic use of a global SC-CO_2 may have plausibly contributed to additional international action. Houser and Larson (2021) estimate that under the Paris Agreement, other countries pledged to reduce 6.1 to 6.8 tons for every ton pledged by the U.S. Kotchen (2018) offers a theoretical perspective showing that non-Nash game theoretic behavior can lead countries to optimally chose a social cost of carbon higher than their domestic value to encourage additional reductions from other countries. Using a global estimate of damages in U.S. analyses of regulatory and other actions allows the U.S. to continue to actively encourage other nations, including emerging major economies, to take significant steps to reduce emissions.

The IWG found previously and is restating here that because of the distinctive global nature of climate change that analysis of Federal regulatory and other actions should center on a global measure of SC-GHG. This approach is the same as that taken in regulatory analyses over 2009 through 2016. In the 2015 response to comments, the IWG noted that the only way to achieve an efficient allocation of resources for emissions reduction on a global basis is for all countries to base their policies on global estimates of damages (IWG 2015). Therefore, the IWG continues to recommend the use of global SC-GHG estimates in analysis of Federal regulatory and other actions. The IWG also continues to review developments in the literature, including more robust methodologies for estimating SC-GHG values based on purely domestic damages, and explore ways to better inform the public of the full range of carbon impacts, both global and domestic.

3 Discounting in Intergenerational Analyses

GHG emissions are stock pollutants, where damages are associated with what has accumulated in the atmosphere over time, and they are long lived such that subsequent damages resulting from emissions today occur over many decades or centuries depending on the specific greenhouse gas under consideration.[20] In calculating the SC-GHG, the stream of future damages to agriculture, human health, and other market and non-market sectors from an additional unit of emissions are estimated in terms of reduced consumption (or consumption equivalents). Then that stream of future damages is discounted to its present value in the year when the additional unit of emissions was released. Given the long time horizon over which the damages are expected to occur, the discount rate has a large influence on the present value of future damages. However, the choice of a discount rate also raises highly contested and exceedingly difficult questions of science, economics, ethics, and law.

In 2010, in light of disagreements in the literature on the appropriate discount rate to use in this context, and uncertainty about how rates may change over time, the IWG elected to use three discount rates to span a plausible range of certainty-equivalent constant consumption discount rates: 2.5, 3, and 5 percent per year. The IWG at that time determined that these three rates reflected reasonable judgments under both descriptive and prescriptive approaches to selecting the discount rate.

The 3 percent value was included as consistent with estimates provided in OMB's Circular A-4 (OMB 2003) guidance for the consumption rate of interest. The IWG found that the consumption rate of interest is the correct discounting concept to use when future damages from elevated temperatures are estimated in consumption-equivalent units as is done in the IAMs used to estimate the SC-GHG (National Academies 2017). The upper value of 5 percent was included to represent the possibility that climate-related damages are positively correlated with market returns, which would imply a certainty equivalent value higher than the consumption rate of interest. The low value, 2.5 percent, was included to incorporate the concern that interest rates are highly uncertain over time. It represents the average certainty-equivalent rate using the mean-reverting and random walk approaches from Newell and Pizer (2003) starting at a discount rate of 3 percent. Using this approach, the certainty equivalent is about 2.2 percent using the random walk model and 2.8 percent using the mean reverting approach. Without giving preference to a particular model, the average of the two rates is 2.5 percent. Additionally, a rate below the consumption rate of interest would also be justified if the return to investments in climate mitigation are negatively correlated with the overall market rate of return. Use of this lower value was also deemed responsive to certain judgments based on the prescriptive or normative approach for selecting a discount rate and to related ethical objections that have been raised about rates of 3 percent or higher. Further details about the process for selecting these rates is presented in the 2010 TSD (IWG 2010). Finally, it is important to note that, while the consumption discount rate is the conceptually correct rate for discounting the SC-GHG, and the three rates originally selected were based on this concept, the latest data as well as recent discussion in the economics literature indicates that the 3 percent discount rate used by the IWG to develop its range of discount rates is likely an overestimate of the appropriate discount rate and warrants reconsideration in future updates of the SC-GHG.

This section discusses three issues related to the selected discount rates: (1) why the social rate of return to capital, estimated to be 7 percent in OMB's Circular A-4, is not appropriate for use in calculating the SC-GHG, (2) new evidence on the consumption rate of interest, which may inform the future updates to the SC-GHG, and (3) analytic consistency across discounting within an analysis.

[20] "GHGs, for example, CO_2, methane, and nitrous oxide, are chemically stable and persist in the atmosphere over time scales of a decade to centuries or longer, so that their emission has a long-term influence on climate. Because these gases are long lived, they become well mixed throughout the atmosphere" (IPCC 2007).

3.1 Social Rate of Return on Capital and Intergenerational Analyses

When analyzing policies and programs that result in GHG emission reductions, it is important to account for the difference between the social and private rate of return on any capital investment affected by the action. Society is not indifferent between a regulation that displaces consumption versus investment in equal amounts. Market distortions, in large part taxes on capital income, cause private returns on capital investments to be different from the social returns. In well-functioning capital markets, arbitrage opportunities will be dissipated, and the cost of investments will equal the present value of future private returns on those investments. Therefore, an individual forgoing consumption or investment of equal amounts as the result of a regulation will face an equal private burden. However, because the social rate of return on the investment is greater than the private rate of return, the overall social burden will be greater in the case where investment is displaced.

OMB's Circular A-4 points out that "the analytically preferred method of handling temporal differences between benefits and costs is to adjust all the benefits and costs to reflect their value in equivalent units of consumption and to discount them at the rate consumers and savers would normally use in discounting future consumption benefits" (OMB 2003). The damage estimates developed for use in the SC-GHG are estimated in consumption-equivalent terms. An application of OMB Circular A-4's guidance for regulatory analysis would then use the consumption discount rate to calculate the SC-GHG, while also developing a more complete estimate of social cost to account for the difference in private and social rates of return on capital for any investment displaced as a result of the regulation. This more complete estimate of social costs can be developed using either the shadow price of capital approach or by estimating costs in a general equilibrium framework, for example by using a computable general equilibrium model. In both cases, displaced investment would be converted into a flow of consumption equivalents.

In cases where the costs are not adjusted to be in consumption-equivalent terms, OMB's Circular A-4 recommends that analysts provide a range of estimates for net benefits based on two approaches. The first approach is based on using the consumption rate of interest to discount all costs and benefits. This approach is consistent with the case where costs are primarily borne as reduced consumption. The second approach, the social opportunity cost of capital (SOC) approach, focuses on the case where the main effect of a regulation is to displace or alter the use of capital in the private sector (OMB 2003). When interpreting the SOC approach from the point of view of whether to invest in a single government project, it is asking whether the benefits from the project would at least match the returns from investing the same resources in the private sector. Interpreting the approach from the standpoint of a benefit-cost analysis of regulation, the approach focuses on adjusting estimates of benefits downward by discounting at a higher rate to offset additional social costs not reflected in the private value of displaced investment.

Harberger (1972) derived a more general version of the social opportunity cost of capital approach, recognizing that policies will most likely displace a mix of consumption and investment and therefore a blended discount rate would be needed to adjust the benefits to account for the omitted costs. In his partial equilibrium approach, the blended discount rate is a weighted average of the consumption interest rate and social rate of return on capital, where the weights are the share of a policy's costs borne by consumption versus investment. This general result has been extended to the general equilibrium context by Sandmo and Drèze (1971) and Drèze (1974) and can be extended to account for changes in foreign direct investment (CEA 2017). This highlights that using the social rate of return for benefits and costs is at best creating a lower bound on the estimate of net benefits that would only be met in an extreme case where regulatory costs fully displace investment. If the beneficial impacts of the regulation induce private investment whose social returns have not been quantified and fully converted to consumption equivalents, then the net benefits calculated using the social rate of return on capital is not even a lower bound.[21] Li and Pizer (2021) further generalize the SOC framework and demonstrate that temporal pattern of benefits is important and that when benefits occur far in the future discounting using the social rate of return on capital again is not even a lower bound on net benefits.

For regulations whose benefits and costs occur over a relatively short time frame, the range of net benefits computed using the two discounting approaches will be relatively narrow. Therefore, there is less risk in maintaining an uninformed prior over the share of regulatory costs that will displace investment and using the potential bounding cases for net benefits. However, for cases where the costs are borne early in the time horizon and benefits occur for decades or even centuries, such as with GHG mitigation, the two estimates of net benefits will differ significantly. In this case, the risk to society of maintaining an uninformed prior over the share of regulatory costs borne by investment is significantly higher. In turn, the preferred approach is to discount benefits using the consumption rate of interest and strive to provide a more complete measure of costs, accounting for displacement of investment whose social rate of return exceeds the private rate of return, either by using a shadow price of capital approach or a general equilibrium framework, like a computable general equilibrium model.

It is important to note that even if an appropriately specified blended SOC rate could be calculated based on the share of regulatory costs that are expected to displace investment that would not obviate the need to carefully consider issues of uncertainty and ethics when discounting in an intergenerational context, pointing to a lower rate.

For these reasons, the IWG is returning to the approach of calculating the SC-GHG based on the consumption rate of interest, consistent with the findings of the National Academies (2017)[22].

3.2 New Evidence on the Consumption Discount Rate

The three discount rates selected by the IWG in 2010 are centered around the 3 percent estimate of the consumption interest rate published in OMB's Circular A-4 in 2003. That guidance was based on the real rate of return on 10-year Treasury Securities from the prior 30 years (1973 through 2002), which averaged 3.1 percent. Over the past four decades there has been a substantial and persistent decline in real interest rates (see Figure 1). Recent research has found that this decline has been driven by decreases in the equilibrium real interest rate (Bauer and Rudebusch 2020).

Re-estimating the consumption rate of interest following the same approach applied in Circular A-4, including using data from the most recent 30 years, yields a substantially lower result. The average rate

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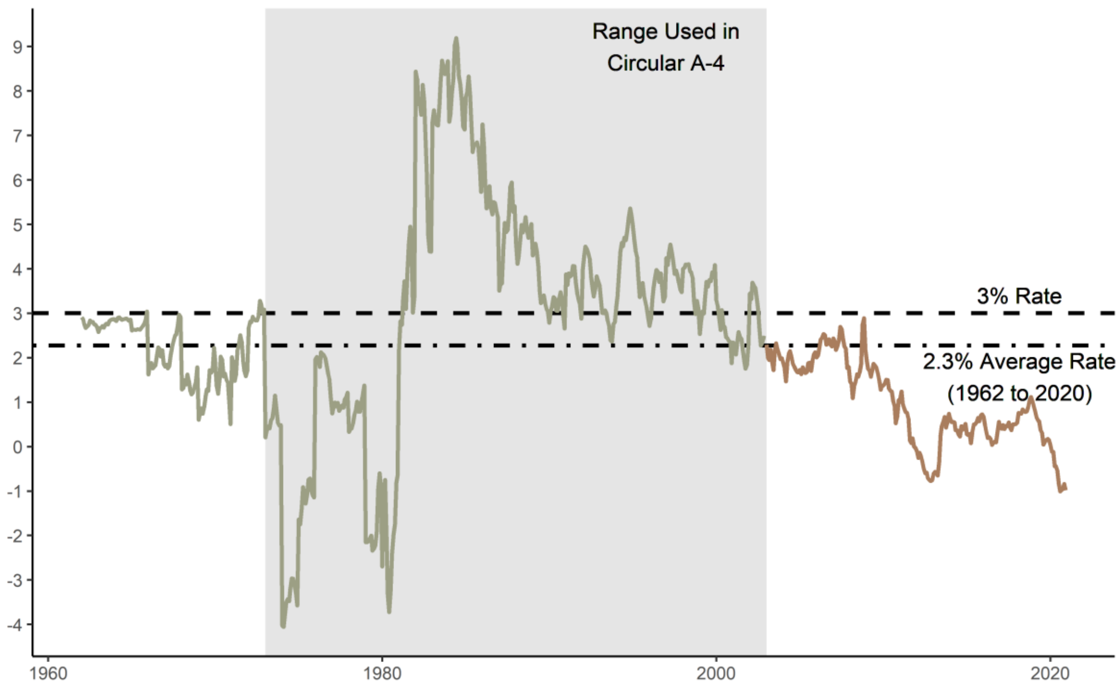
[21] The SOC approach as outlined in OMB's Circular A-4 is most applicable to cases where the benefits are represented as consumption equivalents and costs may not be. If the benefits of the policy include the inducement of new private investment, discounting both benefits and costs at the social rate of return for capital is no longer appropriate. The results of Bradford (1975) show that in a case where regulatory costs are primarily borne through reduced consumption and the beneficial impacts of the policy may induce private investment the appropriate rate under the SOC approach could be below the consumption interest rate.

[22] NAS (2017) stated "The estimates that result from the SC-IAMs are measured in consumption- equivalent units: thus, a discount rate that reflects how individuals trade off current and future consumption is defensible in this setting" (p. 236-7).

of return on inflation adjusted 10-year Treasury Securities over the last 30 years (1991-2020) is 2.0 percent. These rates are not without historic precedent, such that over the last 60 years the inflation adjusted 10-year Treasury Securities is 2.3 percent. Current real rates of returns below 2 percent are expected to persist. The U.S. Congressional Budget Office (CBO) in its September 2020 Long Term Budget Outlook forecasts real rates of return on 10-Year Treasury Securities to average 1.2 percent over the next 30 years (U.S. CBO 2020). This new information suggests that the consumption rate of interest is notably lower than 3 percent. CEA (2017) examined additional forecasts of 10-Year Treasury Securities and data on futures contracts, reaching the conclusion that the appropriate consumption discount rate should be at most 2 percent.

Figure 1: Monthly 10-Year Treasury Security Rates, Inflation-Adjusted[23]



Several surveys have been conducted in recent years to elicit experts' views on the appropriate discount rates to use in an intergenerational context (e.g., Drupp et al. 2018; Howard and Sylvan 2020). For example, Drupp et al. (2018) offers confirming evidence that the economics profession generally agrees that the appropriate social discount rate is below 3 percent as reflected in the recent trends in data. They surveyed over 200 experts and found a "surprising degree of consensus among experts, with more than three-quarters finding the median risk-free social discount rate of 2 percent acceptable" (Drupp et al. 2018).[24]

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[23] Monthly 10-Year Treasury Security returns, adjusted for inflation. Real interest rates prior to 2003 (green line) are calculated by subtracting the annual rate of inflation as measured by the CPI-U from the nominal rate of return on 10-Year constant maturity Treasury Securities. Interest rates from 2003 onwards (brown line) are based on the 10-Year Treasury Inflation-Protected Securities.

[24] For a detailed explanation of discounting concepts and terminology see EPA's *Guidelines for Preparing Economic Analysis* (2010). https://www.epa.gov/environmental-economics/guidelines-preparing-economic-analyses

It is important to note that the new information pointing to a lower consumption rate of interest, lower than 3 percent, does not obviate the need to carefully consider issues of uncertainty and ethics when discounting in an intergenerational context.[25] If 2 percent was used as the consumption interest rate and adjusted for uncertainty using the results of Newell and Pizer (2003) as was done in the 2010 TSD, the process would yield a discount rate lower than 2 percent. Therefore, a consideration of discount rates below 3 percent, including 2 percent and lower, are warranted when discounting intergenerational impacts.

This is consistent with the 2003 recommendation in OMB's Circular A-4 that noted "[a]lthough most people demonstrate time preference in their own consumption behavior, it may not be appropriate for society to demonstrate a similar preference when deciding between the well-being of current and future generations" and found that certainty equivalent discount rates as low as 1 percent could be appropriate for intergenerational problems (OMB 2003). Similarly, if implementing a declining discount rate schedule to account for uncertainty (see next section), an updated consumption rate of interest, based on additional data presented above, may be a starting point for an update.

In light of the evidence and discussion on discount rates presented in this TSD and elsewhere, the recommendation from OMB's Circular A-4 to include further sensitivity analysis with lower discount rates when a rule has important intergenerational benefits or costs, and the direction to the IWG in E.O. 13990 to ensure that the SC-GHG reflect the interest of future generations, the IWG finds it appropriate as an interim recommendation that agencies may consider conducting additional sensitivity analysis using discount rates below 2.5%.

3.3 Analytic Consistency and Declining Discount Rates

While the consumption rate of interest is an important driver of the benefits estimate, it is uncertain over time, as may be observed in Figure 1. Weitzman (1998, 2001) showed theoretically and Newell and Pizer (2003) and Groom et al. (2005) confirmed empirically that discount rate uncertainty can have a large effect on net present values. A main result from these studies is that if there is a persistent element to the uncertainty in the discount rate (e.g., the rate follows a random walk), then it will result in an effective (or certainty-equivalent) discount rate that declines over time. This is because lower discount rates tend to dominate over the very long term (see Weitzman 1998, 1999, 2001; Newell and Pizer 2003; Groom et al. 2005; Gollier 2009; Summers and Zeckhauser 2008; Gollier and Weitzman 2010; Arrow et al. 2013; Cropper et al. 2014; and Arrow et al. 2014).

The proper way to specify a declining discount rate schedule remains an active area of research. One approach is to develop a stochastic model of interest rates that is empirically estimated and used to calculate the certainty equivalent declining discount rate schedule (e.g., Newell and Pizer 2003; Groom et al. 2007). An alternative approach is to use the Ramsey equation based on a forecast of consumption growth rates that accounts for uncertainty (e.g., Cropper et al. 2014; Arrow et al. 2013). If the shocks to consumption growth are positively correlated over time then the result of the Ramsey equation will be a certainty-equivalent discount rate schedule that declines over time (Goiller 2014). Others have argued for a less structural approach to specify a declining discount rate schedule (e.g., Weitzman 2001, the United

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[25] For a more detailed explanation of ethical and uncertainty considerations around discounting see National Academies (2017) and the 2010 TSD (IWG 2010).

Kingdom's "Green Book" for regulatory analysis (HM Treasury 2020), the declining discount schedule in France (Lebègue 2005) and varying the discount rate based on the time period in Germany (Schwermer 2012, U.S. GAO 2020)). This approach uses a higher discount rate initially, like the current estimate of the consumption interest rate, but applies a graduated scale of lower discount rates further out in time.[26]

Instead of explicitly specifying a declining discount rate schedule, the IWG in 2010 elected to use a constant but lower discount rate to capture the directional effect of the literature on discounting under uncertainty. Specifically, the IWG considered two declining discount rate schedules based on the mean-reverting and random walk models from Newell and Pizer (2003) starting at a discount rate of 3 percent. The 2.5 percent discount rate selected by the IWG in 2010 reflected the midpoint between the average certainty equivalent discount rates of both models. The approach of using a lower, but constant, discount rate to capture the effect of uncertainty has led to inconsistency in regulatory analyses, where impacts occurring in a given year are discounted at different rates depending on whether they are related to climate change (Arrow et al. 2014). The National Academies (2017) and EPA's Science Advisory Board (2021) have recommended that the U.S. Government establish an explicit declining discount rate schedule that is applied to all regulatory impacts in an analysis to capture the effect of uncertainty on long-term discount rates, while also maintaining consistency across impact categories in the analysis. The IWG will consider the literature on declining discount rates and the recommendations of the National Academies (2017) and EPA's Science Advisory Board (2021) as it develops future updates to the SC-GHG. In the interim, the IWG is returning to the use of the 2.5, 3, and 5 percent discount rates in calculating the SC-GHG but recommends that agencies describe potential limitations in their analyses to ensure transparency. As noted above, agencies may also consider discount rates below 2.5 percent as part of a sensitivity analysis.

4 Interim Estimates of SC-CO_2, SC-CH_4, SC-N_2O

The interim SC-GHG estimates presented in this TSD rely on the same models and harmonized inputs for the socioeconomic emissions scenarios and equilibrium climate sensitivity distribution used for USG SC-GHG estimates since 2013. Specifically, the SC-GHG estimates rely on an ensemble of three IAMs: Dynamic Integrated Climate and Economy (DICE) 2010 (Nordhaus 2010); Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) 3.8 (Anthoff and Tol 2013a, 2013b); and Policy Analysis of the Greenhouse Gas Effect (PAGE) 2009 (Hope 2013). IAMs are useful because they combine climate processes, economic growth, and feedback between the climate and the global economy into a single modeling framework. They gain this advantage at the expense of a more detailed representation of underlying climatic and economic systems. DICE, PAGE, and FUND all take stylized, reduced-form approaches and have been widely used in the economic and scientific literature since the 1990s. They are periodically updated by the model developers, but as discussed further in Section 5, the versions of the three models used in the 2013 and 2016 TSDs do not reflect the tremendous increase in the scientific and economic understanding of climate-related damages that has occurred in the past decade. The three IAMs

[26] For instance, the United Kingdom applies a discount rate of 3.5 percent to the first 30 years; 3 percent for years 31 - 75; 2.5 percent for years 76 - 125; 2 percent for years 126 - 200; 1.5 percent for years 201 - 300; and 1 percent after 300 years. As a sensitivity, it recommends a discount rate of 3 percent for the first 30 years, also decreasing over time.

were run using a common set of assumptions in each model for future population, economic, and GHG emissions growth, as well as equilibrium climate sensitivity (ECS) – a measure of the globally averaged temperature response to increased atmospheric CO_2 concentrations. The socioeconomic and emission projections included five reference scenarios based on the Stanford Energy Modeling Forum EMF-22 modeling exercise (Clarke, et al. 2009; Fawcett, et al. 2009). The models were run using a probability distribution for ECS, calibrated to the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report findings using the Roe and Baker (2007) distribution. Details on these versions of the IAMs and the harmonized inputs are presented in the 2016 TSD and Addendum and 2010 TSD. (IWG 2010, 2016a, 2016b). The 2016 Addendum also describes the methodology used to calculate the SC-CH_4 and SC-N_2O estimates in greater detail.[27] Finally, for the reasons set forth in Section 3 above, the interim estimates were based on three constant discount rates of 2.5, 3, and 5 percent.

The combination of three models and five scenarios produced 15 separate frequency distributions of SC-GHG estimates for each discount rate in a given year, with each distribution consisting of 10,000 estimates based on draws from the standardized ECS distribution (as well as distributions of parameters treated as uncertain in two of the models (FUND and PAGE)). For each discount rate, the IWG combined the distributions across models and socioeconomic emissions scenarios (applying equal weight to each) and then selected a set of four values for use in benefit-cost analyses: an average value resulting from the model runs for each of three discount rates (2.5%, 3%, and 5%), plus a fourth value, selected as the 95th percentile of estimates based on a 3 percent discount rate. The fourth value was included to provide information on potentially higher-than-expected economic impacts from climate change, conditional on the 3% estimate of the discount rate. For this purpose, the SC-GHG value for the 95th percentile at a 3 percent discount rate was presented.[28] For the purposes of capturing the uncertainties involved in analyses, the IWG emphasized previously and emphasizes in this TSD the importance and value of including all four SC-GHG values. In particular, values based on lower discount rates are consistent with the latest scientific and economic understanding of discounting approaches relevant for intergenerational analysis (described in Section 3).

Tables 1-3 show the four selected values for SC-CO_2, SC-CH_4, and SC-N_2O, respectively, in five-year increments from 2020 to 2050. These estimates are reported in 2020 dollars but are otherwise identical to those presented in the previous version of the TSD and its Addendum, released in August 2016.[29] The

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[27] The IWG calculated the SC-CH_4 and SC-N_2O estimates following the approach used in Marten et al. (2015). In order to develop SC-CH_4 and SC-N_2O estimates consistent with the methodology underlying the SC-CO_2 estimates, Marten et al. (2015) needed to augment the IWG modeling framework in two respects: (1) augment the climate model of two of the IAMs to explicitly consider the path of additional radiative forcing from a CH_4 or N_2O perturbation, and (2) add more specificity to the assumptions regarding post-2100 baseline CH_4 and N_2O emissions. See IWG (2016b) for more discussion of these two modeling modifications and the peer review and public comment processes accompanying their development.

[28] A detailed set of percentiles by model and scenario combination and additional summary statistics for the 2020 values is available in the 2016 TSD and Addendum (IWG 2016a, 2016b).

[29] The values in Tables 1-3 are the same as those reported in the 2016 TSD and Addendum adjusted for inflation to 2020 dollars using the annual GDP Implicit Price Deflator values in U.S. Bureau of Economic Analysis (BEA) NIPA Table 1.1.9: 113.626 (2020)/ 92.486 (2007) = 1.228575 (U.S. BEA 2021). Values of SC-CO_2 presented in this TSD are rounded to the nearest dollar; SC-CH_4 and SC-N_2O are rounded to two significant figures. The annual unrounded estimates are available on OMB's website for use in regulatory and other analyses: https://www.whitehouse.gov/omb/information-regulatory-affairs/regulatory-matters/#scghgs.

full set of annual SC-GHG values between 2020 and 2050, calculated using linear interpolation between the numbers shown in Tables 1-3, is reported in the Appendix and the full set of model results are available on the OMB website.[30] The SC-GHG estimates increase over time within the models – i.e., the societal harm from one metric ton emitted in 2030 is higher than the harm caused by one metric ton emitted in 2025 – because future emissions produce larger incremental damages as physical and economic systems become more stressed in response to greater climatic change, and because GDP is growing over time and many damage categories are modeled as proportional to GDP.

Table 1: Social Cost of CO_2, 2020 – 2050 (in 2020 dollars per metric ton of CO_2)[31]

	Discount Rate and Statistic			
Emissions Year	5% Average	3% Average	2.5% Average	3% 95th Percentile
2020	14	51	76	152
2025	17	56	83	169
2030	19	62	89	187
2035	22	67	96	206
2040	25	73	103	225
2045	28	79	110	242
2050	32	85	116	260

Table 2: Social Cost of CH_4, 2020 – 2050 (in 2020 dollars per metric ton of CH_4)

	Discount Rate and Statistic			
Emissions Year	5% Average	3% Average	2.5% Average	3% 95th Percentile
2020	670	1500	2000	3900
2025	800	1700	2200	4500
2030	940	2000	2500	5200
2035	1100	2200	2800	6000
2040	1300	2500	3100	6700
2045	1500	2800	3500	7500
2050	1700	3100	3800	8200

[30] https://www.whitehouse.gov/omb/information-regulatory-affairs/regulatory-matters/#scghgs

[31] The values reported in this TSD are identical to those reported in the 2016 TSD adjusted for inflation to 2020 dollars using the annual GDP Implicit Price Deflator values in the U.S. Bureau of Economic Analysis' (BEA) NIPA Table 1.1.9: 113.626 (2020)/ 92.486 (2007) = 1.228575 (U.S. BEA 2021). The IWG combined the distributions across models and socioeconomic emissions scenarios for each of three discount rates (2.5%, 3%, and 5%), plus a fourth value, selected as the 95th percentile of estimates based on a 3 percent discount rate. Values of SC-CO_2 are rounded to the nearest dollar; SC-CH_4 and SC-N_2O are rounded to two significant figures. The annual unrounded estimates are available on OMB's website for use in regulatory and other analyses: https://www.whitehouse.gov/omb/information-regulatory-affairs/regulatory-matters/#scghgs.

Table 3: Social Cost of N_2O, 2020 – 2050 (in 2020 dollars per metric ton of N_2O)

	Discount Rate and Statistic			
Emissions Year	5% Average	3% Average	2.5% Average	3% 95th Percentile
2020	5800	18000	27000	48000
2025	6800	21000	30000	54000
2030	7800	23000	33000	60000
2035	9000	25000	36000	67000
2040	10000	28000	39000	74000
2045	12000	30000	42000	81000
2050	13000	33000	45000	88000

Multiplying the SC-GHG in year *t* by the change in emissions in year *t* yields the monetized value of future emission changes from a year *t* perspective. This value must then be discounted to the present before being included in an analysis. For this purpose, the monetized value of future emission changes should be discounted at the same rate used to calculate the initial SC-GHG to ensure internal consistency—i.e., future damages from climate change using the SC-GHG at 2.5 percent should be discounted to the base year of the analysis using the same 2.5 percent rate.

As noted above, to correctly assess the total climate damages to U.S. citizens and residents, an analysis must account for both the impacts that occur within U.S. borders and spillover effects from climate action elsewhere. For the reasons discussed in Section 2 above, estimates focusing on the climate impacts occurring within U.S. borders are an underestimate of the benefits of GHG mitigation accruing to U.S. citizens and residents and, therefore, are not equivalent to a domestic estimate of the SC-GHG. (Section 2 also discusses why analyses should center their attention on a global measure of the SC-GHG). Additionally, models differ in their treatment of regional damages[32] with one of the model developers recently noting that regional damages are "both incomplete and poorly understood" (Nordhaus 2017). The IWG further notes that the domestic focused SC-GHG estimates used under E.O. 13783[33] did not

[32] Both the PAGE and FUND model contain a U.S. region and so the damages for this region are reported directly for those models. The DICE 2010 model does not explicitly include a separate U.S. region in the model. For the domestic focused SC-GHG estimates used under E.O. 13783, the DICE model damages occurring within U.S. borders were approximated as 10 percent of the global estimate from the DICE model runs, based on the results from a regionalized version of the model (RICE 2010) reported in Table 2 of Nordhaus (2017). Although the regional shares reported in Nordhaus (2017) are specific to SC-CO_2, they were also used in approximating the share of marginal damages from CH_4 and N_2O emissions occurring within U.S. borders. Direct transfer of the U.S. share from the SC-CO_2 likely understate the U.S. share of the IWG global SC-CH_4 estimates based on DICE due to the combination of three factors: a) regional damage estimates are known to be highly correlated with output shares (Nordhaus 2017, 2014), b) the U.S. share of global output decreases over time in all five EMF-22 based socioeconomic scenarios used for the model runs, and c) the bulk of the temperature anomaly (and hence, resulting damages) from a perturbation in emissions in a given year will be experienced earlier for CH_4 than CO_2 due to the shorter lifetime of CH_4 relative to CO_2.

[33] For emissions occurring in 2020, the average estimates of marginal damages occurring within the U.S. borders for CO_2, CH_4, and N_2O emissions across all model runs that were used in 2017-2020 regulatory analyses were \$7/mtCO_2,

benefit from a consensus-based IWG process, were not documented in a dedicated TSD, subjected to a SC-GHG specific notice and comment period, or considered by National Academies in their 2017 review. The IWG will request public comments on the new information presented in this TSD, as well as other topics and issues the IWG will address as we develop the next set of updates (see Section 6).

4.1 Treatment of Uncertainty

Uncertainty about the value of the SC-GHGs is in part inherent, as with any analysis that looks into the future, but it is also driven by current data gaps associated with the complex physical, economic, and behavioral processes that link GHG emissions to human health and well-being. Some sources of uncertainty pertain to aspects of the natural world, such as quantifying the physical effects of greenhouse gas emissions on Earth systems. Other sources of uncertainty are associated with current and future human behavior and well-being, such as population and economic growth, GHG emissions, the translation of Earth system changes to economic damages, and the potential extent and costs of adaptation. It is important to note that even in the presence of uncertainty, scientific and economic analysis can provide valuable information to the public and decision makers. Such uncertainty should, however, be acknowledged, communicated as clearly as possible, and taken into account in the analysis whenever possible.

The 2016 TSD and the 2017 National Academies report provide detailed discussions of the ways in which the modeling underlying the development of the SC-GHG estimates addressed quantified sources of uncertainty.

In developing the SC-CO_2 estimates, the IWG considered various sources of uncertainty through a combination of a multi-model ensemble, probabilistic analysis, and scenario analysis. For example, the three IAMs used collectively span a wide range of Earth system and economic outcomes to help reflect the uncertainty in the literature and in the underlying dynamics being modeled. The use of an ensemble of three different models is also intended to, at least partially, address the fact that no single model includes all of the quantified economic damages. It also helps to reflect structural uncertainty across the models, which is uncertainty in the underlying relationships between GHG emissions, Earth systems, and economic damages that are included in the models. Bearing in mind the different limitations of each model (discussed in the 2010 TSD) and lacking an objective basis upon which to differentially weight the models, the three IAMs were given equal weight in the analysis.

The IWG used Monte Carlo techniques to run the IAMs a large number of times. In each simulation the uncertain parameters are represented by random draws from their defined probability distributions. In all three models the equilibrium climate sensitivity is treated probabilistically based on the probability distribution described in the 2010 TSD. The equilibrium climate sensitivity is a key parameter in this

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\$190/mtCH_4, and \$2,300/mtN_2O (in 2020 dollars), respectively, using a 3 percent discount rate, and \$1/mtCO_2, \$59/mtCH_4, and \$380/mtN_2O (in 2020 dollars) using a 7 percent discount rate. These values increased over time; for 2050 emissions, the average estimates of marginal damages occurring within the U.S. borders are \$11/mtCO_2, \$380/mtCH_4, and \$4,000/mtN_2O (in 2020 dollars) using a 3% discount rate and \$3/mtCO_2, \$160/mtCH_4, and \$1,000/mtN_2O (in 2020 dollars) using a 7% discount rate. Using the same approach with a 2.5 percent discount rate, the average estimates of marginal damages occurring within the U.S. borders of CO_2, CH_4, and N_2O for emissions in 2020 are \$10/mtCO_2, \$240/mtCH_4, and \$3,300/mtN_2O (in 2020 dollars), respectively; for 2050 emissions, these values increase to \$15/mtCO_2, \$450/mtCH_4, and \$5,300/mtN_2O (in 2020 dollars).

analysis because it helps define the strength of the climate response to increasing GHG concentrations in the atmosphere. In addition, the FUND and PAGE models define many of their parameters with probability distributions instead of point estimates. For these two models, the model developers' default probability distributions are maintained for all parameters other than those superseded by the IWG's harmonized inputs (i.e., equilibrium climate sensitivity, socioeconomic and emissions scenarios, and discount rates). More information on the uncertain parameters in PAGE and FUND is presented in Appendix C of the 2016 TSD (IWG 2016a).

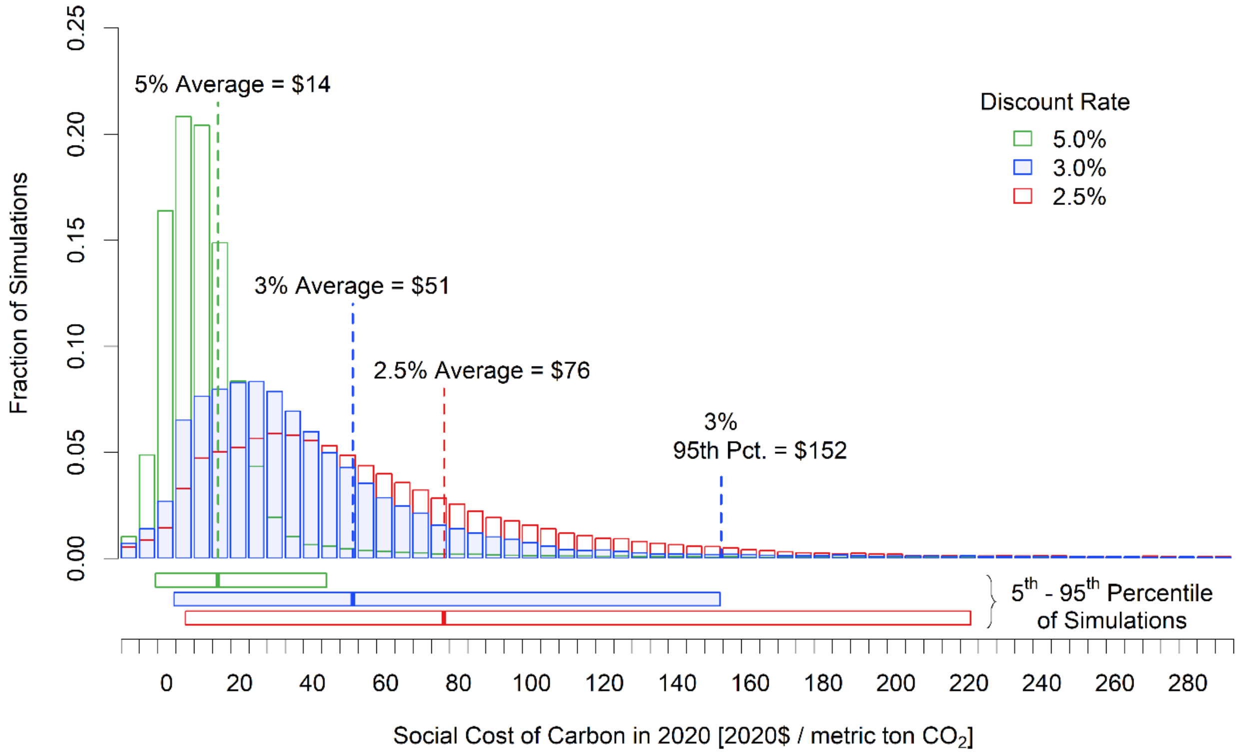
Finally, based on the review of the literature, the IWG chose discount rates that reflect reasonable judgements under both prescriptive and descriptive approaches to intergenerational discounting. As discussed in the 2010 TSD, in light of disagreement in the literature on the appropriate discount rate to use in this context and uncertainty about how rates may change over time, the IWG selected three certainty-equivalent constant discount rates to span a plausible range: 2.5, 3, and 5 percent per year. However, unlike the approach taken for consolidating results across models and socioeconomic and emissions scenarios, the SC-GHG estimates are not pooled across different discount rates because the range of discount rates reflects both uncertainty and, at least in part, different policy or value judgements.

The outcome of accounting for various sources of uncertainty using the approaches described above is a frequency distribution of the SC-CO_2 estimates for emissions occurring in a given year for each of the three discount rates. These frequency distributions reflect the uncertainty around the input parameters for which probability distributions were defined, as well as from the multi-model ensemble and socioeconomic and emissions scenarios where probabilities were implied by the equal weighting assumption. It is important to note that the probability distribution for the SC-GHG calculated using the modeling approach outlined above does not fully characterize uncertainty about the SC-GHG due to impact categories omitted from the models and sources of uncertainty that have not been fully characterized due to data limitations. To name just one example of many known GHG-induced damages omitted in the three IAMs, none of the models include damages associated with ocean acidification, and, therefore, naturally the models do not reflect uncertainty as to the potential severity of those damages.

Figures Figure ***2*** through Figure ***4*** present the frequency distribution of the interim SC-CO_2, SC-CH_4, and SC-N_2O estimates, respectively, for emissions in 2020 and for each discount rate. Each distribution represents 150,000 estimates based on 10,000 simulations for each combination of the three models and five socioeconomic and emissions scenarios. In general, the distributions are skewed to the right and have long right tails, which tend to be longer for lower discount rates. To highlight the difference between the impact of the discount rate on the SC-GHG and other quantified sources of uncertainty, the bars below the frequency distributions provide a symmetric representation of quantified variability in the SC-GHG estimates conditioned on each discount rate. The full set of SC-GHG results through 2050 is available on OMB's website.

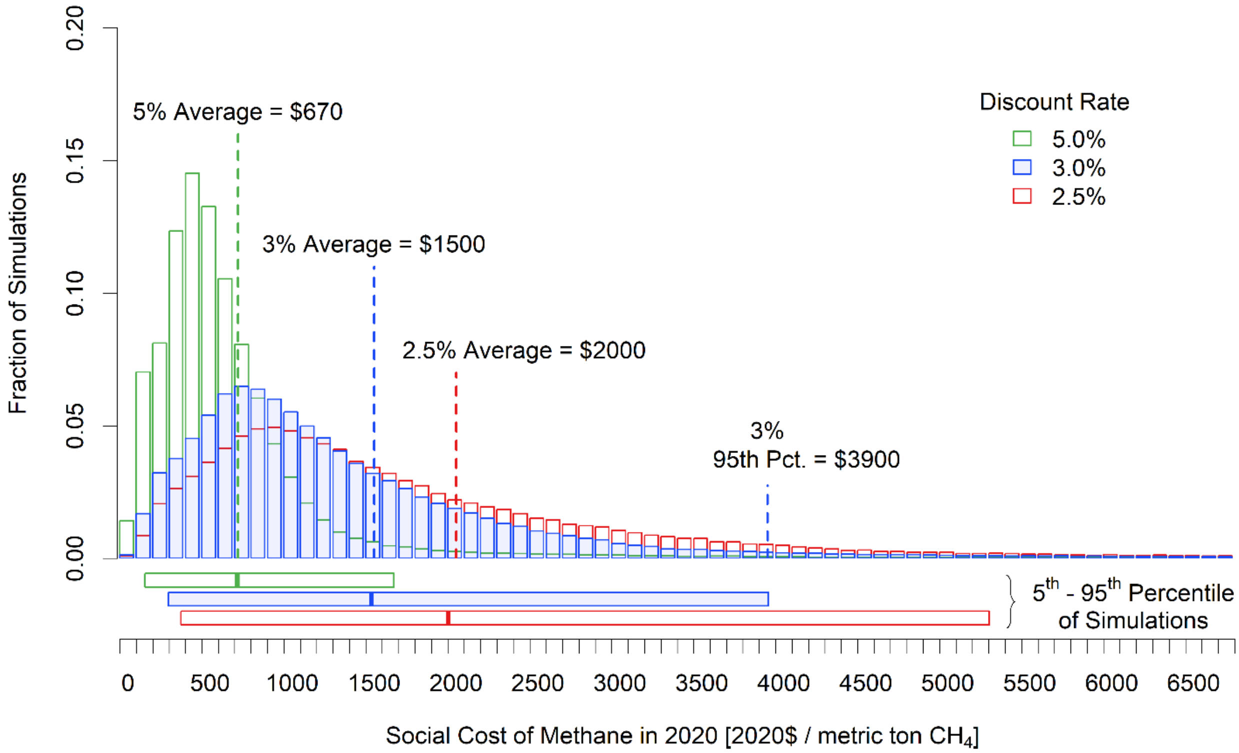
As illustrated by the frequency distributions in Figures Figure ***2*** through Figure ***4*** , the assumed discount rate plays a critical role in the ultimate estimate of the SC-GHG. As explained in Section 3, this is because GHG emissions today continue to impact society far out into the future, so with a higher discount rate, costs that accrue to future generations are weighted less, resulting in a lower estimate. As discussed in Section 3.1, new data and evidence strongly suggest that the consumption interest rate is likely to be less than 3, near 2 percent or lower.

Figure 2: Frequency Distribution of SC-CO_2 Estimates for 2020[34]



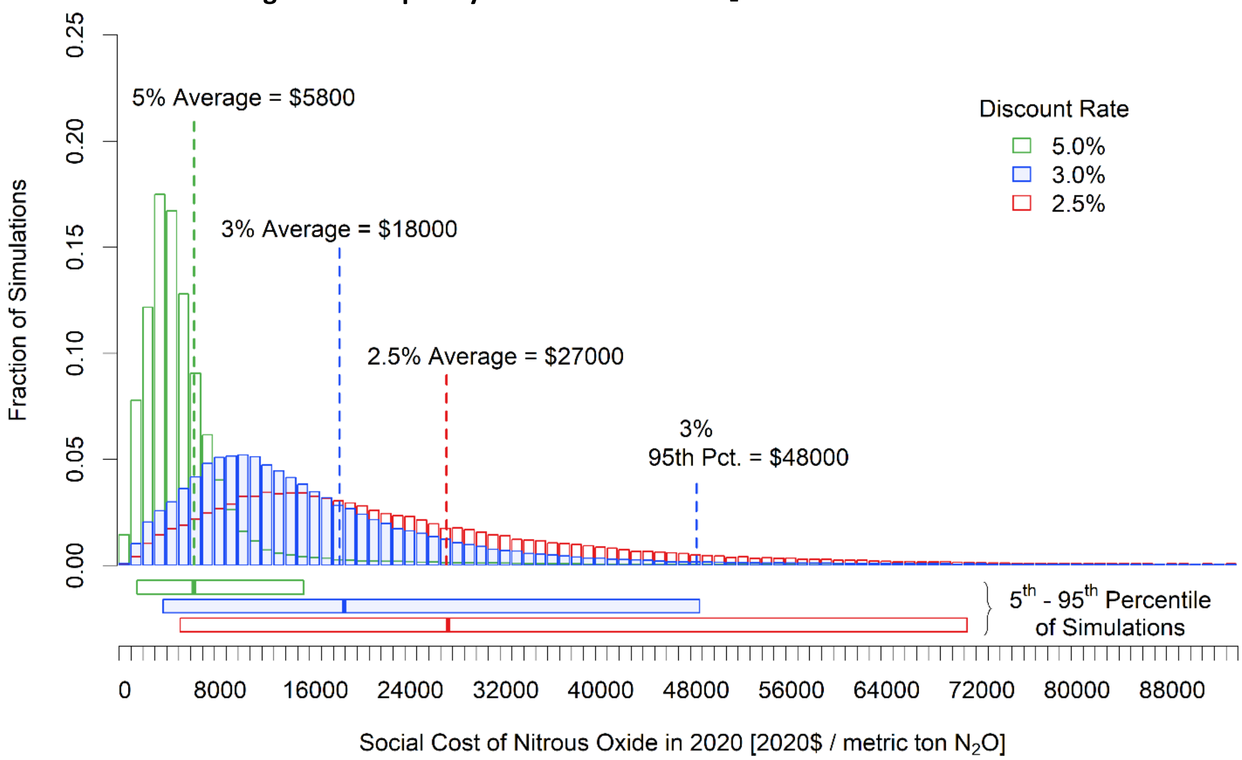
[34] Although the distributions and numbers in Figure 2 are based on the full set of model results (150,000 estimates for each discount rate), for display purposes the horizontal axis is truncated with 0.81 percent of the estimates falling below the lowest bin displayed and 3.56 percent of the estimates falling above the highest bin displayed.

Figure 3: Frequency Distribution of SC-CH_4 Estimates for 2020[35]



[35] Although the distributions and numbers in Figure 3 are based on the full set of model results (150,000 estimates for each discount rate), for display purposes the horizontal axis is truncated with 0.12 percent of the estimates falling below the lowest bin displayed and 2.84 percent of the estimates falling above the highest bin displayed.

Figure 4: Frequency Distribution of SC-N_2O Estimates for 2020[36]



While the figures above reflect the uncertainties that are explicitly considered in a quantitative manner, there are other areas of uncertainty that are not quantitatively reflected in the interim SC-GHG estimates. The scientific and economics literature has further explored known sources of uncertainty related to estimates of the SC-GHG. For example, published studies explore the sensitivity of IAMs and the resulting SC-GHG estimates to different assumptions embedded in the models (see, e.g., Hope 2013, Anthoff and Tol 2013a, and Nordhaus 2014). However, there remain additional sources of uncertainty that have not been fully characterized and explored due to data limitations and lack of consensus in the scientific or economic literature about how to represent them. Additional research is needed to expand the quantification of various sources of uncertainty in estimates of the SC-GHG (e.g., developing explicit probability distributions for more inputs pertaining to climate impacts and their valuation).

4.2 Other Modeling Limitations

The interim SC-GHG estimates presented in this TSD have a number of limitations, as would be expected for any modeling exercise that covers such a broad scope of scientific and economic issues across the complex global landscape. These include the incomplete treatment of catastrophic and non-catastrophic impacts in the IAMs, their incomplete treatment of adaptation and technological change, the incomplete way in which inter-regional and intersectoral linkages are modeled, uncertainty in the extrapolation of

[36] Although the distributions and numbers in Figure 4 are based on the full set of model results (150,000 estimates for each discount rate), for display purposes the horizontal axis is truncated with 0.1 percent of the estimates falling below the lowest bin displayed and 2.85 percent of the estimates falling above the highest bin displayed.

damages to high temperatures, and inadequate representation of the relationship between the discount rate and uncertainty in economic growth over long time horizons.

There are newer versions available of each of the IAMs used to calculate the interim SC-GHG estimates in this TSD that offer improvements in some of these areas beyond the version of the models used for the interim estimates. For example, the latest version of the PAGE model, PAGE-ICE (Yumashev et al. 2019, Yumashev 2020), extends PAGE09 (Hope 2013) with representation of two nonlinear Arctic feedbacks (permafrost carbon feedback and surface albedo feedback) on the global climate system and economy, among other changes. The newest version of the DICE model, DICE2016-R3 (Nordhaus 2017), includes numerous updates, including changes to the carbon cycle (to better simulate the long-run behavior of larger models with full ocean chemistry) and updated methods for estimating economic activity.[37] At comparable discount rates, DICE2016-R3 would result in SC-CO_2 estimates roughly twice that of the interim estimates presented in this TSD. For example, using a 3% constant discount rate and other IWG modeling assumptions, DICE2016-R3 yields an average SC-CO_2 of $104 (2018 international dollars) for 2020 emissions (Nordhaus 2019a). However, even DICE2016 and PAGE-ICE do not include all of the important physical, ecological, and economic impacts of climate change recognized in the climate change literature and the science underlying their damage functions lags behind the most recent research. Likewise, the socioeconomic and emissions scenarios used as inputs to the models in this TSD do not reflect new information from the last decade of scenario generation or the full range of projections.

The modeling limitations discussed above do not all work in the same direction in terms of their influence on the SC-GHG estimates. However, it is the IWG's judgment that, taken together, the limitations suggest that the interim SC-GHG estimates presented in this TSD likely underestimate the damages from GHG emissions. In particular, the IPCC's Fourth Assessment Report (IPCC 2007), which was the most current IPCC assessment available at the time when the IWG decision over the ECS input was made, concluded that SC-CO_2 estimates "very likely…underestimate the damage costs" due to omitted impacts. Since then, the peer-reviewed literature has continued to support this conclusion, as noted in the IPCC's Fifth Assessment report (IPCC 2014) and other recent scientific assessments (e.g., IPCC 2018, 2019a, 2019b; U.S. Global Change Research Program (USGCRP) 2016, 2018; and National Academies 2016b, 2019). These assessments confirm and strengthen the science, updating projections of future climate change and documenting and attributing ongoing changes. For example, sea level rise projections from the IPCC's Fourth Assessment report ranged from 18 to 59 centimeters by the 2090s relative to 1980-1999, while excluding any dynamic changes in ice sheets due to the limited understanding of those processes at the time (IPCC 2007). A decade later, the Fourth National Climate Assessment projected a substantially larger sea level rise of 30 to 130 centimeters by the end of the century relative to 2000, while not ruling out even more extreme outcomes (USGCRP 2018). Section 5 briefly previews some of the recent advances in the

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[37] Relative to the previous version of DICE, DICE2013, the DICE2016 updates to the carbon cycle and the methods for estimating economic activity had the greatest impact on the SC-CO_2. Based on Archer et al. (2009), DICE2016's three-box carbon cycle model aims to better simulate the long-run behavior of larger models with full ocean chemistry. In measuring economic activity, one of the important changes in DICE2016 was to move from market exchange rates to measures adjusted for purchasing power parity when comparing monetary values across countries. See Nordhaus (2017, 2019a) for more discussion of these and other updates included in DICE2016-R3. Nordhaus has also recently explored side extensions of DICE2016. For example, DICE-GIS extends DICE2016 to include representation of sea level rise from melting of the Greenland Ice Sheet (Nordhaus 2019b, Pizer 2019).

scientific and economic literature that the IWG is actively following and that could provide guidance on, or methodologies for, addressing some of the limitations with the interim SC-GHG estimates.

5 Scientific and Economic Advances

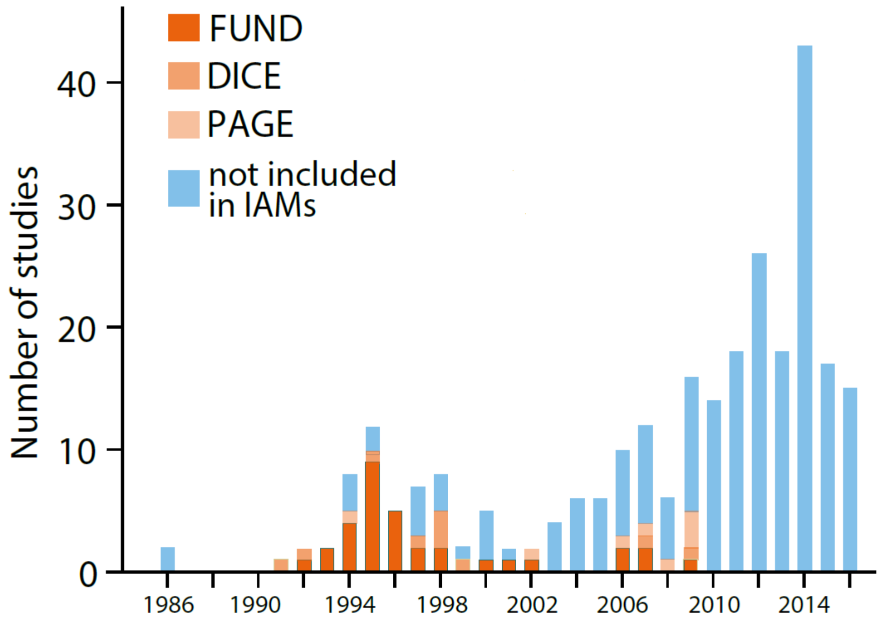
The research community has made considerable progress in developing new data and methods that will provide a path forward for bringing the USG SC-GHG estimates closer to the current frontier of climate science and economics and could address many of the National Academies' (2017) recommendations. This research since 2010/2013 has advanced knowledge regarding each key component in the process of estimating the SC-GHG. This TSD does not intend to provide a detailed review of all these advancements, but this section does highlight some of the key research and new information that the IWG will be reviewing as it works to improve the SC-GHG estimates. As part of the process for updating the SC-GHG estimates by January 2022, the IWG will survey the scientific literature, including the economic literature, to identify advances to address the National Academies (2017) recommendations.

Climate system representation. There have been advancements in climate science since the publication of the IPCC's Fourth Assessment Synthesis report (IPCC 2007), which was the basis for the IWG decision on what equilibrium climate sensitivity (ECS) input to use in the IAM model runs. The conclusions of recent scientific assessments, e.g., from the IPCC (2014, 2018, 2019a, 2019b), the USGCRP (2016, 2018), and the National Academies (2016b, 2019), confirm and strengthen the science, updating projections of future climate change and documenting and attributing ongoing changes. In addition, there are reduced complexity climate models that could offer meaningful improvement over current representation of climate dynamics in existing IAMs (Nicholls et al. 2020). For example, the National Academies (2017) stated that the FAIR model (Smith et al., 2018) satisfies all of the criteria set by National Academies (2017) recommendations related to the representation of climate system dynamics, generates projections of future warming consistent with more complex, state of the art models, can be used to accurately characterize current best understanding of uncertainty, and can be easily implemented and transparently documented. Reduced complexity sea level rise models are also being developed that can provide projections for damage functions that require sea level estimates, including the contributions of thermal expansion and glacial and ice sheet melting based on recent scientific research (e.g., Wong et al. 2017).

***Damage functions*.** At the core of IAMs are "damage functions" that map global mean temperature changes and other physical impacts of climate change into economic (both market[38] and nonmarket[39]) damages. Relative to how much progress has been made in modeling and improving our understanding of climate system dynamics and the physical impacts resulting from temperature change, efforts involved in, and the public resources targeted at, understanding how these physical changes translate into economic impacts have been significantly smaller (Auffhammer 2018). Even so, as illustrated in Figure 5, in the time since the versions of the IAMs used in this TSD were published, there has been an explosion of research on climate impacts and damages.

[38] Examples of market damages include changes in net agricultural productivity, energy use, and property damage from increased flood risk.
[39] Examples of nonmarket damages include services that natural ecosystems provide to society.

Figure 5. New Research on Climate Impacts[40]



Source: Greenstone (2016).

Several efforts are underway to draw on recent literature for improving damage functions and to generate new damage estimates. In particular, the Climate Impact Lab is undertaking an effort to quantify and monetize damages at a fine spatial scale, relying on rigorous empirical methods to develop plausibly causal estimates for several sectors, including health (Carleton et al. 2020), energy (Rode et al. 2021), labor productivity (Rode et al. 2020), agriculture, conflict, and sea level rise.[41] Other research efforts have sought to update the damage function for one sector in an existing IAM based on an updated review of the empirical literature on climate impacts pertaining to that sector (e.g., Moore et al. (2017) for agriculture damages in the FUND model). Damage functions specific to impacts within the U.S. have also been developed and improved for a number of sectors, such as impacts on coastal property, mortality due to extreme temperatures, transportation infrastructure, electricity supply and demand, water quality, recreation, and allergies (Neumann et al. 2020) and impacts of climate change on air quality and human health (Fann et al. 2021). There is also an emerging literature focused on incorporating interactions among

[40] In many cases, the three IAMs used different studies for calibration. This is particularly true of FUND, which used studies relating to different subsectors of the model, whereas DICE and PAGE did not have as detailed a sectoral breakdown. That means that summing across these different models is likely valid in all but a few isolated cases. The blue bars include studies uncovered from a comprehensive literature review in the economics literature (and a few others in public health or relevant disciplines) by the Climate Impact Lab (CIL) through early 2016. Each of the studies counted in blue was determined by CIL to have employed a research design that allowed for the causal interpretation of results (Greenstone 2016).

[41] The Climate Impact Lab is a multidisciplinary collaboration of climate scientists, economists, computational experts, researchers, analysts, and students working to build empirically derived, local-level estimates of climate change damages and an empirically based SC-CO_2. More information on the Climate Impact Lab can be found at: http://www.impactlab.org/.

regions and impacts. For example, biodiversity loss (e.g., animal pollinators) as a result of climate-driven ecosystem stress could amplify impacts of climate change on agriculture. See National Academies (2017) for more discussion of recent research addressing these and other types of interactions.

Related to the development of damage functions, damages from climate change are uncertain and hence pose additional risks. Reductions in GHG emissions reduce not only expected damages, but also reduce the uncertainty and risks of catastrophic events. Evaluating the damages using the mean outcome does not account for the benefits of reducing uncertainty. Some researchers have raised the need to include this consideration in the SC-GHG (e.g., Carleton and Greenstone 2021) consistent with the observation that individuals are regularly willing to pay for insurance against bad outcomes.

Furthermore, E.O. 13990 instructs the IWG to consider how best to reflect environmental justice and intergenerational equity concerns in assessing climate damages. In the context of climate policy, equity considerations are discussed by economists, ethicists, and others in several ways: distributional effects within a specific country, effects across countries, and intergenerational equity impacts. Economists, ethicists, and others have proposed potential ways to incorporate equity into the SC-GHG. For example, IAM developers have introduced the use of equity weights potentially incorporate these concerns (e.g., Hope 2008; Anthoff and Emmerling 2019).

Socioeconomic and Emissions Projections. The socioeconomic and emissions projections underlying current USG SC-GHG estimates were developed around 2007. Since that time, there have been efforts to develop updated baseline scenarios. Several researchers have started using deterministic scenarios available as part of the IPCC's Fifth Assessment Report Working Group 3 database and the Shared Socioeconomic Pathways (SSPs) linked with the Representative Concentration Pathway (RCP) emissions scenarios (Riahi et al. 2017 and Moss et al. 2010) as benchmark scenarios. Resources for the Future (RFF) has engaged in a research effort to implement each of the National Academies' (2017) recommendations, in collaboration with research partners.[42] One part of this effort is focused on developing probability distributions for future paths of population, GDP, and emissions via using econometrics and expert elicitation techniques. For example, economic growth projections are being built off the results of a formal expert elicitation of leading growth economists together with recent research by Muller, Stock and Watson (2020), who have refined a foundational statistical methodology for generating long-run projections of economic growth at the country level. RFF plans to make these probabilistic scenarios easily usable on Mimi.jl, an open-source modular computing platform used for creating, running, and performing analyses on IAMs.[43]

Discounting. Another area of active research relates to discounting, including the best available evidence on the consumption rate of interest and the application of discount rates to regulations in which some costs and benefits accrue intra-generationally while others accrue inter-generationally. As described in Section 3.2, new empirical evidence suggests that consumption interest rates are now below the previous estimate of 3 percent presented in OMB's Circular A-4. This empirical evidence is also consistent with long-term forecasts by the Congressional Budget Office, suggesting these lower rates will persist (U.S. CBO

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[42] For more information on RFF's Social Cost of Carbon Initiative, see: https://www.rff.org/topics/scc/.

[43] Mimi.jl was developed by a team of researchers at UC Berkeley led by David Anthoff in response to a core recommendation from the National Academies (2017) to create an integrated modular approach to draw more readily on expertise from the wide range of scientific disciplines relevant to SC-CO_2 estimation. Mimi.jl provides an interface for defining components and building models in a modularized, transparent way (mimiframework.org).

2020). Future updates to the SC-GHGs estimates will need to reflect the best available evidence from the time series of risk-free rate data and expectations of these rates into the future.

As described in Section 3.3 uncertainty in the discount rate over time yields a declining certainty-equivalent discount rate schedule and can have a dramatic effect on the size of the SC-GHG. While this is not a new theoretical result, new literature has proposed methods for how to incorporate discount rate uncertainty (e.g., Arrow et al., 2013; Cropper et al., 2014) and other nations have implemented declining discount rate schedules for policy analysis (e.g., United Kingdom, France, and Germany). Recent recommendations by the National Academies (2017) and EPA's Science Advisory Board (2021) have encouraged the development and use of a declining certainty-equivalent discount rate schedule as theoretically appropriate and as a method of introducing consistency into analyses that have both near-term and long-term impacts.

In light of new science and evidence, including many of those highlighted in the paragraphs above, other jurisdictions are already considering or have implemented some of the scientific and economic advances discussed above. For example, some states that use SC-GHG estimates in policy analysis have recently updated their approach to discounting based on the increasing evidence that a 3% discount rate is too high for intergenerational analysis. In December 2020, New York issued guidance recommending state agencies use SC-GHG estimates based the same IWG modeling and input decisions as presented in this TSD but with lower discount rates: 2 percent in central scenarios (\$125/mtCO_2 for 2020 emissions (2020 dollars), along with sensitivity analysis at 1 percent and 3 percent (New York Department of Environmental Conservation 2020). Similarly, in Washington state an April 2019 law required utilities to use estimates based on the IWG methodology with a 2.5% discount rate when developing "lowest-cost analyses" for its integrated resource planning and clean energy plans.[44]

Canada is also in the process of updating the SC-GHG estimates used in their regulatory analyses. While the update is underway, they are continuing to use the estimates they adopted in 2016 (which are an adaptation of the IWG global SC-GHG estimates presented in this TSD) as well as a side analysis based on more recent estimates from the academic literature. Based on their review of the literature and latest climatological and economic evidence, they present their current estimates as a "likely underestimate [of] climate-related damages to society" and the side analysis as a way "to illustrate a range of plausible values if the Department were to update its [social cost of carbon] estimate based on new versions of the models currently used."[45] Specifically, the side analysis includes SC-CO_2 estimates based on DICE2016 and PAGE-ICE (\$135 and \$440/mtCO_2 for 2020 emissions (2019 Canadian dollars)).[46]

The IWG will consider the new science and evidence as it works towards a more comprehensive update, including the new research and information described in this section.

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[44] Wash. Sen. Bill. 5116 (signed by Gov. Inslee on May 7, 2019). More information on Washington and other states' use of SC-GHG estimates is compiled by the Institute for Policy Integrity at NYU School of Law (see http://www.costofcarbon.org/states) and discussed in U.S. GAO (2020).

[45] Proposed Clean Fuel Regulations (published for public comment on 12/20/20) http://www.gazette.gc.ca/rp-pr/p1/2020/2020-12-19/pdf/g1-15451.pdf.

[46] Proposed Clean Fuel Regulations (published for public comment on 12/20/20) http://www.gazette.gc.ca/rp-pr/p1/2020/2020-12-19/pdf/g1-15451.pdf.

6 Path Forward

E.O. 13990 reaffirms that "[a]n accurate social cost is essential for agencies to accurately determine the social benefits of reducing greenhouse gas emissions when conducting cost-benefit analyses of regulatory and other actions" (E.O. 13990 2021). The E.O. instructs the IWG to publish interim SC-CO_2, SC-CH_4, and SC-N_2O estimates (collectively, SC-GHG estimates) within 30 days and to publish a set of final estimates by no later than January 2022.[47] In doing so, the E.O. instructs the IWG to consider the recommendations of the National Academies of Science, Engineering, and Medicine as reported in Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide (2017) and other pertinent scientific literature; solicit public comment; engage with the public and stakeholders; seek the advice of ethics experts; and ensure that the SC-GHG estimates reflect the interests of future generations in avoiding threats posed by climate change.

In developing the SC-GHG estimates in 2010, 2013, and 2016 the IWG used consensus-based decision making, relied on peer-reviewed literature and models, and took steps to disclose limitations and incorporate new information by considering public comments and revising the estimates as updated research became available (U.S. GAO 2014). Going forward the IWG commits to maintaining a consensus driven process for making evidence-based decisions that are guided by the best available science and input from the public, stakeholders, and peer reviewers.

While the IWG assesses the current state of the science in each component of the SC-GHG modeling exercise, the IWG is beginning by asking for public comment on how best to incorporate the latest, peer reviewed science to develop an updated set of SC-GHG estimates. The IWG will soon issue a Federal Register notice with a detailed set of requests for public comments on the new information presented in this TSD, as well as other topics and issues the IWG will address as we develop the next set of updates. Among other things, the IWG will ask for public comment on how to incorporate the best available science in the updated SC-GHG estimates, due to be published by January 2022, and how to incorporate the recommendations of the National Academies (2017).

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[47] The Executive Order also requests that the IWG assess the application of the SC-GHG to inform government decision making beyond regulations, in addition to recommending a robust long-term structure for ensuring the SC-GHGs continue to reflect the best available science and economic and that long-term research needs are met.

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Appendix – Annual SC-CO_2, SC-CH_4, and SC-N_2O Values, 2020-2050

The values in Tables A-1 through A-3 are the same as those reported in the 2016 TSD and Addendum adjusted for inflation to 2020 dollars using the annual GDP Implicit Price Deflator values in U.S. Bureau of Economic Analysis (BEA) NIPA Table 1.1.9: 113.626 (2020)/ 92.486 (2007) = 1.228575 (U.S. BEA 2021). Values of SC-CO_2 presented in this TSD are rounded to the nearest dollar; SC-CH_4 and SC-N_2O are rounded to two significant figures. The annual unrounded estimates are available on OMB's website for use in regulatory and other analyses: https://www.whitehouse.gov/omb/information-regulatory-affairs/regulatory-matters/#scghgs.

Table A-1: Annual SC-CO_2, 2020 – 2050 (in 2020 dollars per metric ton of CO_2)

	Discount Rate and Statistic			
Emissions Year	5% Average	3% Average	2.5% Average	3% 95th Percentile
2020	14	51	76	152
2021	15	52	78	155
2022	15	53	79	159
2023	16	54	80	162
2024	16	55	82	166
2025	17	56	83	169
2026	17	57	84	173
2027	18	59	86	176
2028	18	60	87	180
2029	19	61	88	183
2030	19	62	89	187
2031	20	63	91	191
2032	21	64	92	194
2033	21	65	94	198
2034	22	66	95	202
2035	22	67	96	206
2036	23	69	98	210
2037	23	70	99	213
2038	24	71	100	217
2039	25	72	102	221
2040	25	73	103	225
2041	26	74	104	228
2042	26	75	106	232
2043	27	77	107	235
2044	28	78	108	239
2045	28	79	110	242
2046	29	80	111	246
2047	30	81	112	249
2048	30	82	114	253
2049	31	84	115	256
2050	32	85	116	260

Table A-2: Annual SC-CH_4, 2020 – 2050 (in 2020 dollars per metric ton of CH_4)

Emissions Year	Discount Rate and Statistic 5% Average	3% Average	2.5% Average	3% 95th Percentile
2020	670	1500	2000	3900
2021	690	1500	2000	4000
2022	720	1600	2100	4200
2023	750	1600	2100	4300
2024	770	1700	2200	4400
2025	800	1700	2200	4500
2026	830	1800	2300	4700
2027	860	1800	2300	4800
2028	880	1900	2400	4900
2029	910	1900	2500	5100
2030	940	2000	2500	5200
2031	970	2000	2600	5300
2032	1000	2100	2600	5500
2033	1000	2100	2700	5700
2034	1100	2200	2800	5800
2035	1100	2200	2800	6000
2036	1100	2300	2900	6100
2037	1200	2300	3000	6300
2038	1200	2400	3000	6400
2039	1200	2500	3100	6600
2040	1300	2500	3100	6700
2041	1300	2600	3200	6900
2042	1400	2600	3300	7000
2043	1400	2700	3300	7200
2044	1400	2700	3400	7300
2045	1500	2800	3500	7500
2046	1500	2800	3500	7600
2047	1500	2900	3600	7700
2048	1600	3000	3700	7900
2049	1600	3000	3700	8000
2050	1700	3100	3800	8200

Table A-3: Annual SC-N_2O, 2020 – 2050 (in 2020 dollars per metric ton of N_2O)

Emissions Year	Discount Rate and Statistic 5% Average	3% Average	2.5% Average	3% 95th Percentile
2020	5800	18000	27000	48000
2021	6000	19000	28000	49000
2022	6200	19000	28000	51000
2023	6400	20000	29000	52000
2024	6600	20000	29000	53000
2025	6800	21000	30000	54000
2026	7000	21000	30000	56000
2027	7200	21000	31000	57000
2028	7400	22000	32000	58000
2029	7600	22000	32000	59000
2030	7800	23000	33000	60000
2031	8000	23000	33000	62000
2032	8300	24000	34000	63000
2033	8500	24000	35000	64000
2034	8800	25000	35000	66000
2035	9000	25000	36000	67000
2036	9300	26000	36000	68000
2037	9500	26000	37000	70000
2038	9800	27000	38000	71000
2039	10000	27000	38000	73000
2040	10000	28000	39000	74000
2041	11000	28000	39000	75000
2042	11000	29000	40000	77000
2043	11000	29000	41000	78000
2044	11000	30000	41000	80000
2045	12000	30000	42000	81000
2046	12000	31000	43000	82000
2047	12000	31000	43000	84000
2048	13000	32000	44000	85000
2049	13000	32000	45000	87000
2050	13000	33000	45000	88000

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Updating the United States Government's Social Cost of Carbon

Tamma Carleton and Michael Greenstone

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Updating the United States Government's Social Cost of Carbon

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Abstract

This paper outlines a two-step process to return the United States government's Social Cost of Carbon (SCC) to the frontier of economics and climate science. The first step is to implement the original 2009-2010 Inter-agency Working Group (IWG) framework using a discount rate of 2%. This can be done immediately and will result in an SCC for 2020 of $125. The second step is to reconvene a new IWG tasked with comprehensively updating the SCC over the course of several months that would involve the integration of multiple recent advances in economics and science. We detail these advances here and provide recommendations on their integration into a new SCC estimation framework.

We thank Jared Stolove for exceptional research assistance and Trevor Houser, Amir Jina, Robert Kopp, Ishan Nath, and Cass Sunstein for valuable critiques and suggestions. This working paper will also appear in a forthcoming book of energy and environmental policy proposals to be published by the Energy Policy Institute at the University of Chicago (EPIC). Contact information: tcarleton@ucsb.edu and mgreenst@uchicago.edu.

I. Heart of the Problem

All over the world, climate policies have the potential to provide large benefits by reducing the harms that result from carbon dioxide (CO_2) emissions. However, these policies can be costly, with some more expensive than others. The value of reducing such emissions is not $0, and it is not infinite. Some imaginable fuel economy standards, for example, would be very stringent, while others would be very lenient. What level of stringency is optimal, if a central goal of those standards is to reduce carbon dioxide emissions? To confront the challenge of climate change effectively, the public is best served by policies that have benefits in excess of costs, and that maximize net benefits.

A key tool in identifying such policies is the social cost of carbon (SCC), which represents the monetized damages associated with a one metric ton increase in CO_2 emissions. In principle, the SCC illustrates the dollar value all of the future damages associated with the change in climate due to the release of an additional ton of CO_2, including (but not limited to), mortality and other health effects from excess heat and natural disasters, depressed agricultural production, reductions in labor productivity, disruption of energy systems, increased risk of violent conflict, property damage from hurricanes and floods, and mass migration out of affected regions. The SCC therefore reflects how much society should be willing to pay to reduce carbon dioxide emissions by a ton.

With this information, policymakers can easily conduct cost-benefit analysis of regulations that reduce CO_2 emissions. The costs to the economy of lowering emissions (e.g., imposing fuel economy standards on car manufacturers) are naturally calculated in dollars. And with the SCC, the benefits of CO_2 emissions reductions are converted into dollars. The result is an apples-to-apples comparison of an individual regulation's benefits and costs, both measured in dollars.

From the standpoint of law and practice, this conversion is extraordinarily helpful. In the United States, some legislation formally requires agencies to conduct cost-benefit analysis, and prevailing Executive Orders, supported by both Republican and Democratic presidents, require such an analysis for all major regulations, including those designed to reduce carbon emissions. Though the use of cost-benefit analysis is not without controversy, there is a strong argument in favor of conducting such an analysis, and giving serious consideration to it, if the goal is to ensure that regulations best promote the American people's interests.[1]

Following the Supreme Court's decision in U.S. EPA vs. Massachusetts (2007), the U.S. government has been required to issue at least some regulations to reduce greenhouse gas emissions, but it lacked a consistent SCC with which to inform its judgments. In 2009, therefore, the Obama administration issued a temporary SCC and formed an Inter-agency Working Group (IWG) that was tasked with developing a robust SCC, based on the best available science and economics. The work was completed in 2010 and then successively updated, which ultimately produced a value of $52 per ton of CO_2 in 2020.[2] The same methods were used to develop a social cost of methane, another potent greenhouse gas, in 2016.[3] Following a request from the Obama administration, the National Academies of Sciences, Engineering, and Medicine (NAS) released a report on how to bring the SCC closer to the frontier of climate science and economics in January 2017.

Not long after that report's release, the Trump administration disbanded the IWG and reduced the SCC to between $1 and $7 (see left panel of Figure 1), making changes in assumptions that did not follow the NAS recommendations and that were difficult to justify based on science and economics.[4] In the past four years, the controversial and substantially lower SCC estimates used by the Trump administration have helped to pave the way for the rollback of environmental regulations. For example, as illustrated in Figure 2, the Trump administration's 2017 reconsideration and substantial weakening of Obama-era fuel economy standards was merited, on cost-benefit grounds, with its lower SCC, but would not have been so justified with the IWG SCC.

[1] Livermore and Revesz, *Reviving Rationality*.
[2] Interagency Working Group, "Technical Support Document" (2013).
[3] Interagency Working Group, "Technical Support Document" (2016).
[4] Greenstone, Congressional Testimony.

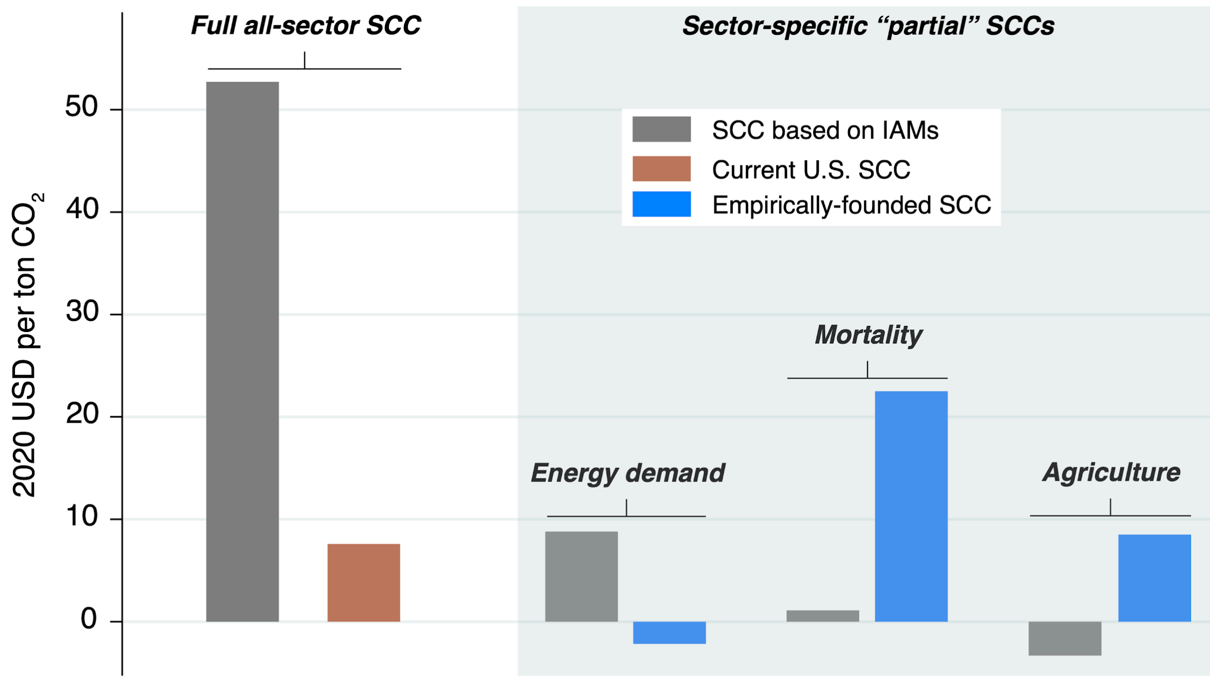

Figure 1: Current U.S. Social Cost of Carbon (SCC) is behind frontier science. This figure compares current and past U.S. federal SCCs to those produced by recent scientific and economic research. The full all-sector SCCs shown on the left are U.S. federal SCCs used under the Obama administration (grey) and the Trump administration (brown). Sector-specific "partial" SCCs on the right come from the Interagency Working Group (IWG) 2013 implementation of the FUND model (grey) and recent scientific literature (blue). *Sources:* Rode et al. (2020b), Carleton et al. (2020), Moore et al. (2017), and Anthoff and Tol (2014), as decomposed by Diaz (2014). All estimates indicate the willingness-to-pay to avoid an increase in emissions in the year 2020, are shown in 2020 USD, rely on an approximate "business-as-usual" emissions scenario (e.g., RCP 8.5), and use a 3 percent discount rate.

Since its release in 2010, the SCC has played a central role in climate policy both domestically and internationally. For example, as of 2017 the federal government had used the SCC to assess the value of over eighty regulations with a combined $1 trillion in estimated gross benefits.[5] At least eleven state governments have begun using an SCC to guide policy, most notably in Illinois and New York, where governments use the SCC to value "zero-emissions credits" paid to producers of clean energy.[6] Meanwhile, several other countries, including Canada, France, Germany, Mexico, Norway, and the United

[5] Nordhaus, "Revisiting the Social Cost of Carbon."
[6] Institute for Policy Integrity, "The Cost of Carbon Pollution."

Kingdom, have referred to the experience of the United States to implement their own SCC estimates, with some adopting estimates wholesale from the IWG.[7]

Figure 2: Current U.S. SCC used to justify rollbacks of fuel-economy standards. Figure displays an example regulatory cost-benefit analysis (CBA) using two different SCCs. The values shown are the costs and benefits of a 2017 Environmental Protection Agency (EPA) and National Highway Traffic and Safety Administration (NHTSA) rollback of fuel economy standards for 2021-2026 model-year vehicles. The top row displays the benefits and costs of the rollback using the 2017 Trump administration 3 percent discount rate SCC, taken directly from Table I-I and Table VII-286 of EPA and NHTSA (2017). The bottom row uses the same benefit estimate, but calculates the costs using the 2013 IWG 3 percent discount rate SCC (i.e., the Obama administration SCC), leaving all other assumptions the same across rows (IWG, 2013). Cost estimates incorporate damages from carbon emissions and other factors, such as the monetary cost of fuel. Costs from sources other than carbon emissions account for $178 billion of costs in both rows. Both costs and benefits are converted from 2018 to 2020 dollars using the BEA CPI inflation calculator.

In many respects, the SCC is the "straw that stirs the drink" for most domestic climate policies, determining in some cases whether or not regulatory action can proceed.[8] But the national SCC can also influence the direction of international climate negotiations: experience demonstrates that meaningful U.S. action can leverage large reductions in emissions from other countries that reduce the climate damages that Americans must contend with.[9]

Rapid scientific and economic advances in the last decade mean that there is now an urgent need to update the SCC. The Obama-era SCC relied on the science and data

[7] U.S. GAO, "Social Cost of Carbon"
[8] Sunstein, "Watch for Biden Decision on Unsung Climate Metric."
[9] Houser, "Calculating the Climate Reciprocity Ratio."

available at the time, often making simplifying assumptions that are now understood to be invalid or unnecessary. Recognizing the likely advance of understanding, the IWG explicitly called for "update[s] over time to reflect increasing knowledge of the science and economics of climate impacts."[10] Despite some incremental changes, however, a wholesale update was never conducted. The consequence is that neither the Trump nor Obama SCC incorporates the explosion of data and research since 2010 that has dramatically expanded knowledge of the climate, economy, and the relationship between the two. A defining feature of the best new research is that it relies on large-scale data sets, rather than assumptions that are often unverifiable.

A number of these new, empirically grounded studies indicate that the underpinnings of the current SCC are no longer valid in terms of, for example, their projected impacts on mortality rates, energy demand, and agricultural productivity.[11] The right panel of Figure 1 shows three of the sector-specific component or "partial" SCC estimates developed in recent years (blue), as they compare to the same components of the federal SCC developed in 2013 (grey). New estimates for two of three recently studied SCC sectors (mortality and agriculture) indicate substantially larger damages from CO_2, suggesting that the SCC, as settled in 2013, is too low.

Besides advancing understanding about the overall impacts of climate change, these data-driven updates to the SCC have uncovered large differences in the impacts of climate change both within and across countries that were invisible with previous approaches. The key finding is that climate change is projected to disproportionately harm today's poorest populations, exacerbating concerns about environmental justice.[12] These distributional findings are only visible with the detailed data that characterize the new wave of research. As just one example, even within a wealthy country like the United States, climate change is projected to cause economic damages in the poorest 5 percent of counties that are approximately nine times larger on average by the end of the century than in those in the richest 5 percent.[13] Put plainly, this new research

[10] Interagency Working Group, "Technical Support Document" (2010).
[11] Carleton et al., "Valuing the Global Mortality"; Rode et al., "Estimating a Social Cost of Carbon"; Diaz & Moore, "Quantifying the Economic Risks"; Moore et al., "New Science of Climate Change Impacts".
[12] See, for instance, Hsiang et al., Estimating Economic Damage from Climate Change in the United States."
[13] Id

makes it possible to assess *who* is most affected by climate policies—insight that is out of reach under the current SCC framework.

Revising the U.S. SCC based on a new and more durable foundation would return the SCC to the frontier of understanding about the risks from climate change and lead to better policy that protects Americans against unnecessary climate risks. Moreover, such an update would undoubtedly influence policy abroad, which directly affects the well-being of Americans, since the climate is equally affected by emissions from Chicago, as those from Beijing, Mumbai, Paris, and Riyadh.

This paper outlines a two-step approach to updating the U.S. SCC that returns it to the frontier of knowledge. The Biden administration can initiate the first step immediately and simply involves implementing the IWG's approach again with a discount rate of no higher than 2 percent, which reflects profound changes in international capital markets that make the current values difficult to justify. At a discount rate of 2% the SCC in 2020 is $125.[14]

The second step is for the Biden administration to launch a reconstituted IWG and task it with a comprehensive updating of the SCC. There are seven key "ingredients" that should go into such a process and the next section identifies each of them, explains what was done in the past, describes how understanding has advanced since 2009-2010, and makes a specific recommendation. The paper's final section details multiple pathways towards combining these ingredients to produce an updated SCC. Importantly, none of these pathways can be implemented immediately; a reconstituted IWG's work could take several months.

II. The Seven Key Ingredients for a Revised SCC

Calculating the SCC requires a model that accounts for the future growth of the economy, the relationship between emissions and climate change, the effect of climate change on the economy, and a number of other factors. Such models are referred to as Integrated Assessment Models (IAMs), since they combine scientific and economic

[14] New York State Department of Environmental Conservation, "Establishing a Value of Carbon"; New York State Energy Research and Development and Resources for the Future, "Estimating the Value of Carbon: Two Approaches."

models to evaluate the impacts of carbon emissions. The Obama-era IWG estimated the SCC using three existing IAMs—DICE, FUND, and PAGE—which were developed in the 1990s and have been widely used in the economic and scientific literature.[15]

There are seven "ingredients" necessary to construct the SCC. The first four are often referred to as "modules" (see Figure 3):

1. A socioeconomic and emissions trajectory, which predicts how the global economy and CO_2 emissions will grow in the future;
2. A climate module, which measures the effect of emissions on the climate;
3. A damages module, which translates changes in climate to economic damages; and
4. A discounting module, which calculates the present value of future damages.

In addition, there are three cross-cutting modeling decisions that affect the entire process:

1. Whether to include global or instead only domestic climate damages;
2. How to value uncertainty; and
3. How to treat equity.

[15] Nordhaus, "Economic Aspects of Global Warming"; Anthoff and Tol, "The Income Elasticity of the Impact of Climate Change"; Hope, "The PAGE09 Integrated Assessment Model."

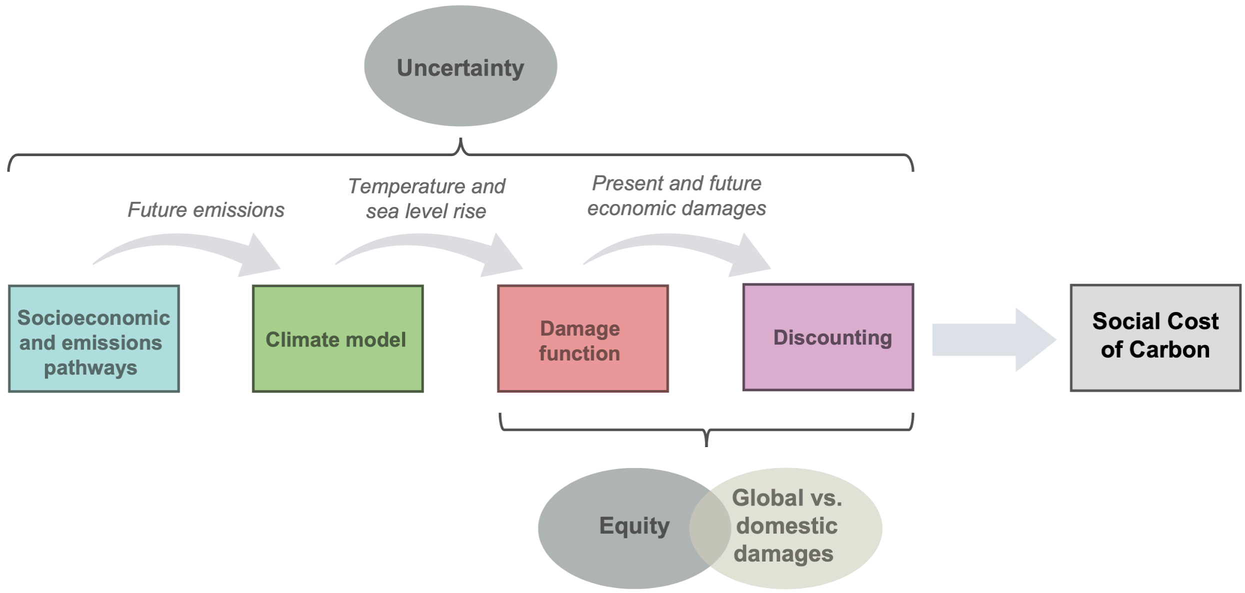

Figure 3: Seven ingredients for calculating the Social Cost of Carbon. This figure displays the four "modules" that compose the SCC (colored boxes), and the three key modeling decisions (grey ovals) that together form the seven "ingredients" necessary to compute an SCC.

Updating the SCC so that it is built on a foundation of frontier science and economics would require a newly constituted IWG to make decisions regarding each of these seven ingredients. However, the IWG need not start from scratch; some required updates are already clear. Due to significant advances in climate modeling and in climate impact analysis, as well as profound changes in global capital markets, it is *essential* to update the climate and damage modules and to change the rate of discounting. It is additionally essential to update the Trump administration's U.S. SCC to reflect global, as opposed to domestic only, damages, based on an overwhelming consensus amongst scientific and economic experts. Failing to account for these advances would leave any new SCC open to well-founded scientific criticism. It could also leave a new SCC vulnerable to legal invalidation; courts review agency decisions to ensure that they are not "arbitrary or capricious," and if a new SCC were not based on scientific advances it could be challenged on exactly that ground. There are also valuable opportunities to update the other three ingredients, but to varying degrees the scientific and/or policy case for doing so is less urgent.

This paper can be thought of as a "recipe," outlining ways to bring the U.S. government's SCC back up to the scientific frontier. This section briefly explains each of the seven key ingredients, describes how they were handled by the IWG in 2010, and makes recommendations to update each.

A. Essential Updates to the SCC

Ingredient 1: Climate Module

Background: The development of an SCC requires a climate model that converts carbon emissions into changes in the global climate. Specifically, these models must characterize the relationship between emissions and atmospheric CO_2 concentrations and the relationship between atmospheric CO_2 and changes in the climate, including both warming and sea level rise. All three IAMs used by the IWG included highly simplified climate models. A core input into each of these models was the Equilibrium Climate Sensitivity (ECS), which determines the total global warming realized from a doubling of atmospheric carbon concentrations. The ECS has a substantial impact on the SCC but its true value is not known with scientific certainty.

2010 IWG Approach: The IWG relied on the climate models within each IAM. However, to ensure that the ECS values used reflected the best available science at the time, the IWG harmonized the ECS across all models by using a probability distribution that reflected the likelihood of different possible climate outcomes at the end of the century according to the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report. This was the only component of each IAM's climate model that the IWG calibrated to match scientific evidence.

Progress: Recent evidence makes clear that the IAMs used to calculate the IWG SCC, even with a harmonized ECS, are outdated, as they do not reflect a substantial body of new research quantifying multiple links in the causal chain from emissions to temperature change.[16] In particular, DICE, FUND, and PAGE substantially underestimate the *speed* of temperature increase, relative to climate models that satisfy the NAS criteria for meeting scientific standards (Figure 4).[17] For example, higher atmospheric CO_2 concentrations cause the oceans to warm and acidify, which makes

[16] Dietz et al., "Are Economists Getting Climate Dynamics Right"; Mattauch et al., "Steering the Climate System"; NAS, "Valuing Climate Damages."
[17] NAS, "Valuing Climate Damages," Recommendation 4-1

them less effective at removing CO_2 from the atmosphere. The consequence is a positive feedback loop that accelerates warming.[18] However, this dynamic is missing from both the DICE and PAGE climate modules.

The fact that existing IAMs do not reflect the well-developed climate science literature substantially influences the magnitude of the SCC.[19] Importantly, the delayed projection of warming in the IAMs' climate models means that resulting estimates of the SCC are likely to be too low. The delay pushes warming further into the future, which is discounted more heavily, as shown in the bottom panel of Figure 4.

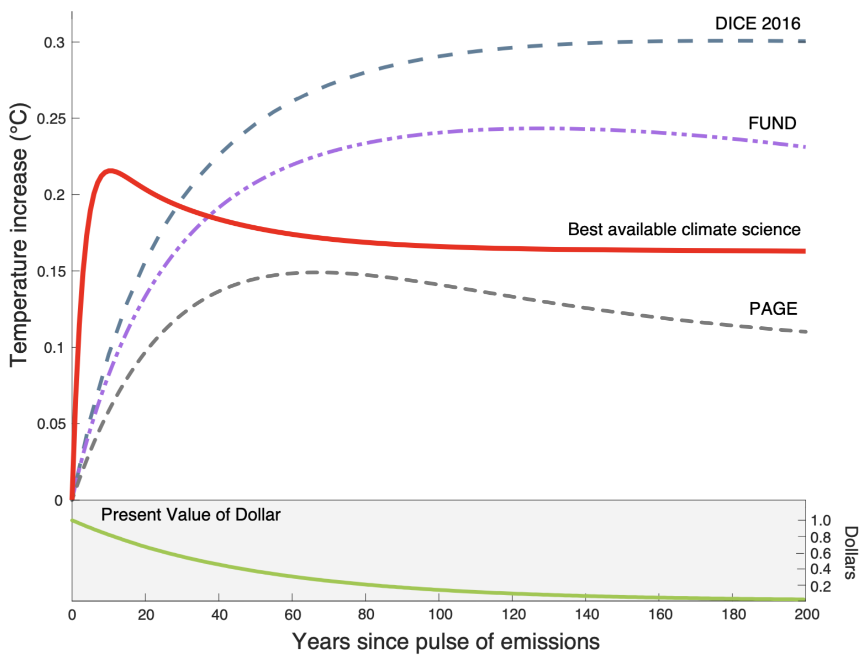

Figure 4: Current Integrated Assessment Models do not reflect well-developed climate science. Dynamic temperature response to a 100GtC impulse of CO_2 from the CMIP5 climate model ensemble (red solid line, labeled "best available climate science") versus the three IAMs used to compute the U.S. government's SCC (DICE, FUND, and PAGE). The lower panel shows the present discounted value of $1, discounted using a 2 percent discount rate. Source for top panel: Dietz et al., 2020.

Recommendation: It is vital that an updated SCC relies on a climate model that accurately reflects the climate system's functioning. Because any SCC calculation requires fully capturing the uncertainty surrounding the impact of CO_2 on temperature

[18] Dietz et al., "Are Economists Getting Climate Dynamics Right."
[19] Id

and other climate variables, however, it would be computationally infeasible to replace IAM climate models with state-of-the-art Earth system models that capture the physics, chemistry, and biology of the atmosphere, oceans and land at high spatial resolution. Therefore, a simple Earth system model that can conduct uncertainty analysis while also matching predictions from these more complex models is necessary.

The first part of our[20] climate model recommendation is that IWG use the simple Earth system model FAIR to project changes in temperature.[21] The FAIR model satisfies all criteria set by the NAS for use in an SCC calculation.[22] Importantly, this model generates projections of future warming that are consistent with comprehensive, state-of-the-art models *and* it can be used to accurately characterize current best understanding of the uncertainty regarding the impact that an additional ton of CO_2 has on global mean surface temperature (GMST). Finally, FAIR is easily implemented and transparently documented,[23] and is already being used in updates of the SCC.[24]

A key limitation of FAIR and other simple climate models is that they do not represent the change in global mean sea level rise (GMSL) due to a marginal change in emissions. However, statistical methods can be used in combination with long historical records of both temperature and sea level to build a semi-empirical model of the relationship between GMSL and GMST.[25] Such models are readily available[26] and can enable the inclusion of marginal damages due both to warming *and* to projected changes in sea level. An important potential caveat is that available semi-empirical models of GMSL, in addition to more complex bottom-up models, may underestimate future sea level rise due to their inability to capture plausible future dynamics that are not observed in the historical record (e.g., ice cliff collapse).

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[20] Throughout, "we" or "our" refers solely to the views of Carleton and Greenstone and not necessarily those of EPIC, the University of Chicago, or the University of California, Santa Barbara.
[21] Millar et al., "A Modified Impulse-Response Representation."
[22] NAS, "Valuing Climate Damages."
[23] FAIR's source code can be accessed here: https://github.com/OMS- NetZero/FAIR/.
[24] Dietz et al. "Are Economists Getting Climate Dynamics Right"; Carleton et al., "Valuing the Global Mortality Consequences"; Rode et al., "Labor Supply in a Warmer World"; Rode et al., "Estimating a Social Cost of Carbon for Global Energy Consumption."
[25] NAS, "Valuing Climate Damages."
[26] See, for example, Kopp et al., "Temperature-Driven Global Sea-Level Variability."

The second part of our climate model recommendation is that the IWG use semi-empirical models to project changes in sea level based on changes in global mean surface temperature from FAIR.

Finally, a strength of simple climate models like FAIR is that they can project GMST, accounting for climatological uncertainty, both with and without a marginal increase in emissions, which is necessary to compute the social cost of one additional ton of CO_2. However, they are not able to provide local climate projections at, for example, the county level. This introduces a challenge, as socioeconomic trajectories are available nationally and, as discussed below, recovering a valid damage function requires that climate impacts be estimated locally. It is possible, however, to use high spatial detail in socioeconomic and climatic conditions to estimate damages that are then calibrated to GMST (and GMSL, for sectors where sea level rise is an important driver of climate change impacts) in a second stage.[27]

Therefore**, the third part of our climate model recommendation is that the damage function itself should relate total socioeconomic damages to changes in global mean surface temperature (and global mean sea level rise where appropriate)**.

<u>Ingredient 2: Damages Module</u>

Background: A "damage function" translates changes in the physical climate (e.g., temperature and sea level rise) into monetized impacts on the economy. In some IAMs, a single damage function is calibrated to represent all categories of climate impact (e.g., PAGE), while in others, separate damage functions are modeled for individual impact categories (e.g., FUND). In DICE, a single damage function is used, but it is calibrated based on individual sector-specific damage estimates.[28]

At least two problems have plagued the IAM damage functions. First, they are primarily derived from ad-hoc assumptions and simplified relationships, not large-scale empirical evidence. Further, the IAM damage functions have tended to treat the world as nearly homogeneous, dividing the globe into at most sixteen regions. This aggregation

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[27] NAS, "Valuing Climate Damages"; Carleton et al., "Valuing the Global Mortality Consequences;" Rode et al., "Labor Supply in a Warmer World;" Rode et al., "Estimating a Social Cost of Carbon for Global Energy Consumption."
[28] Nordhaus, "The 'DICE' Model."

misses a great deal, especially because there are important nonlinearities in the relationship between temperature and human well-being that are obscured by substantial aggregation. For example, a given increase in temperature will have very different impacts in Arizona than it will in northern Minnesota. For both of these reasons, these damage functions have been heavily criticized in recent years.[29]

2010 IWG Approach: When the IWG developed the first SCC in 2010, existing IAM damage functions were essentially the only feasible option. As a result, there were few if any alternatives and the IWG kept the damage functions originally included in DICE, FUND, and PAGE.

Progress: In the last dozen years, there have been great advances in computing power, access to data from around the world, and econometric methods designed to quantify climate change impacts. A result has been an explosion of empirical research that has greatly deepened science's understanding of the economic impacts of climate change.[30] Relative to 2009, there is almost an embarrassment of riches, with, for example, at least 110 empirical studies on climate change's economic impacts published between 2010 and 2016 alone.[31]

So how should one choose among all of these studies when developing an updated damage function? To make full use of scientific advances, any modern damage function must now meet three criteria:

1. **Empirically derived and plausibly causal:** Damage functions should be derived from empirical estimates that reflect plausibly causal impacts of weather events on socioeconomic outcomes.

   Because the climate has remained stable throughout modern human history, it is difficult to isolate experimental variations in the long-run climate. However, a large and growing empirical literature leverages modern econometric methods to uncover causal impacts of short-run weather events on a host of socioeconomic

[29] Pindyck, "Climate Change Policy: What Do the Models Tell Us?"
[30] Carleton and Hsiang, "Social and Economic Impacts of Climate;" Dell et al., "What Do We Learn from the Weather?"; Deschenes and Greenstone, "The Economic Impacts of Climate Change."
[31] Carleton and Hsiang, "Social and Economic Impacts of Climate."

outcomes, from agricultural output to mortality rates to energy use.[32] When combined with empirical estimates of differences in populations' responses to weather events (discussed in criterion three below), this literature provides a strong foundation for understanding the socioeconomic effects of weather, and its approach should be reflected in a new IWG's damage function.

The damage functions from FUND, DICE, and PAGE used by the IWG do not meet this criterion. They are only loosely calibrated to empirical evidence and/or rely on outdated estimates that fail to isolate the role of changes in the climate from economic variables such as income and institutions. For example, the majority of the studies used in FUND's sector-specific damage functions were published prior to 2000, and all likely suffer from the influence of unobserved factors that are correlated with temperature. Similarly, early versions of DICE utilized a damage function that was only loosely tied to empirical literature (Diaz and Moore, 2017; Nordhaus, 2010), while the recent DICE update continues to rely on empirical papers that fail to identify plausibly causal effects (Nordhaus and Moffat, 2017).

2. **Capture local-level nonlinearities for the entire global population:** Damage functions should be estimated with data that represent the entire global population (not just high-income, temperate regions). Further, damage functions should account for "nonlinear" effects of climate variables at a local level.

   Dramatic reductions in computing costs and increased data availability have enabled researchers to identify the effects of climate change on social and economic conditions at local scale across the globe. This body of work has uncovered that many socioeconomic outcomes display a strongly nonlinear relationship with climate variables—that is, the effects of climate change are not identical everywhere, but are instead sensitive to prior socioeconomic and climatic conditions.[33] For example, both extreme cold and extreme heat increase mortality rates, while moderate temperatures have little impact.[34] In addition,

[32] Carleton and Hsiang, "Social and Economic Impacts of Climate;" Dell et al., "What Do We Learn from the Weather?"
[33] Carleton and Hsiang, "Social and Economic Impacts of Climate."
[34] Gasparinni et al., "Mortality Risk Attributable to High and Low Ambient Temperature;" Deschênes and Greenstone, "Climate Change Mortality, and Adaptation."

this research has documented large differences in climate impact relationships between rich and poor,[35] hot and cold,[36] and agricultural and non-agricultural[37] regions. The significant differences in the results across different places imply that the additional damage caused by a given increment of warming may lead to substantially different outcomes around the globe, depending on the characteristics of the local economy, demographics, and region.

The existing IAMs' damage functions fail to adequately characterize nonlinearities, to disaggregate local impacts around the world, or to include information from lower-income, hotter regions of the globe. For example, the PAGE model damage function is calibrated based on an empirical analysis that only includes data from the United States.[38] Similarly, the FUND mortality-specific damage function is calibrated by an analysis[39] that draws on multiple studies, but only one of these studies[40] leverages actual mortality data, and only from Los Angeles, New York, Tokyo, Israel, the Netherlands, Taiwan, and the United Kingdom. None of these locations have the combination of a hot climate and low incomes that characterize the regions where several billion people currently live. Moreover, these models divide the globe into at most sixteen distinct regions, missing important spatial detail.

A failure to capture globally representative, locally varying, nonlinear relationships is a grave threat to the validity of damage functions. This is illustrated in Figure 5, where distinct mortality-temperature responses are shown for Oslo, Norway and Accra, Ghana, as well as for the global average. In Oslo, climate change is likely to save lives, as the mortality rate is highly sensitive to cold and temperatures become more moderate under climate change. In contrast, low incomes in Accra lead to extremely high mortality-sensitivity to heat, and large increases in heat-related mortality under climate change. It is also apparent that the global average mortality-temperature response function is a very poor representation of the impact of climate change in both Oslo and Accra. Ignoring

[35] Davis and Gertler, "Contribution of Air Conditioning Adoption."
[36] Heutel et. al., "Adaptation and the Mortality Effects of Temperature."
[37] Cai et al., "Climate Variability and International Migration."
[38] Cline, "The Economics of Global Warming."
[39] Tol, "Estimates of the Damage Costs of Climate Change."
[40] Martens, "Climate Change, Thermal Stress, and Mortality Changes."

such differences by applying the global response function to Oslo and Accra, instead of the local responses, would dramatically misrepresent the impacts of climate change around the world.

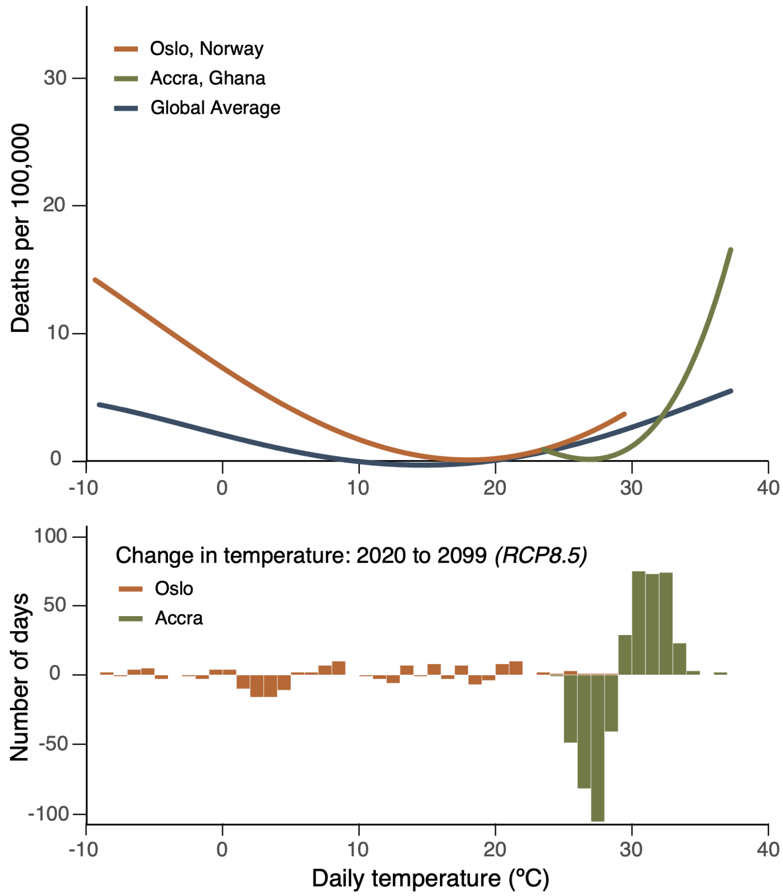

Figure 5: Climate change will have disparate impacts on different geographic regions. Figure displays estimated relationships between mortality rates for ages >65 years and temperature (top panel), along with anticipated changes in the temperature distribution from climate change (bottom panel), for Oslo, Norway (orange) and Accra, Ghana (green). The top panel also shows a multi-country average mortality-temperature relationship (blue). In the bottom panel, the difference between the 2099 and 2020 temperature distributions is shown for Oslo and Accra, using a high-emissions scenario (RCP8.5) from the CCSM4 climate model. Top panel mortality-temperature relationships for Oslo and Accra are only shown for the range of temperatures projected to be experienced in each location between 2020 and 2099. The global average response includes data from 38 percent of the global population. *Source:* Carleton et. al., 2020.

While further advances in data collection and computing power are needed to derive damage functions for all sectors in all countries at high spatial resolution, substantial improvements over the existing IAMs are feasible. Further, recent research has developed methods for estimating worldwide climate impacts by inferring damages in data-poor regions based on data-rich regions that have similar characteristics.[41]

3. **Inclusive of adaptation:** Damage functions should reflect that people, firms, and governments make defensive investments that provide protection against climate-related risks, and that these investments are costly.

   As climate change unfolds, individuals, governments, and firms will make innumerable decisions and investments to respond to the gradually changing environment. Damage functions within DICE, FUND, and PAGE involve very different assumptions about such compensatory investments and their costs, the majority of which are not based on real-life observations of adaptation.[42]

   The damage function should include both the estimated benefits and costs of future adaptive investments. While earlier empirical studies failed to account for the benefits of adaptation,[43] a growing literature covering multiple sectors is developing damage estimates that reflect the benefits of adaptation.[44]

   However, these compensatory investments are not free—any updated damage function should also account for costs of adaptation.[45] Some progress has been made to infer these costs from available data,[46] but this is an active area of research. Damage functions should capture adaptation costs wherever possible.

Estimated damage functions that meet the above criteria lead to dramatically different understandings about the economic impacts of climate change, compared to the older

[41] Carleton et al., "Valuing the Global Mortality Consequences."
[42] Diaz and Moore, "Quantifying the Economic Risks of Climate Change."
[43] See, for example, Deschênes and Greenstone, "The Economic Impacts of Climate Change."
[44] See, for example, Auffhammer, "Climate Adaptive Response Estimation;" Deryugina and Hsiang, "The Marginal Product of Climate;" Heutel et al., "Adaptation and the Mortality Effects of Temperature."
[45] Estimates of adaptation costs are essential when computing the total damages of climate change. In contrast, under a strict set of assumptions, the marginal benefits and marginal costs of additional adaptation cancel each other out in the calculation of the damages from a marginal ton of CO_2 emissions, making adaptation cost estimates unnecessary for the SCC when these assumptions are taken.
[46] Carleton et al., "Valuing the Global Mortality Consequences."

damage functions. For example, one recent study found a mortality-only SCC estimate that is more than ten times larger than the total health impacts within the FUND IAM.[47] Further, its estimate of the loss from higher mortality rates in 2100 accounts for 49-135 percent of *total* damages across all sectors from the three leading IAMs. Another recent study derived an agricultural damage function that meets some aspects of the criteria above and found a substantial, positive, agriculture-only SCC, while FUND's agricultural SCC is negative (see Figure 1).[48] In other words, by using more comprehensive techniques, this study overturned past findings that suggested that climate change would benefit agriculture, instead finding that it would cause substantial damage.

It is noteworthy that meeting these criteria does not always increase estimated damages. For example, one study quantifying the impacts of climate change on global energy expenditures found a small, energy-only SCC estimate of -$2. This finding was attributable largely to net savings from reductions in heating and differences in the responsiveness of electricity demand to high temperatures in high- versus low-income regions of the world.[49] This estimate stands in stark contrast to the FUND model, where the energy-only SCC is $8 ($6 of which is attributable to Chinese cooling demand only) and constitutes 90 percent of the total, all-sector SCC.[50]

These examples demonstrate that research that meets the three criteria described here will fundamentally alter prior estimates of the economic impacts of climate change.

BEGIN BOX

Box title: Top-down GDP-based estimates of climate damages

Another approach to updating damage functions guided by the three listed criteria is "top-down" in nature, relying on statistical relationships between GDP and climate variables (generally, temperature) to quantify the impacts of climate change on aggregate growth in (or levels of) income.[51] The idea is to use GDP as a wide-reaching measure of economic well-being such that individual socioeconomic sectors do not need

[47] Id

[48] Moore et al., "New Science of Climate Change Impacts."

[49] Rode et al., "Estimating a Social Cost of Carbon for Global Energy Consumption."

[50] Diaz, "Evaluating the Key Drivers."

[51] See, for example, Burke et al., "Global Non-Linear Effect of Temperature;" Dell, et al., "Temperature Shocks and Economic Growth."

to be separately analyzed nor do their interactions need to be explicitly modeled. These top-down empirical results have recently been used to compute updated SCCs. For example, one recent study generated SCCs of about $400, nearly an order of magnitude larger than the Obama SCC.[52]

This is an important and rapidly evolving line of research. However, several critiques cause us to conclude that top-down empirical analysis is not currently ready for use in determining the SCC. First, GDP is an incomplete measure of economic well-being and of willingness-to-pay for reducing greenhouse gas emissions. For example, it misses non-market outcomes such as mortality and morbidity that are large in magnitude,[53] and current top-down analyses omit the damages associated with flooding and sea level rise. However, a bottom-up approach that sums sector-specific damages will also be incomplete, as discussed in this paper's last section.

Second, there is a long history of skepticism about the ability of cross-country GDP regressions to provide reliable information on the determinants of growth.[54] Many of these concerns boil down to questions of misspecification. Regression models can be designed to identify causal relationships between various phenomena—in this case, between GDP growth and its potential causes. With limited available data, however, it is difficult to specify a regression model that can accurately recover the dynamic and potentially slow-moving influence of individual determinants of growth. Moreover, in GDP regressions, each country-year observation is treated as independent from the others, when in fact the growth process is strongly interlinked across countries.[55] Modeling these interdependencies across space and time is exceptionally difficult with available data.

Third, it is unclear whether a change in temperature affects the level or growth rate of GDP. A test for growth effects of temperature shocks requires estimating a distributed lag model with many lags, but these models (which measure the effects of temperature on growth over time) are difficult to estimate with available data, leaving a good deal of uncertainty in the results. For example, one model was empirically unable to distinguish

[52] Ricke et al., "Country-Level Social Cost of Carbon," using statistical estimates from Burke et al., "Global Non-Linear Effect of Temperature," and Dell et al., "Temperature Shocks and Economic Growth."
[53] Hsiang et al., "Estimating Economic Damage from Climate Change in the United States."
[54] Note that this skepticism in the macroeconomics literature has applied both to purely cross-sectional analyses (comparing countries' growth experiences to one another) and to growth regressions exploiting panel data (comparing GDP over time within a country). See Durlauf (2009) for a detailed discussion.
[55] Klenow and Rodriguez-Clare, "Externalities and Growth."

between growth and level effects,[56] while another rejected evidence of growth effects[57] and a third found evidence in support of growth effects (at the subnational level)[58]. The answer to this question has first order consequences on climate change projections, so this lack of clarity is not trivial.

Fourth, a paper in this literature notes that the estimated effects of temperature shocks on GDP growth rates appear implausibly large: "If an extra 1°C reduces growth by 1.1 percentage points, then it would take only eight years of sustained temperature differences to explain the overall cross-sectional relationship between temperature and income observed in the world today."[59] The magnitude of these effects along with concerns about whether there are plausible mechanisms through which temperature can affect economic growth (as opposed to the level of economic activity) together have led to some additional skepticism.

A top-down approach to damage function estimation has strong potential to inform the SCC, particularly because it is challenging to empirically ground the overlap, spillovers, and interactions among individual sectors of damages used in a bottom-up approach.[60] Therefore, resolving the uncertainties in this expanding literature is an urgent line of inquiry. In the meantime, we believe that a bottom-up approach like that outlined in this paper is a more promising avenue for determining an SCC grounded in real-world data.

END BOX

Recommendation: **We recommend that the Biden administration replace all existing IAM damage functions with those that meet these three criteria.**

Ingredient 3: Discount Module

Background: Along with a set of socioeconomic and emissions scenarios, discussed below, the climate and damages modules together translate a single additional ton of CO_2

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[56] Burke et al. (2015) estimate a five-year distributed lag model that cannot reject zero growth effects (cumulative effect of -0.010 per °C with a 95% confidence interval of [-.027, 0.008]). The authors conclude: "...we cannot reject the hypothesis that this effect is a true growth effect[s] nor can we reject the hypothesis that it is a temporary level effect."

[57] Kalkuhl and Wenz, "The Impact of Climate Conditions on Economic Production."

[58] Burke and Tanutama, "Climatic Constraints on Aggregate Economic Output."

[59] Dell, Jones and Olken, "Temperature and Income."

[60] NAS, "Valuing Climate Damages"; Kopp and Mignone, "The U.S. Government's Social Cost Of Carbon Estimates."

emissions into a trajectory of additional warming, and a stream of future damages. The final step in the SCC calculation is to express this stream of damages as a single *present* value, so that future costs and benefits can be directly compared to costs and benefits of actions taken today. Discounting is the process by which each year's future values are reduced to enable comparison with current costs or benefits to society. The "discount rate" determines the magnitude of this reduction. Because CO_2 emissions persist in the atmosphere and lead to long-lasting climatological shifts, small differences in the choice of discount rate can compound over time and lead to meaningful differences in the SCC.

There are two reasons for "discounting the future," or more precisely for discounting future monetary amounts, whether benefits or costs. The first is that an additional dollar is worth more to a poor person than a wealthy one, which is referred to in technical terms as the *declining marginal value of consumption*. The relevance for the SCC is that damages from climate change that occur in the future will matter less to society than those that occur today, because societies will be wealthier. The second, which is debated more vigorously, is the *pure rate of time preference*: people value the future less than the present, regardless of income levels. While individuals may undervalue the future because of the possibility that they will no longer be alive, it is unclear how to apply such logic to society as a whole facing centuries of climate change. Perhaps the most compelling explanation for a nonzero pure rate of time preference is the possibility of a disaster (e.g., asteroids or nuclear war) that wipes out the population at some point in the future, thus removing the value of any events that happen afterwards.

The government regularly has to make judgments about the discount rate when trading off the costs and benefits of a regulation or project that will endure for multiple years. In general, U.S. government agencies have relied on the Office of Management and Budget's (OMB's) guidance to federal agencies on the development of regulatory analysis in Circular A-4, and used 3 percent and 7 percent discount rates in cost-benefit analysis. [61] These two values are justified based on observed market rates of return, which can be used to infer the discount rate for the SCC since any expenditures incurred today to mitigate CO_2 emissions must be financed just like any other investment. The 3 percent discount rate is a proxy for the real, after-tax riskless interest rate associated with U.S. government bonds and the 7 percent rate is intended to reflect

[61] OMB, "Circular A-4."

real equity returns like those in the stock market. However, climate change involves intergenerational tradeoffs, raising difficult scientific, philosophical and legal questions regarding equity across long periods of time. There is no scientific consensus about the correct approach to discounting for the SCC.[62]

2010 IWG Approach and Progress: There are two possible approaches to discounting in SCC calculations. First, a fixed discount rate can be used, as was implemented in the IWG SCC calculations. The 2010 IWG used discount rates of 2.5 percent, 3 percent, and 5 percent, while the Trump administration applied 3 percent and 7 percent, in accordance with OMB Circular A-4. The 2010 IWG set the 3 percent discount rate as the central case to be consistent with guidance from the OMB (2003) regarding the interest rate on U.S. government bonds. This decision was also motivated by the assumption that climate damages were projected to be uncorrelated with overall market returns (eliminating the 7 percent rate, derived from equity markets) and thus used insights from asset pricing theory that the riskless interest rate was appropriate.[63]

There have been profound changes in global capital markets since the publication of Circular A-4 in 2003 that make it extraordinarily challenging to justify 3 percent as an accurate estimate of the return on riskless investments. For example, the average ten-year Treasury Inflation-Indexed Security (TIPS) rate over the available record of the index (2003-present) is just 1.01 percent (see Figure 6).[64] Similarly, recent research has shown that the equilibrium real interest rate has declined substantially since the 1990s, suggesting a lower discount rate is justified.[65] Additionally, evidence from long-term real estate investments suggests that for climate mitigation, which has payoffs over very long periods of time, discount rates should be even lower than those used to discount costs and benefits of shorter-lived investments.[66] Overall, our judgement is that it is difficult to defend a 3 percent discount rate for climate investments and there is now a compelling case for a riskless discount rate of no higher than 2 percent.[67]

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[62] Gollier and Hammitt, "The Long-Run Discount Rate Controversy."
[63] Greenstone et al., "Developing A Social Cost of Carbon"
[64] Board of Governors of the U.S. Federal Reserve System, "10-Year Treasury Inflation-Indexed Security."
[65] Bauer and Rudebusch, "Interest Rates Under Falling Stars."
[66] Giglio et al., "Climate Change and Long-run Discount Rates."
[67] A fixed rate below 2 percent does not contradict OMB Circular A-4 when a long-lived benefit stream is under consideration: "If your rule will have important intergenerational benefits or costs you might consider a further sensitivity analysis using a lower but positive discount rate in addition to calculating net benefits using discount rates of 3 and 7 percent." See OMB, "Circular A-4."

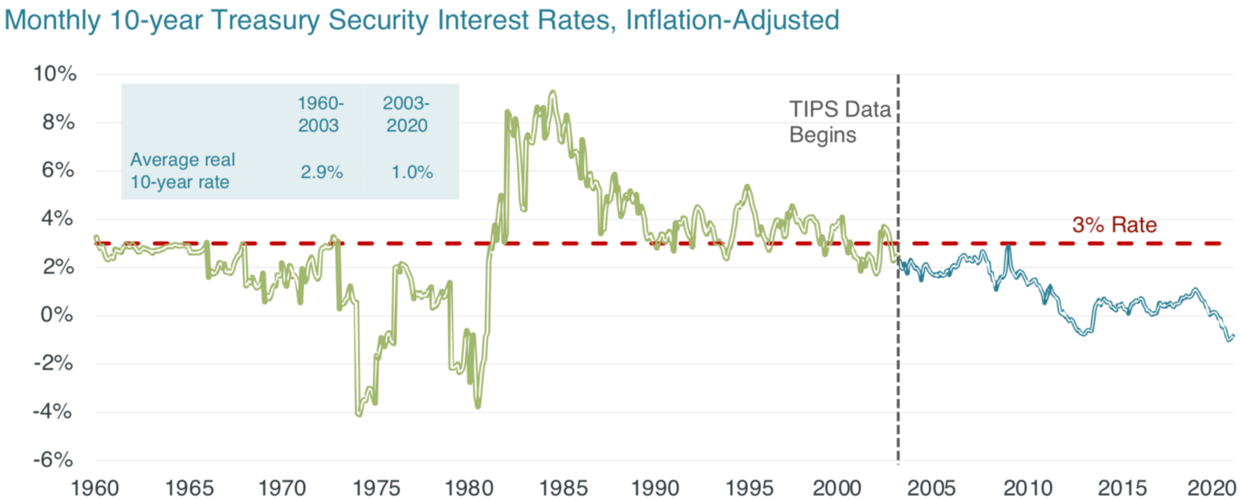

Figure 6: Monthly 10-year inflation-adjusted Treasury security interest rates. Figure shows monthly 10-year Treasury security interest rates, adjusted for inflation, over the period 1960 to 2020. Nominal interest rates, TIPS, and inflation data were retrieved from the Federal Reserve Bank of St. Louis. The Treasury Inflation-Indexed Security (TIPS) rate is available starting in January 2003. Interest rates prior to 2003 are imputed by subtracting the annual inflation rate from the nominal interest rate.

There is also the possibility, however, that the riskless rate itself is not appropriate as the central discount rate due to the unique risk properties of climate change and uncertainty about future interest rates. Because discount rates reflect the returns to investments that mitigate climate change, Americans are best served by using an interest rate associated with investments that match the structure of payoffs from climate mitigation. Capital asset pricing models recommend low discount rates in scenarios where investments (in this case CO_2 mitigation) pay off in "bad" states of the world—that is, if climate damages are likely to coincide with a slowing overall economic growth rate that for example could be due "tipping points" or large-scale human responses to climate change, including mass migration.[68] If on the other hand climate damages act as tax on the economy (i.e., total damages are larger when the economy grows faster), then higher discount rates like the average return in equity markets would be merited.

[68] Greenstone et al., "Developing A Social Cost of Carbon."

A second potential approach to deriving a discount rate is to explicitly account for future economic growth using the so-called Ramsey equation,[69] which is often referred to as the prescriptive approach. This approach has been recommended by the NAS as a "feasible and conceptually sound framework" (NAS, 2017). Rather than rely on observed interest rates, it derives a discount rate from assumptions about three parameters: the pure rate of time preference, the growth rate of consumption, and a parameter capturing the decreasing marginal utility of consumption. Values for the first and third parameters have been estimated in a large literature, while the consumption growth rate will depend on the set of socioeconomic scenarios developed in the socioeconomic and emissions module described above.[70]

The Ramsey approach has two key limitations. First, future economic growth is uncertain, while the Ramsey equation is deterministic. Second, climate damages are likely to be the highest in possible future scenarios where economic growth is the lowest. Both facts imply that climate mitigation policies act as a form of insurance for the future and imply a lower discount rate than is given by the Ramsey equation. Besides these limitations, some find it unappealing that the Ramsey approach requires several judgments by "experts" about the value of key parameters, rather than relying on observed market interest rates.

Recommendation: **We recommend continuing to rely on existing asset markets to guide the choice of discount rates. Based on recent asset market trends, we recommend a discount rate of no higher than 2 percent.**

Ingredient 4: Global or Domestic Damages

Background and 2010 IWG Approach: Traditionally, regulatory cost-benefit analyses (CBAs) have only considered the domestic benefits and costs of policies, on the theory that what matters for U.S. policy are the effects of regulations on U.S. citizens. However, unlike nearly every other environmental pollutant, CO_2 emissions are

[69] Ramsey, "A Mathematical Theory of Saving."
[70] The Ramsey equation expresses the discount rate as $r = \delta + \eta \times g$, where δ measures the pure rate of time preference, g measures the growth rate of consumption, and η captures the decreasing marginal utility of consumption. The consensus is that δ likely ranges between zero and two. Values for η have been estimated in a large literature, and range from one to four, but are generally centered around two (e.g., Arrow, 2007; Dasgupta, 2007, 2008; Hall, 2009; Weitzman, 2007, 2009).

overwhelmingly a global problem. The damages caused by a ton of carbon emissions in the United States are felt globally. Perhaps even more importantly, the United States is harmed by emissions from abroad, so that when emissions are reduced in China, the European Union, India, and elsewhere, Americans benefit. In light of the global nature of the problem, and as a means to aid international negotiations in obtaining emissions reduction commitments abroad, the IWG chose to use global damages to calculate the SCC. In 2017, the Trump administration switched to only counting domestic damages in the calculation of the SCC.

Progress: The overwhelming consensus amongst scientific and economic experts is that the best policy is to include global damages.[71] Although focusing exclusively on the domestic costs of climate change may appear to put U.S. interests first, it does not; indeed, a growing body of evidence demonstrates the opposite. Nearly 90 percent of global emissions take place outside the United States, and since the climate does not differentiate between a ton of carbon emitted in New York and a ton emitted in Beijing, the United States will never be able to protect its citizens from climate change without negotiating emissions reductions from other countries. If every nation uses a domestic figure, all nations will lose; a global figure is necessary to overcome what might be seen as a classic prisoner's dilemma.[72]

Importantly, history shows us that when the United States accounts for the full global cost of climate change it incentivizes other countries to reduce their own emissions, which ultimately benefits the United States more than any purely domestic climate policy could. As noted above, some nations simply borrowed the U.S. SCC. And in some cases, the use of a global SCC, by the United States, plausibly contributed to international action. For example, in 2014 the U.S. EPA proposed the Clean Power Plan, and within four months the United States extracted a promise from China to make significant reductions in its own emissions.[73] Altogether, it is estimated that the United States was able to leverage 6.1-6.8 tons of CO_2 reductions from other countries for every ton that it pledged to cut in the Paris Climate Agreement.[74] The global SCC—that is, an SCC informed by global damages, not just domestic—is an ingredient in efforts to procure the necessary international action.

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[71] NAS, "Valuing Climate Damages."

[72] For relevant discussion, see Kotchen, "Which Social Cost of Carbon?"

[73] Greenstone, "United States House Committee."

[74] Houser, "Calculating the Climate Reciprocity Ratio."

Though for many regulations it is standard to use only domestic measures of costs and benefits, on the grounds that what matters are the effects of regulations on U.S. citizens, that should not be the case with the social cost of carbon. Indeed, the use of the domestic measure for the SCC could actually *harm* U.S. citizens. What the United States does sets an example for the world. If Washington only measures the domestic impacts of its emissions, it will not only discount the effects of its actions on other countries, but also contribute to a situation in which multiple nations are allowing levels of emissions that harm their citizens. The cumulative effect of the U.S. decision could be higher emissions in many countries around the world, which would harm U.S. citizens. Even if policymakers decide that the effects of regulations on U.S. citizens are what matter (in terms of both law and policy), it would make sense to use the global measure, as it would protect U.S. citizens against a range of adverse effects from unmitigated climate change.

Our recommendation is to use global damages in calculating the SCC. The United States has a central role in global diplomacy and its leadership is necessary to protect its citizens from climate damages. To use a domestic SCC would be to abandon this role of global leadership. It would also create an incentive for other nations to do the same, creating a risk of losing out on the benefits from potential foreign emissions reductions.

B. Additional Scientific Advances

Ingredient 5: Socioeconomic and Emissions Module

Background: To calculate the SCC, it is necessary to compare a baseline trajectory of economic growth and CO_2 emissions to a trajectory in which one more ton of CO_2 is released. All else equal, a higher baseline CO_2 emissions trajectory will result in a greater SCC, because projected climate change damages are nonlinear; that is, an additional ton of CO_2 emissions is projected to cause more damages at higher atmospheric concentrations of CO_2. Baseline economic growth affects the SCC in a variety of competing ways. Richer economies consume more energy and generate higher emissions, such that marginal tons do more damage and populations have higher willingness-to-pay to avoid climate change, which increases the SCC. That said, richer countries are better prepared to invest in adaptations—such as increased air conditioning—that reduce the social costs of climate change. Changing population demographics can also alter the magnitude of future climate change damages by, for example, increasing the total population and raising the share of the population at higher risk of heat-induced mortality.

2010 IWG Approach: Since future emissions and economic growth are unknown, the IWG combined a range of five possible trajectories developed by the Stanford Energy Modeling Forum (EMF-22) with crude probabilistic assumptions. Four of these scenarios represent business-as-usual (BAU) trajectories, while the last assumes that aggressive climate policies dramatically reduce future emissions. The IWG calculated the SCC under all five scenarios and averaged the result, giving equal weight to each scenario.

Progress: In the past ten years, there has been only modest scientific progress in developing baseline scenarios due to the stubborn difficulties in making long-run population and economic growth projections. The IPCC and many researchers have moved towards using the Shared Socioeconomic Pathways (SSPs, built collaboratively by a group of climate researchers over the last several years) as benchmark scenarios. The SSPs may be a worthwhile update over the EMF-22 pathways, as the latter under-sample possible future scenarios.[75] Moreover, the SSPs can be linked to the Representative Concentration Pathway (RCP) emissions scenarios, a standardized set of emissions trajectories used widely across the climate modeling community.[76]

However, while the range of different modeling groups generating SSP and RCP scenarios captures some degree of model and parameter uncertainty, these scenarios do not systematically characterize uncertainty in emissions or socioeconomic projections. In recent years, economists have developed[77] more sophisticated modeling techniques that rely on historical data to generate probabilistic[78] economic projections and demographers have done the same for population[79]. An alternative is to rely on expert elicitation techniques, that is, a process by which researchers synthesize the informed opinion of experts. The weakness of this technique is that it relies on a potentially

[75] O'Neill, "Multi-Century Scenario Development;" Kopp and Mignone, "The U.S. Government's Social Cost of Carbon Estimates."
[76] Riahi et al., "The Shared Socioeconomic Pathways."
[77] See, for example, Müller et al., "An Econometric Model of International Long-run Growth Dynamics"
[78] Probabilistic projections describe the likelihood of experiencing a particular future condition. A weather forecast warning of a 30 percent chance of rain tomorrow, for example, is a probabilistic projection.
[79] United Nations, "World Population Prospects 2019: Highlights."

unrepresentative sample of experts' subjective judgments, while its strength is that those individuals may add information that is not captured by existing statistical approaches. As outlined by the NAS, empirically based projections can be combined with expert elicitation to formulate new socioeconomic and emissions projections that represent the many sources of uncertainty involved in generating long-run forecasts.[80]

Recommendation: **To generate socioeconomic and emissions projections, our recommendation is to rely either on a combination of the SSPs and the RCPs *or* on new probabilistic projections that combine statistical methods with expert elicitation.** The probabilities assigned to each projection should be chosen to best represent the most *likely* future global pathway.

Ingredient 6: Valuing Uncertainty about Climate Risk

Background and 2010 IWG: There are several sources of uncertainty in the calculation of the SCC. These include uncertainty about future economic growth, the sensitivity of the global climate to additional emissions, and the economic damages for a given level of climate change. Economic theory and empirical evidence (see, for instance, the general existence of the insurance industry) reveal that people dislike risk and are willing to pay to reduce their exposure to it. The IWG chose not to account for uncertainty in valuing climate damages but noted that this decision "demands further attention."[81]

Progress: Economic theory and empirical research decisively support the idea that people are risk-averse and value reducing uncertainty. In the last decade, advances in computing have enabled probabilistic climate change projections that capture multiple measures of uncertainty about the magnitude of climate damages. Thus, for the first time, it is possible to characterize these uncertainties and to incorporate them into the calculation of the SCC. For example, one recent study provided estimates of the total change in energy expenditures under climate change, accounting for both statistical and climatological uncertainty.[82] Two other recent studies provide the analogous information for mortality[83] and labor supply[84]. A large theoretical literature demonstrates that

[80] NAS, "Valuing Climate Damages."
[81] Greenstone et. al, "Developing a Social Cost of Carbon."
[82] Rode et al., "Estimating a Social Cost of Carbon for Global Energy Consumption."
[83] Carleton et al., "Valuing the Global Mortality Consequences of Climate Change."
[84] Rode et al., "Labor Supply in a Warmer World."

accounting for this uncertainty when individuals are modeled as risk averse can substantially increase the SCC.[85] Although these methods have not yet been applied to new empirically derived probabilistic damage estimates, it would be straightforward to do so.[86]

We recommend that the calculation of the SCC account for the considerable uncertainty from multiple sources about damages using standard economic tools for valuing this uncertainty.[87]

Ingredient 7: Equity

Background: An additional dollar is worth more to a poor person than a wealthy one. Applying this principle to the SCC would require "equity weighting" within the United States such that a given amount of climate damages projected to occur in poorer counties or states of the United States contribute more to the SCC than equal damages that occur in wealthier regions. Indeed, this idea is the basis for the environmental justice movement in the United States. Taken one step further, this logic would mean that damages occurring in poor countries are weighted more highly than damages in wealthy countries.

2010 IWG Approach: The IWG chose to omit equity weighting in its analysis, citing theoretical and practical concerns. Theoretically, the IWG determined the economic literature on equity weighting was insufficiently mature. Practically, the IWG determined that standard operating procedure for the U.S. government required separate distributional analyses of policies, rather than incorporating distributional concerns into cost-benefit analyses.[88]

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[85] See, for example, Lemoine, "The Climate Risk Premium;" Jensen and Traeger, "Pricing Climate Risk;" Jensen and Traeger, "Optimal Climate Change Mitigation Under Long-term Growth Uncertainty;" Traeger, "Analytic integrated assessment and uncertainty."

[86] The application of standard methods of uncertainty valuation to empirically derived probabilistic damage estimates is a central feature of Pathway "C", one of the recommended pathways for development of a new SCC described below.

[87] Specifically, this should be done by accounting for risk aversion using standard parameterizations of the shape of the utility function (e.g., $\eta = 2$) from the existing literature to determine the "certainty-equivalent" value of damages under climate change (Traeger, "Why Uncertainty Matters"). A "certainty-equivalent" value is computed by determining the consumption loss that society would accept as a certain outcome in place of the distribution of future uncertain outcomes.

[88] Greenstone et al., "Developing a Social Cost of Carbon."

Progress: The same logic that justifies discounting and the valuation of uncertainty over future states of the world implies that equity weights should be applied in any SCC calculation; declining marginal value of consumption is the fundamental economic concept behind all three concerns. Therefore, the most intellectually coherent approach to treating equity would be to calibrate equity weights from the large literature studying the marginal value of consumption, and to apply these weights at the spatial resolution of damages.[89]

However, OMB Circular A-4,[90] which guides cost benefit analysis across the U.S. government, has not been altered since its release and does not clearly allow for equity weighting within cost benefit calculations. Therefore, conducting equity weighting would represent a significant departure from standard U.S. cost benefit analysis. Further, it would have significant precedential implications far beyond climate regulations and environmental policy.

Though we believe there is a strong theoretical and empirical case for equity weighting, we recommend that it not be incorporated into the SCC until there is an overhaul of Circular A-4. Such a review would allow for a full consideration of the implications across multiple domains.

III. Three Pathways Toward an Updated SCC

Of the four ingredients that are essential to update in a new SCC, only two can be immediately implemented by the Biden administration upon inauguration: changes to the discount rate and the inclusion of global damages. A holistic update to the SCC that integrates substantial scientific progress in the other two essential ingredients—the climate model and damage function—will involve reconvening the Inter-agency Working Group (IWG) to assess the costs and benefits of three distinct possible implementation pathways:

- Pathway A: Update the original IAMs (as much as possible)

[89] Standard parameterizations of utility function curvature (e.g., $\eta = 2$) can be used to calibrate equity weights.
[90] OMB, "Circular A-4."

- Pathway B: Build a new IAM (under the current Circular A-4)
- Pathway C: Build a new IAM (under an updated Circular A-4)

Each of these pathways will require an integration of research components that would entail several months of work.

We recommend that the Biden administration immediately update the SCC by returning to the 2013 IWG's approach, applying a 2 percent discount rate to reflect the profound changes in global capital markets in recent years. Simultaneously, we recommend that the Biden administration should reconvene the IWG to conduct a more holistic update, following Pathway B. While the IWG should consider the pros and cons of all three pathways for a comprehensive SCC update, we believe Pathway B is the most feasible, transparent, and accommodating of evolving scientific research (Figure 7). If Circular A-4 were to be updated in the future, we believe that Pathway C should be given careful consideration for adoption by a new IWG.

Regardless of which path the Biden administration chooses, it is imperative that a new SCC incorporate an updated climate model, a new set of damage functions, a lower discount rate, and global damages. These four essential changes will ensure that the U.S. SCC is once again near the frontier of understanding in a rapidly evolving area and in so doing will best serve the American people. Updates to the other three SCC ingredients would be valuable, but our view is that they are generally judgment calls that turn on several factors including scientific and/or economic evidence and political considerations like precedential effects on regulatory policy in other domains. Among these three other ingredients, however, we think there is an especially strong case for valuing the substantial uncertainty around climate damages.

The following sections describe the potential pathways for a holistic update to the SCC.

Figure 7: Three pathways toward an SCC that updates all seven ingredients. Figure uses checkmarks to indicate whether bringing each SCC ingredient to the current scientific frontier is feasible within each of three possible pathways for a new SCC framework. Black checkmarks indicate a feasible update, while grey checkmarks indicate substantial implementation challenges. See text for a detailed discussion of each pathway.

<u>Pathway A: Update Existing IAMs as Much as Possible</u>

The first SCC updating pathway closely mimics the structure used by the IWG in its original SCC calculation. This requires wherever possible updating each of the seven SCC ingredients *within* the three IAMs. One would then run each of the updated versions of these three models and produce new distributions of SCCs. An appeal of this pathway is that it is relatively straightforward to replace the existing climate models in each IAM with the FAIR model, including the construction of a semi-empirical model of global mean sea level rise. Moreover, this approach may be attractive because the Biden administration could rely on the original IAM model parameters when updated scientific evidence is not available or cannot objectively inform a key modeling decision.[91]

The Achilles heel of Pathway A is that while the ultimate goal of the exercise is to estimate the damages from an additional ton of CO_2, there is not a compelling way to base this estimate on the latest evidence on climate change damages under this pathway. The challenges are both conceptual and practical.

On the conceptual side, it is not straightforward to replace the existing damage functions with improved damage functions for any of the three IAMs. In the case of FUND, it is possible to subdivide the overall damage function into sector-specific functions that can roughly be mapped to the existing improved sectoral damage functions.[92] But the result would be an imperfect melding of new, scientifically robust analysis with older modeling assumptions that are only loosely tied to empirical evidence. The challenge of replacing the damage functions in DICE and PAGE is even greater, because their overall damage functions cannot readily be subdivided into categories that map to the empirically founded sectoral damage functions. The best case is that there would be some risk of double counting and then a mixing of the newer empirically founded and the older assumption-driven approaches with unclear weightings between the two. Overall, there is not a clear correspondence between

[91] For example, some key sectors have insufficient empirical evidence for damage function calibration (e.g., ecosystem services, vector-borne disease). Similarly, evidence on the climatological likelihood and socioeconomic impact of tipping points such as ice sheet melt, breakdown of ocean currents, or release of methane from the permafrost are lacking.

[92] For example, energy demand in FUND can be mapped directly to the energy demand damage function derived in Rode et al. (2020b), while the mortality damage function empirically derived in Carleton et al. (2020) covers only some of the causes of death forming mortality-related damages in FUND.

empirically founded, sector-specific damage functions and IAM damage functions, which makes combining them conceptually complicated.

On the practical side, the nature of recent damage function estimates makes it challenging to replace components of the existing IAMs' damage functions with the new, empirically founded sectoral damage functions for at least two reasons.[93] First, none of the existing IAMs have sufficient spatial resolution in socioeconomic projections to align population and income trajectories with new damage functions that reflect differences in climate change impacts at the local level (e.g., county). Second, adaptation is treated very differently in each model,[94] such that adjustments to incorporate real-world evidence on sector- and region-specific adaptation will require substantial changes to each model's original structure.

In addition to these challenges, it will be difficult to fully follow the recommendations above with respect to both the valuation of uncertainty (Ingredient six) and the treatment of equity (Ingredient seven). With respect to uncertainty, DICE is not designed to account for the many uncertain parameters in the SCC calculation, and FUND and PAGE can only enable valuation of uncertainty to the extent that sector-specific damage functions and their corresponding uncertainties can be integrated into the modeling framework; as discussed above, this is not a straightforward task. If equity weighting were pursued by the Biden administration, the low spatial resolution of all IAMs limits their ability to capture and value differences in the welfare effects of climate change.[95]

Although Pathway A is feasible and was recommended by the NAS for use in the near-term, the integration of new, empirically founded sectoral damage functions into the

[93] Initial efforts to update the damage module within a single IAM (e.g., DICE, FUND) have each constituted a significant academic publication, given the challenges involved in conforming new, generally richer, information to the existing IAM frameworks. For example, Moore et al. (2017) replace the agricultural damage function in FUND using a meta-analysis of the empirical agricultural-impacts literature, and Bressler (2020) does the same by adding a mortality damage function on top of existing DICE damages.

[94] Diaz and Moore, "Quantifying the Economic Risks of Climate Change;" Moore et al., "New Science of Climate Change Impacts on Agriculture."

[95] Note that one possible solution would be to incorporate equity weighting into the aggregate damage function of each IAM by valuing welfare differences across high-resolution empirical damage estimates. This is done in Pathway C. However, this is only feasible within Pathway A to the extent that sector-specific damage functions can be integrated into each IAM; the challenges of doing so are discussed above.

existing IAMs has conceptual inconsistencies and is likely to be practically challenging. No existing implementation exists for near-term use. Thus, Pathway A is a viable option, but it cannot fully accommodate one of the key advances in understanding about climate change that have taken place in the last decade.

Pathway B: Build a new IAM (under the current Circular A-4)

The second pathway is to build a new SCC framework that fully integrates scientific advances in each of the seven SCC ingredients. This is the approach recommended for longer-term implementation by the NAS.[96]

As above in the case of Pathway A, such a new IAM framework is not available for immediate use. However, the Climate Impact Lab (CIL),[97] of which both authors are core members, is aiming to release such a framework in the first half of 2021. The CIL combines the SSP economic and population projections, high-resolution climate projections for multiple RCP emissions scenarios, and rich historical socioeconomic and climate datasets to estimate sector-specific, flexible, globally-representative damage functions that capture heterogeneity across approximately 25,000 global regions and account for adaptation and its costs. It then applies the simple Earth system model FAIR and a wide range of valuation and discounting approaches to transform these damage functions into a full distribution of SCC estimates, accounting for multiple sources of uncertainty.

This approach has some strengths and weaknesses. A great appeal of this approach is that each of the seven ingredient recommendations can be addressed, including the four essential updates. On the other hand, this pathway's main weakness is that damage functions meeting the above criteria are not currently available for all sectors likely to be affected by climate change. Damage functions for some of these sectors are currently under development, both by the CIL and by other researchers, so this pathway will become more complete as science and economics advance. However, at least in the medium term, the resulting SCC will be based on an incomplete measure of climate

[96] NAS, "Valuing Climate Damages."

[97] The Climate Impact Lab is a collaboration of climate scientists, economists, computational experts, researchers, analysts, and students working to build empirically derived, local-level estimates of climate change damages and an empirically based SCC. More information on the Climate Impact Lab can be found at: http://www.impactlab.org/.

damages. Although this is an important shortcoming, many of the most important areas of incomplete knowledge—such as catastrophic risks and interactions across regions and sectors—remain overly simplistic or completely absent in the IAMs themselves.[98]

While an initial SCC built under this pathway will be incomplete, an important strength of this approach is that it can accommodate future advances in understanding. In particular, in a new IAM built from empirical damage estimates, it is straightforward to integrate results from new studies updating sector-specific damages or providing estimates for previously unquantified sectors. Similar updates to other modules, such as the climate model, are also easily accommodated. Of course, any such revisions should be limited to changes that meet the damage function, climate model, or other corresponding criteria laid out above.

An important additional benefit of a new SCC framework built from recent empirical damage estimates is that the different effects of climate change across socioeconomic groups can be explicitly described. Recent, local-level estimates of sectoral damages have shown that climate change disproportionately affects today's poorest populations.[99] An SCC framework based on such studies will enable the Biden administration to evaluate and consider the distributional effects of climate policies for localities within and beyond the United States.

Our conclusion is that scientific and economic understanding has advanced enough that a revised SCC should be fully based on empirical evidence that meets modern standards. This will best serve the interests of the American people. While this approach may initially omit certain categories of damages, existing updated SCC results suggest that even partial accounting of sector-specific damages is likely to raise the existing U.S. SCC (see Figure 1), particularly if discount rates are updated and uncertainty is properly valued. Further, we think that the SCC's political and legal durability would be enhanced by this approach, which is built to accommodate a scientific literature that will undoubtedly continue to evolve.

[98] Kopp and Mignone, "The U.S. Government's Social Cost of Carbon Estimates."
[99] See, for example, Hsiang et al., "Estimating Economic Damage From Climate Change."

Pathway C: Build a new IAM (under an updated Circular A-4)

A third pathway constructs the same new SCC framework as described for Pathway B, only departing from Pathway B when valuing the sector-specific, empirically derived climate impacts that form the damage function. In particular, this approach builds a damage function that embeds discounting (Ingredient three), the valuation of uncertainty (Ingredient six), and the treatment of equity (Ingredient seven) into a single cohesive step. In so doing, this pathway directly contradicts some of the individual recommendations for these three ingredients listed above; if this pathway is taken by a future IWG, we recommend updating these ingredients as described below. All other aspects of this pathway follow Pathway B described above.

This pathway is based on the recognition that a simple economic principle—declining marginal value of consumption—underlies the motivation for discounting *as well as* the valuation of both equity and uncertainty.[100] This principle is based on the straightforward observation that $100 is worth more to a person living in poverty than a wealthy person. In the climate setting, declining marginal value implies that one should attach a higher value to future *and* present impacts of climate change when they occur to populations experiencing lower incomes. It also means that when future incomes are uncertain, one has to account for the risk of severe damages occurring when average global income is very low, and thus when the value of an additional dollar is relatively high.[101]

Therefore, an argument can be made for computing an SCC in which the damage function represents the difference in the "certainty-equivalent" value of consumption across all years, populations, and possible future states of the world with and without climate change.[102] In this approach, the valuation of climate damages is conducted from the perspective of a person who does not know their circumstances in advance, so they account for all potential income levels (e.g., whether they earn $25,000 or $250,000

[100] Anthoff et al., "Discounting for Climate Change."
[101] Jensen and Traeger, "Optimal Climate Change Mitigation."
[102] A "certainty-equivalent" value is computed by determining the consumption loss that society would accept as a certain outcome (e.g., a certain future income growth) in place of the distribution of future uncertain outcomes (e.g., a set of likelihoods for different future incomes). In other words, it is an indicator of what people are willing to sacrifice in service of more equitable outcomes. This approach is similar in spirit to John Rawls' "veil of ignorance" thought experiment, in which an individual makes decisions about social policy without knowing who in that society they will be (Rawls, 1971).

annually) and degrees of climate risk they might face (e.g., whether they live in Miami or Minneapolis). This calculation can be limited to those living in a particular country or applied to those living in any country.

Under this approach, discounting, uncertainty valuation, and accounting for equity implications are all incorporated into the construction of a single, certainty-equivalent damage function.[103] To compute this damage function, estimates of possible local-level climate change damages and their associated probabilities are combined with evidence on how the marginal value of consumption declines as people become wealthier.[104] Such a calculation is possible only with updated damage estimates from the recent scientific literature, which can show effects down to the local level and fully capture economic, statistical, and climatological uncertainty. A paper implementing this pathway will be released by the CIL team in 2021.[105]

The appeal of this approach is that it is the most intellectually coherent method for valuing the damages from climate change. However, it is not entirely clear that pursuing Pathway C would be consistent with Circular A-4; therefore, doing so would likely have implications for policies beyond climate and environmental regulation.

We therefore recommend Pathway B, which is the approach that will deliver a transparent, internally consistent, and scientifically robust set of SCC estimates that can accommodate evolving research and be implemented within the current legal framework. However, we believe that Pathway C should be carefully considered for adoption in the medium term.

III. Conclusion

This paper details a recipe to return the SCC to the frontier of climate science and economics. There are seven key ingredients in this recipe. The paper outlines

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[103] A similar certainty-equivalent welfare metric was analogously derived in Jones and Klenow (2016) to compare well-being across countries in historical data.
[104] Only a single utility function parameter, η, is needed, as long as a standard constant relative risk aversion utility function is employed. A large literature generally estimates that η is approximately equal to 2 (e.g., Arrow, 2007; Dasgupta, 2007, 2008; Weitzman, 2007, 2009).
[105] Nath et al., "Estimating an Empirically Founded Social Cost of Carbon."

recommendations for each of them, along with recommendations for how to pull them together to update the SCC.

We propose a two-step process that will return a seriousness of purpose to U.S. climate policy that the climate challenge demands. The first step involves an immediate update to the SCC that returns to the original IWG approach. Specifically, we propose that damage estimates again include global damages and that the 3 percent central discount rate be replaced with a 2 percent discount rate (left panel of Figure 8). These changes produce an SCC of $125 in 2020. The second step is to reconvene the IWG to conduct a comprehensive update by building a new SCC framework (right panel of Figure 8).

Following this recipe means that the SCC would reflect the substantial changes in understanding about climate change that have emerged over the last decade. Further, we believe that it would best serve the interests of the American people.

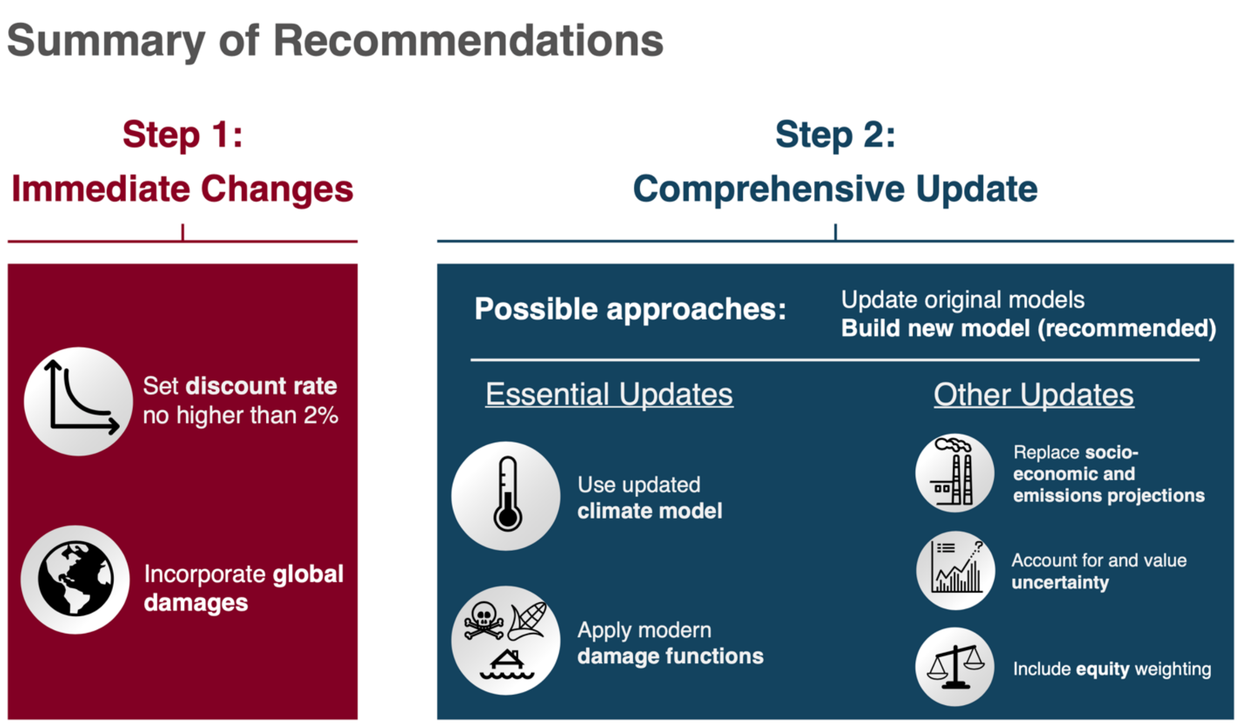

Figure 8: Summary of the recommendations made under a two-step process for updating the U.S. government's Social Cost of Carbon. Step 1 can be implemented immediately, while Step 2 requires a new IWG conduct a holistic update to the SCC framework.

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EDF’S
EXHIBIT III

FIND MEASURE FIX

JOBS IN THE U.S. METHANE EMISSIONS MITIGATION INDUSTRY

A REPORT BY DATU RESEARCH
2021

ABOUT THIS REPORT

This work was prepared on behalf of Environmental Defense Fund.
edf.org

ABOUT DATU RESEARCH

Datu Research is an international consulting firm that provides the right data to the leading foundations, NGOs and governments that are working to solve humanity's most important challenges, including food security, soil health, and climate change.
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notchcode.com

COMPANIES AND POLICY VIEWS

Inclusion of company names in this report does not imply a position on federal or state policies regarding methane emissions.

None of the opinions or comments expressed in this study are endorsed by the companies mentioned or individuals interviewed. Errors of fact or interpretation remain exclusively with the authors. We welcome comments and suggestions.

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Datu data for the big picture

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EXECUTIVE SUMMARY

The following report introduces policy makers, firms, researchers, and the general public to the growing methane emissions mitigation industry, describing its recent innovations, growth potential, and ability to provide U.S. jobs. These manufacturing and service firms offer solutions to oil and gas companies across the United States by finding, measuring, and mitigating methane emissions. Recent advances in emerging technology and advanced data analytics are making it possible to do so in ways never before possible.

Our research updates and builds upon two similar reports released in 2014 and 2017 — demonstrating that this growing industry:

Creates U.S. Jobs. Firms in the industry offer well-paid employment opportunities across the country that provide upward mobility and often involve fieldwork that cannot be offshored.

Saves Operators Money. Methane emissions mitigation reduces waste by keeping otherwise lost product in the sales line.

Improves Environment and Climate. Addressing natural gas leaks across the country reduces emissions of a highly potent greenhouse gas, while contributing to cleaner air in surrounding areas.

SEVEN KEY RESEARCH FINDINGS ABOUT THE METHANE EMISSIONS MITIGATION INDUSTRY

1) The industry is growing rapidly. Today it includes at least 101 manufacturing firms (a 33-percent increase over our 2014 count) and 114 service firms (a 90-percent increase over our 2017 count). Together, these firms have at least 748 employee locations nationwide.

2) The industry comprises dozens of job types, with annual salaries ranging from $37,150 to $140,960 (as compared to the U.S. annual mean wage of $56,310 for all occupations).[1] Common entry-level jobs such as assemblers and fabricators offer opportunity for upward mobility.

3) Most of the firms (70 percent) are small businesses, known to serve as an economic engine for new job growth.

4) Nearly 25 percent of the manufacturing firms and over 40 percent of the service firms were founded in the past 12 years, indicating a fast-growing industry.

5) Firms are adding new U.S. employee locations. In 2021, we identified a total of 748 employee locations for manufacturing and service firms, an increase of 26 percent over the number previously identified.

6) Firms anticipate growing jobs. Of 57 firms that responded to our survey, 75 percent of the manufacturing firms and 88 percent of the service firms reported that if future state or federal methane emission rules were put in place, they would anticipate hiring more employees.

7) These jobs appear poised to grow soon, since the current Administration and at least eight states are preparing either to introduce new methane rules or expand the scope of existing ones.

INTRODUCTION

> **IN THIS 2021 FOLLOW-UP STUDY, WE UPDATE AND EXPAND THE INVENTORY OF RELEVANT FIRMS THAT PLAY EITHER A MANUFACTURING OR SERVICES ROLE IN METHANE EMISSIONS MITIGATION.**

PURPOSE

The purpose of this research is to describe and understand the growing industry of firms that provide methane emissions mitigation services and equipment to the oil and gas industry. Provided is an inventory of relevant companies, including size, maturity stage, and technologies used. Also documented are the geography, roles and wages of the methane emissions mitigation workforce. Through this research, we seek to answer key questions such as: What kinds of jobs are created by methane emissions mitigation? Where is the work performed? What kind of growth do these firms anticipate as a result of existing and potential state and federal regulations?

This report is a follow-up to two previous Datu Research reports. First, *The Emerging U.S. Methane Mitigation Industry* (2014) documented the manufacture of existing methane control technologies, analyzed the size and geographic distribution of the industry, and assessed future growth potential. The 2014 study found that the methane mitigation industry included at least 72 manufacturing firms, with over 500 locations across the United States. Second, *Find and Fix: Job Creation in the Emerging Methane Leak Detection and Repair Industry* (2017), identified 60 service firms that provided methane leak detection and repair (LDAR) services to oil and gas companies in 45 states.

In this 2021 follow-up study, we update and expand the inventory of relevant firms that play either a manufacturing or services role in methane emissions mitigation. This time, we include two added industry categories: Advanced Data Analytics (firms that use Artificial Intelligence (AI) and other advanced data techniques to detect and measure methane emissions) and Strategic Advisory (consulting firms that help operators plan for reducing or eliminating their methane emissions). Also new in this 2021 edition are several evolving technologies — for instance, those that enable operators to monitor emissions continuously, analyze methane data from satellites, and capture “associated” gas from oil sites either for use onsite or for distribution elsewhere.

METHODOLOGY

We identified 389 potentially relevant firms through purposive sampling and online research. Vetting this large list based on primary and secondary data collected in January and February 2021, we identified a total sample of at least 215 firms that comprise the U.S. methane emissions mitigation industry. To analyze this industry's contribution to job creation and its ability to provide methane emissions mitigation nationwide as demand grows, we reached out to firms via interviews and phone and email surveys. For six representative firms, we prepared brief profiles by conducting interviews with company executives and managers, followed by several additional communications to collect further information. Inclusion of company names in this report does not imply a position on federal or state policies regarding methane emissions.

WHY METHANE?

THE INTERNATIONAL ENERGY AGENCY ESTIMATES THAT 75% OF TOTAL METHANE EMISSIONS FROM OIL AND GAS OPERATIONS COULD BE AVOIDED WITH TECHNOLOGIES THAT ARE AVAILABLE TODAY.

MITIGATING CLIMATE CHANGE AND AIR POLLUTION

Methane is the largest component of natural gas. It has an extraordinarily high heat-trapping potential, making it a potent factor in global warming. To illustrate, in 2019, methane represented 10% of all greenhouse gas emissions in the United States, second only to carbon dioxide (CO_2).[2] However, in comparison to carbon dioxide, methane has a warming potential that is significantly higher: for the first 20 years after it is released into the atmosphere, methane has 84 times the heat-trapping effect of carbon dioxide and 28 times after 100 years.[3] The largest industrial source of methane emissions is the oil and gas industry, accounting for 33% of all U.S. methane emissions.[4] In addition to global warming, co-pollutants released by oil and gas operations contribute to smog formation and ozone, threatening public health on a global scale.

The International Energy Agency estimates that 75% of total methane emissions from oil and gas operations could be avoided with technologies that are available today — and since the captured gas can be sold, an estimated 40% of total emissions could be avoided at no net cost, based on 2019 natural gas prices.[5] This report takes inventory of the U.S. manufacturing and service firms that stand ready to help operators achieve these dramatic, often profitable reductions.

CREATING GOOD JOBS

Methane emissions mitigation means jobs. A wide and steadily expanding range of skills are required, from field technicians to chemical engineers to data scientists. Interviews with firms indicate that these jobs offer upward mobility. Many firms expect to expand their workforce if new federal and/or state methane rules are put into place. Of the eight states that either have methane rules or are considering them, seven are among the top states for employee locations in the methane emissions mitigation industry, including California, Colorado, Pennsylvania, New York, Wyoming, New Mexico, and Ohio. This would suggest that employee locations are poised to grow if the federal government and/or states roll out new rules on methane emissions.

TURNING WASTED NATURAL GAS INTO REVENUE

Methane is released into the atmosphere from equipment leaks and malfunctions in oil and gas operations and infrastructure. These methane emissions represent lost product for the oil and gas industry. When captured, this resource can be sold, leading to an increase in the amount of gas available to power U.S. homes, factories, and more. Reducing methane emissions capitalizes on previously lost revenue for the industry.

METHANE EMISSIONS MITIGATION INDUSTRY: FOUR CATEGORIES

HOW AND WHERE EMISSIONS OCCUR

Methane is emitted throughout the oil and gas supply chain, which consists of four stages: production; gathering and processing; transmission and storage; and distribution (see Figure 1). Production, gathering and processing occur at or near the site of the well. In these phases, companies drill, build (or "complete") and operate wells to produce natural gas. Once the gas is produced, compressors gather and "boost" it, sending it to plants where it is processed before moving to the next phase. In the transmission and storage phase, a series of compressors move the gas from the well site through pipelines to customers or storage facilities. Distribution occurs in the end market area, where natural gas is delivered to end users of various sizes.

Methane emissions in the supply chain occur in two ways — vented emissions and fugitive emissions. Vented emissions are intentional and occur by product and/or process design. For instance, many sites have pneumatic devices that use energy from pressurized gas to operate mechanical equipment; these devices vent gas continuously or intermittently to modulate a process. Fugitive emissions, by contrast, are unintentional, primarily in the form of leaks — such as those caused by failing seals or corroded material, or valves that are stuck open.

FIGURE 1. FOUR STAGES OF THE NATURAL GAS SUPPLY CHAIN

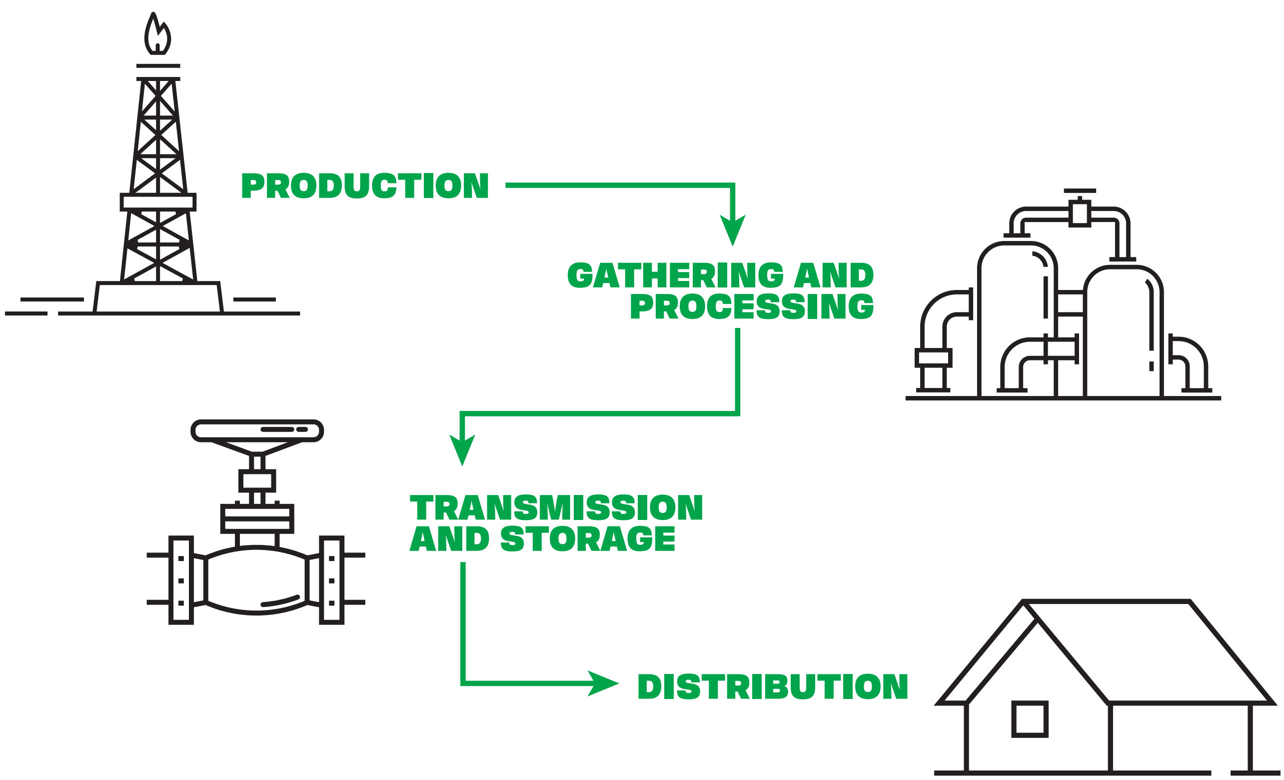


TABLE 1. FOUR CATEGORIES OF METHANE EMISSIONS MITIGATION FIRMS

LEAK DETECTION, MEASUREMENT & REPAIR	ADVANCED DATA ANALYTICS	MITIGATION TECHNOLOGIES	STRATEGIC ADVISORY
These firms provide leak detection, measurement, and/or repair services, using optical gas imagery, handheld sensors, fixed sensors, or sensors mounted on vehicles, drones, or aircraft.	These firms use big data, artificial intelligence, and machine learning techniques to find and/or measure methane emissions based on data from a range of sources, in some cases including satellite data.	These firms manufacture technologies that replace or add to existing devices to reduce emissions by preventing leaks, reducing venting, mitigating flaring, and/or capturing gas for use either on- or off-site.	These firms help oil and gas operators prepare their plans for reducing methane emissions from their operations, including net-zero commitments, energy transition, greenhouse gas verification markets and other opportunities.

Both vented and fugitive methane emissions occur in all stages of the natural gas supply chain, and they are nearly all avoidable. The methane emissions mitigation industry consists of firms that address avoidable emissions either by manufacturing equipment or providing services. These firms fall into four major categories: leak detection, measurement and repair; advanced data analytics; mitigation technologies; and strategic advisory, as summarized in Table 1.

The following section discusses each of these four categories in greater detail, along with the relevant technologies and promising innovations that have emerged in recent years.

1) LEAK DETECTION, MEASUREMENT, AND REPAIR

Methane is a colorless, odorless gas, which makes it challenging for oil and gas operators to detect methane leaks. Many operators find it cost effective to outsource leak detection services. Common leak detection technologies and platforms are summarized in Table 2. Leak detection is most commonly performed with handheld devices. Traditionally, the most-frequently-used devices have been infrared cameras and tunable diode lasers. Infrared or Optical Gas Imaging (OGI) cameras have become dominant in recent years; since they translate methane emissions into an easy-to-see gas plume, they make leak detection intuitive and user-friendly.

Many service firms amplify the coverage that is possible with handheld (or close-range) detection technologies by mounting them to road vehicles, unmanned aerial vehicles (UAVs, also called drones), helicopters, or airplanes. This enables them to cover much more of a facility in a shorter time. And to maximize the frequency of inspection, two additional approaches provide continuous screening, particularly useful to detect intermittent sources: fixed sensors installed throughout a facility, and even methane-sensing satellites.[6]

Continuous screening via fixed sensors is especially useful in high-risk areas, and can include an alarm that triggers if methane emissions exceed certain levels. Also promising is the prospect of satellite methane detection. Today, satellites can detect and measure methane concentrations in specific basins, but they are typically not yet capable of screening below the level of a particular facility. Governments and the private sector are making rapid progress, however, such that some researchers believe that facility-scale screening based on satellite data will be available in the near future.[7]

Since screening and close-range devices each have unique advantages, in the future they increasingly could play complementary roles in methane leak detection.

TABLE 2. METHANE LEAK DETECTION AND MEASUREMENT TECHNOLOGIES AND PLATFORMS

OPTICAL GAS IMAGING (OGI)
OGI cameras are thermal devices that create infrared images of methane plumes. Because they display results in a visual and intuitive manner, they enable operators to quickly and safely expose gas leaks. In recent years they have become the dominant close-range method.
NON-OGI CLOSE-RANGE INSTRUMENTS
Another widely used, effective close-range technology is laser spectroscopy. The device points a laser beam towards a suspected leak, and the target reflects back a diffused beam. The device then measures the absorptivity of the beam and calculates its methane column density.
FIXED SENSORS
Fixed sensors are installed in a facility — typically in high-risk areas — to provide continuous, real-time readings of methane concentration. These devices will trigger an alarm if concentrations exceed certain limits.
MOBILE GROUND LABS
Consisting of a vehicle with a global positioning system and a methane sensor, this enables an operator to generate a map of methane concentrations along the vehicle's path. Because it is limited to the path (usually a road), this method collects data in a two-dimensional space.
UNMANNED AERIAL VEHICLES (UAVS)
Also called drones, these can reach dangerous or hard-to-reach places and can fly very close to the source of plumes. They can be equipped with OGIs and other relatively small, lightweight sensor devices and, like aircraft, can operate in three-dimensional space.
AIRCRAFT
Various sensor types can be mounted on helicopters and small airplanes to detect methane emissions over relatively long periods while covering longer distances. Like drones, aircraft can collect data in three dimensions.
SATELLITES
Satellites can be equipped to measure methane concentrations in the troposphere. These readings can be combined with other data to identify large sources of emissions.

Source: Fox et al., "A review of close-range and screening technologies for mitigating fugitive methane emissions in upstream oil and gas." Note: Here, the source's original first category, "handheld instruments," is divided into OGI and non-OGI categories.[8]

Although screening technologies can cover larger areas and provide continuous monitoring, for instance, they cannot identify specific components that are leaking. But in a combined approach, screening technologies would quickly find high-emitting sites, and close-range devices would then follow up and identify the precise source of each leak.[9]

Once leak detection and repair firms have located leaks, their clients can choose to have them send out professionally certified technicians to perform the needed repairs. These boots on the ground help an operator's facility avoid wasting lost product and stay in compliance. Some firms even provide preventative maintenance and repair, such as detailed valve inventories and specialty valve repair.

IN A COMBINED APPROACH, SCREENING TECHNOLOGIES WOULD QUICKLY FIND HIGH-EMITTING SITES, AND CLOSE-RANGE DEVICES WOULD THEN FOLLOW UP AND IDENTIFY THE PRECISE SOURCE OF EACH LEAK.

2) ADVANCED DATA ANALYTICS

In this age of explosive growth in data availability, oil and gas operators can now collect and interpret data in different ways to identify leaks and quantify them. This newly emerging category within the methane emissions mitigation industry represents jobs quite different from those typically associated with the industry, including new skillsets required for data science, design thinking, artificial intelligence, and related approaches.

The role of data is evolving quickly. Not only does today's data help to detect more leaks in less time; it also makes it possible to detect leaks early, continuously monitor much larger spatial areas, and increasingly, even predict where future leaks are likely to occur.

Several relevant technologies and advanced data analytics techniques are summarized in Table 3. Drones are used to perform remote sensing, making it possible to cover much more territory than is possible with manual inspection, and to go into areas that may be dangerous or hard to reach. Continuous monitoring generates large amounts of useful data, helping operators manage their physical assets and make informed decisions about when to inspect, repair or replace them.

All of this data can be analyzed with AI techniques to create specific, actionable information that often exceeds what can be achieved with sensors alone. The potential to harness AI is greatest in operations that invest in IoT communication and extensive instrumentation — for example, to record and analyze temperatures, pumping rates, flow rates, and numerous other variables — although many upstream oil and gas facilities currently lack such instrumentation.

TABLE 3. ADVANCED DATA ANALYTICS IN METHANE EMISSIONS MITIGATION

REMOTE SENSING
Leak inspections can be done via remote sensing with the use of drones and other aircraft, which can expand the quantity and frequency of leaks found and repaired.
CLOUD COMPUTING
Moving to the cloud helps operators gain access to cutting edge technology applications, undertake enormous analytic workloads, and perform complex modeling to help identify and quantify methane emissions.
ARTIFICIAL INTELLIGENCE
AI is the umbrella over several "thinking" techniques that computers are now capable of performing. For instance, remote sensing data can be combined with AI algorithms to create smart methane emissions detection. AI experts are developing additional ways to perform high-level tasks that involve prediction or problem solving.
MACHINE LEARNING
A common AI technique is machine learning, in which the machine learns from experience, as opposed to being programed to follow specific instructions. For instance, the machine can be trained to "learn the shape that a methane leak takes as it is released and spreads."[10]
DEEP LEARNING
In Deep Learning, the machine finds hidden patterns in the data and combines them to come up with efficient decision rules. The machine can recognize images and sounds, enabling it, for instance, to reliably identify a methane plume.
INTERNET OF THINGS
IoT enables a system of computing devices (mechanical and digital) to transfer data over a network without requiring human participation. In oil and gas facilities, the data generated and shared in this way can be used to provide efficient and early leak detection.
PREDICTIVE MODELLING
Historical data can be used to "train" a model on the relationships between methane concentrations and certain variables. Those variable values can then be applied to real-time data to predict methane concentration values.

3) MITIGATION TECHNOLOGIES

Methane mitigation technologies are long established and well known in the oil and gas industry. In many cases they pay for themselves via the natural gas they save; the International Energy Agency (IEA) estimates that 40% of total emissions could be avoided with measures that have no net cost.[11] The main technologies, along with a description for each, are found in Table 4.

TABLE 4. METHANE EMISSIONS MITIGATION TECHNOLOGIES

LOW-EMISSION ROD PACKING AND DRY SEALS
Compressors are used to pressurize and transport natural gas; replacing typical seals with these low-emission seals and rod packing helps prevent compressor leaks.
LOW-EMISSION VALVES
Various valves are used to vent excess gas pressure for safety, or to stop the flow of gas when a line is severed or a pilot light is unlit. To avoid leaks, operators can replace failing valves early, preferably with low-leak valves.
ALTERNATIVES TO PNEUMATIC DEVICES
Pneumatic devices such as actuators, controllers and pumps use energy from pressurized gas to operate equipment. They vent gas to modulate pressure, flow, and more. Sites with electricity can replace gas-driven devices with compressed instrument air, electric, and solar alternatives.
REDUCED EMISSIONS COMPLETIONS (GREEN COMPLETIONS)
At sites that use hydraulic fracturing, excess fluid and produced water must be removed before routine production can begin. During the process, a large amount of methane escapes. Instead, temporary REC equipment can be brought to separate the gas and send it to the sales line.
LIQUIDS UNLOADING: PLUNGER LIFTS AND VELOCITY TUBING
A well's productivity can be impeded by accumulating liquids, often removed via a "blowdown," which allows the gas under pressure to push out the liquids--releasing large amounts of methane. Plunger lifts and velocity tubing can be used to release far less methane.
VAPOR RECOVERY UNITS
Vapor recovery units (VRUs) collect gas vapors from storage tanks. Methane vaporizes and collects between the liquid and the top of the tank, creating emissions that are often vented or flared. VRUs can capture them for on-site generators or compress them into a sales pipeline.
CAPTURE OF ASSOCIATED GAS FOR USE OR DISTRIBUTION
Instead of venting and flaring natural gas associated with oil operations, operators can use it as fuel for oil field activities by compressing it, or convert it to electric power using small-scale generators, or convert it to methanol or LNG.[12]
IMPROVED COMBUSTION FOR FLARING
If flaring is used, technologies can optimize combustion efficiency and ensure flares stay lit.

Significant emission reductions can come simply from replacing devices such as compressor rods and seals before they can corrode or get clogged, leading to gas leaks. Ideally, compressor rods and wet seals can be replaced with low-emission rod packing and dry seals, which further reduce emissions.

Some devices used in natural gas production emit methane routinely as part of everyday operations, including pneumatic devices (those that use energy from pressurized gas to operate equipment). At sites with electric power, gas-driven devices can be replaced with instrument air, electric, and solar alternatives. Also available are devices that exist expressly to cut emissions, such as vapor recovery units (VRUs), which recover gas found near the top of storage tanks that is otherwise vented or flared.

Large opportunities exist to reduce or even eliminate methane emissions from routine venting and flaring, especially at remote facilities — or at oil sites, where natural gas is not considered a product, but rather only "associated" with oil production. The World Bank's estimates from satellite data show that in 2019, global gas flaring increased to 150 billion cubic meters (bcm), equal to the total annual gas consumption of Sub-Saharan Africa.[13] This wasted gas could instead be used for energy, even while reaching net-zero emissions. For instance, several technologies capture associated natural gas and either use it onsite as fuel, or convert it to electricity or liquid fuels for distribution off-site. Others can improve flare combustion performance to achieve 99.99% efficiency, also using the waste heat to generate power.[14]

4) STRATEGIC ADVISORY

Oil and gas companies have long engaged the services of third-party service firms to help them with compliance and reporting. Many of the same firms that perform leak detection services also offer services to do this compliance work with their oil and gas clients. But in recent years, along with climate awareness, a new type of consulting has emerged, to help operators make strategic plans to reduce their methane emissions. These strategic advisory services go far beyond regulatory compliance and instead help operators envision how they can manage methane emissions to create a future business model that could differ considerably from a company's current configuration.

Much of the growth in this type of strategy consulting is motivated by investors' increasing embrace of Environmental, Social, and Governance (ESG) factors in their analysis of the financial metrics of a company. ESG has become an important aspect of risk assessment and investment decisions. The general public is also becoming more discerning, as climate awareness increases, and likelier to hold oil and gas operators accountable for their emissions.

Oil and gas companies that are focusing on ESG may work with traditional environmental consulting firms to set ambitious goals, such as those to reduce or even eliminate fugitive emissions — treating them not as an unavoidable downside of operations, but rather as an opportunity to recover lost product and to improve their greenhouse gas footprint.

THE WORLD BANK'S ESTIMATES FROM SATELLITE DATA SHOW THAT IN 2019, GLOBAL GAS FLARING INCREASED TO 150 BILLION CUBIC METERS (BCM), EQUAL TO THE TOTAL ANNUAL GAS CONSUMPTION OF SUB-SAHARAN AFRICA.

One of the largest opportunities to address methane emissions is to reduce or eliminate venting and flaring — two practices that are increasingly avoidable, given improvements in flaring alternatives, including efficient combustion technology.

Consultants can help by offering not only technical advice but also modifications to a company's business model, including how to make productive use of the recovered gas.

CHARACTERISTICS OF THE U.S. METHANE EMISSIONS MITIGATION INDUSTRY

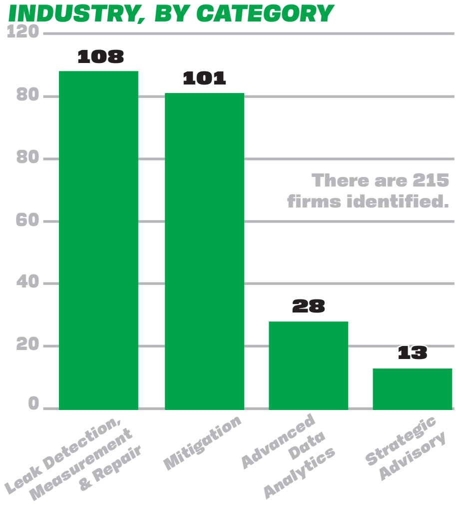
COUNT OF FIRMS

Our research identified a total of 215 firms that either manufacture technology for, or provide services to the oil and gas industry to manage methane emissions. This total is nearly evenly split between mitigation manufacturing firms (101) and service firms (114), as shown in Figure 2.

The industry appears to be growing rapidly. For the manufacturing firms, our 2021 total is a 33-percent increase over our 2014 count. For service firms, our current total is a 90-percent increase over our 2017 count. Service firms are mostly performing leak detection, measurement and repair (108 firms), while 28 service firms provide advanced data analytics, and 13 provide strategic advisory to oil and gas operators. Not exhaustive, this research is almost certainly an undercount in all manufacturing and service categories.

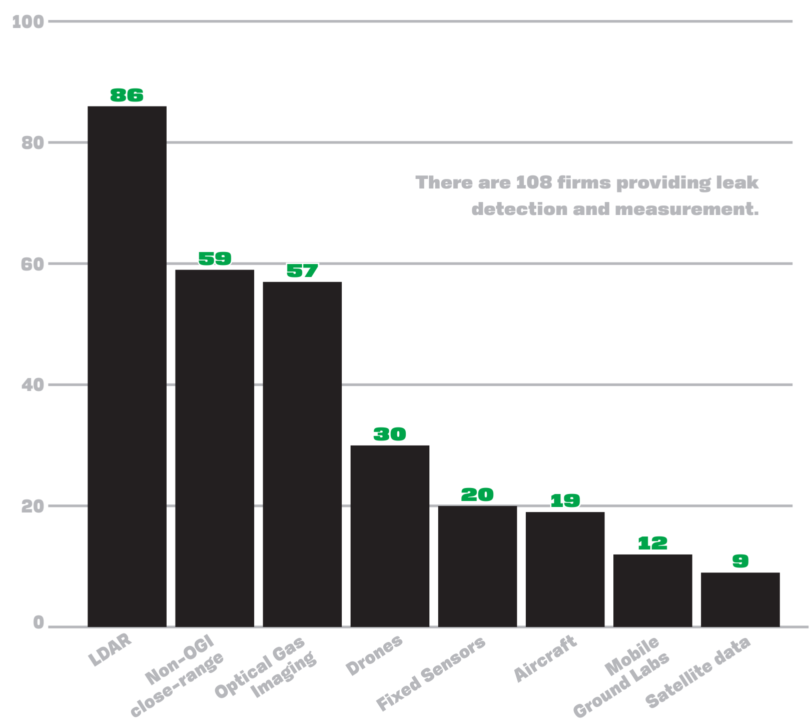
For two of our industry categories — Leak Detection, Measurement and Repair; and Mitigation — we assigned a number of relevant subcategories. Leak Detection, Measurement and Repair comprised eight subcategories, found in Figure 3. We chose to treat LDAR services (86 firms) as its own subcategory to distinguish these firms from the growing number of service firms that provide other detection- and measurement-related services. These include, for instance, New York-based start-up Bluefield Technologies, which uses artificial intelligence and machine learning techniques to analyze methane emissions data from ground sensors and satellites. Among firms

FIGURE 2. NUMBER OF FIRMS IN U.S. METHANE EMISSIONS MITIGATION INDUSTRY, BY CATEGORY



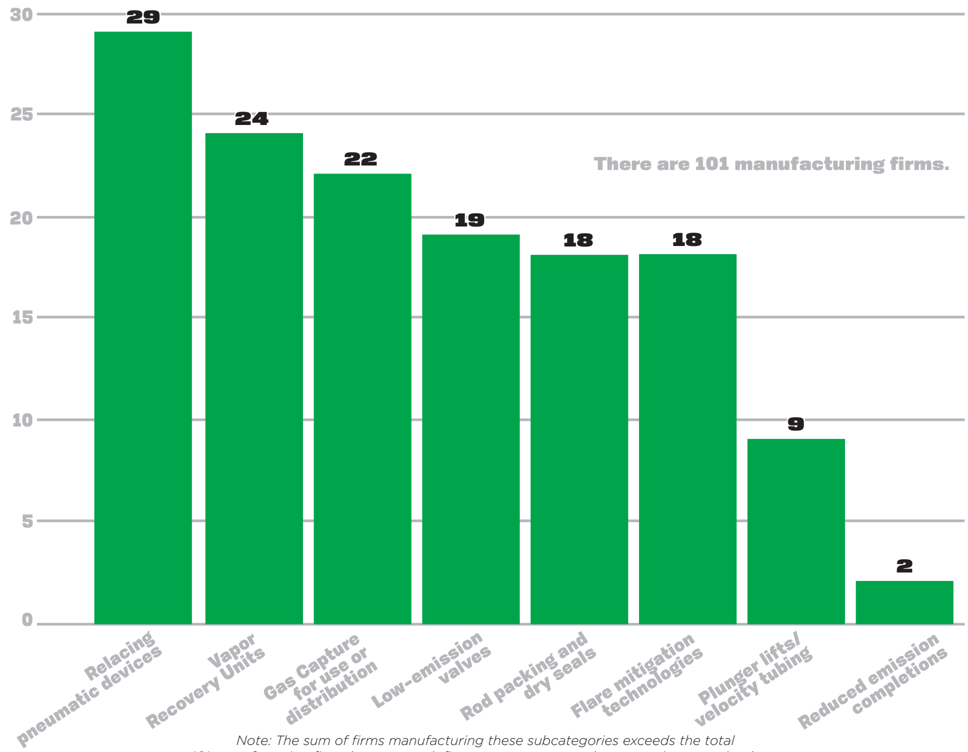
Note: The sum of firms in each category exceeds the total 215 firms because each firm may be active in two or more categories.

FIGURE 3. NUMBER OF FIRMS PROVIDING LEAK DETECTION & MEASUREMENT, BY TECHNOLOGY



Note: The sum of firms in these subcategories exceeds the total 108 firms providing leak detection and measurement services because each firm may report more than one relevant technology.

FIGURE 4. NUMBER OF FIRMS PROVIDING METHANE EMISSIONS MITIGATION, BY TECHNOLOGY



Note: The sum of firms manufacturing these subcategories exceeds the total 101 manufacturing firms because each firm may report more than one relevant technology.

that do perform traditional LDAR, 57 reported using OGI technology, roughly equal to those using all other handheld or close-range technologies (59 firms). This reflects how dominant infrared cameras have become in recent years, in part because of regulatory requirements like EPA's 0000a rulemaking.

Within Mitigation, we divided the manufacturing firms also into eight technology subcategories, found in Figure 4. The largest number of firms (29) reported that they manufacture alternatives to pneumatic devices, followed by vapor recovery units (24), and technologies to capture gas for use or distribution (22). Together, these three categories accounted for 74 percent of the 101 mitigation firms identified, meaning that nearly three-fourths of the firms in the mitigation space are manufacturing one or more of these three technologies. This is in sharp contrast to the two smallest categories; plunger lifts and velocity tubing are provided by only nine manufacturing firms, and reduced emission completion technology, only two.

FIRMS' EMPLOYEES, REVENUES, AND MATURITY STAGE

Most firms identified in this study are small businesses. The U.S. Small Business Administration (SBA) provides varying definitions of small businesses according to the characteristics of each sub-industry. The definitions are usually based on number of employees. For this study, we use 500 employees as the upper benchmark for small manufacturing firms, and 200 employees for service firms, which tend to have smaller staffs. According to these criteria, 62 manufacturing firms and 78 service firms — that is, 70% of identified firms, qualify as small businesses (see Figure 5).

Similar to the size ranges for number of employees, the size ranges for sales begin much higher at the low end for manufacturing firms than for service firms. Accordingly, the lowest sales range for manufacturing, $1M to $38.5M, applied to 48 firms. Six firms were in the highest range, those topping $10B in sales. Service firms had a steep drop-off between the 0-$15M range (61 firms) and the $15M-50M range (18 firms). The highest sales range for manufacturing and services--$10B and above — applied in several cases to firms that perform both manufacturing and services, such as ABB Group, Ball Corporation, and Schlumberger.

FIGURE 5. NUMBER OF EMPLOYEES, METHANE-RELEVANT MANUFACTURING AND SERVICE FIRMS

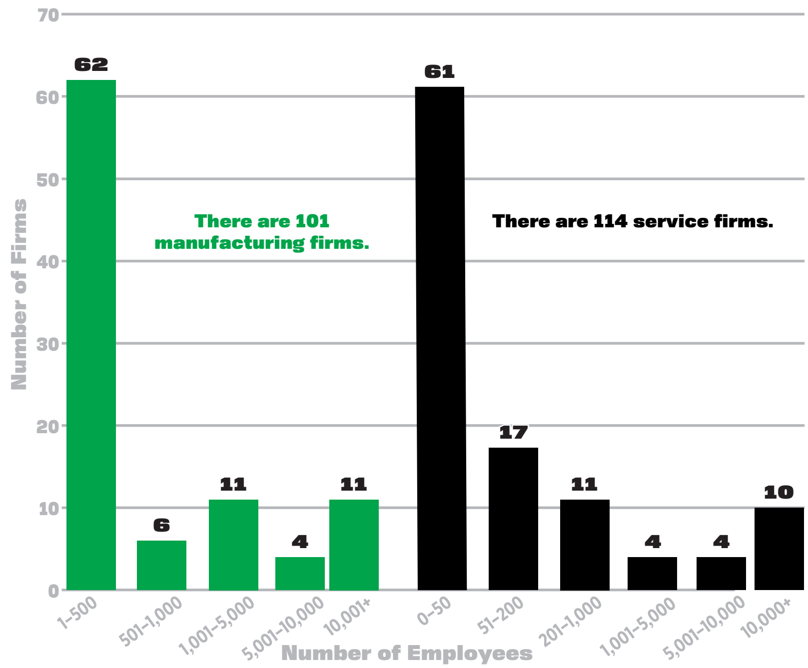
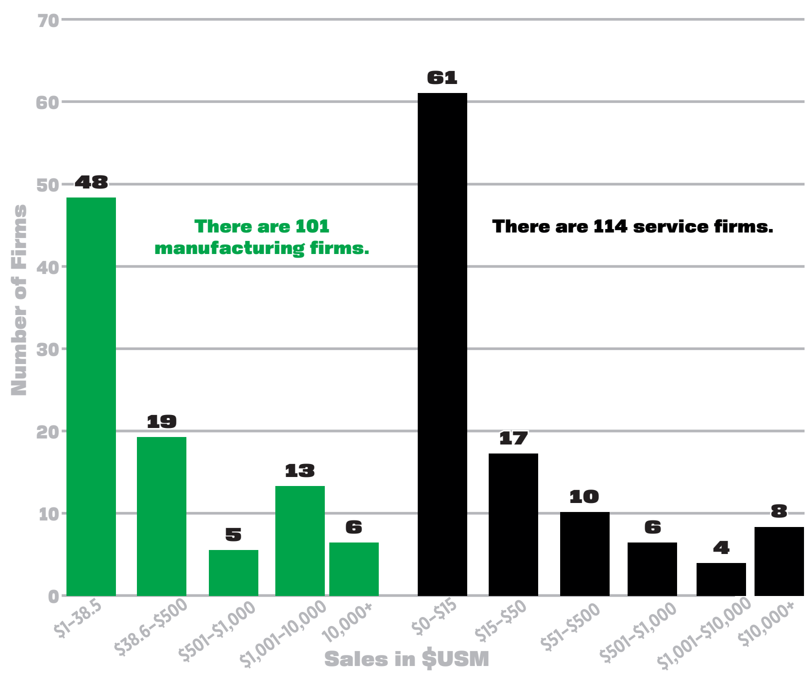
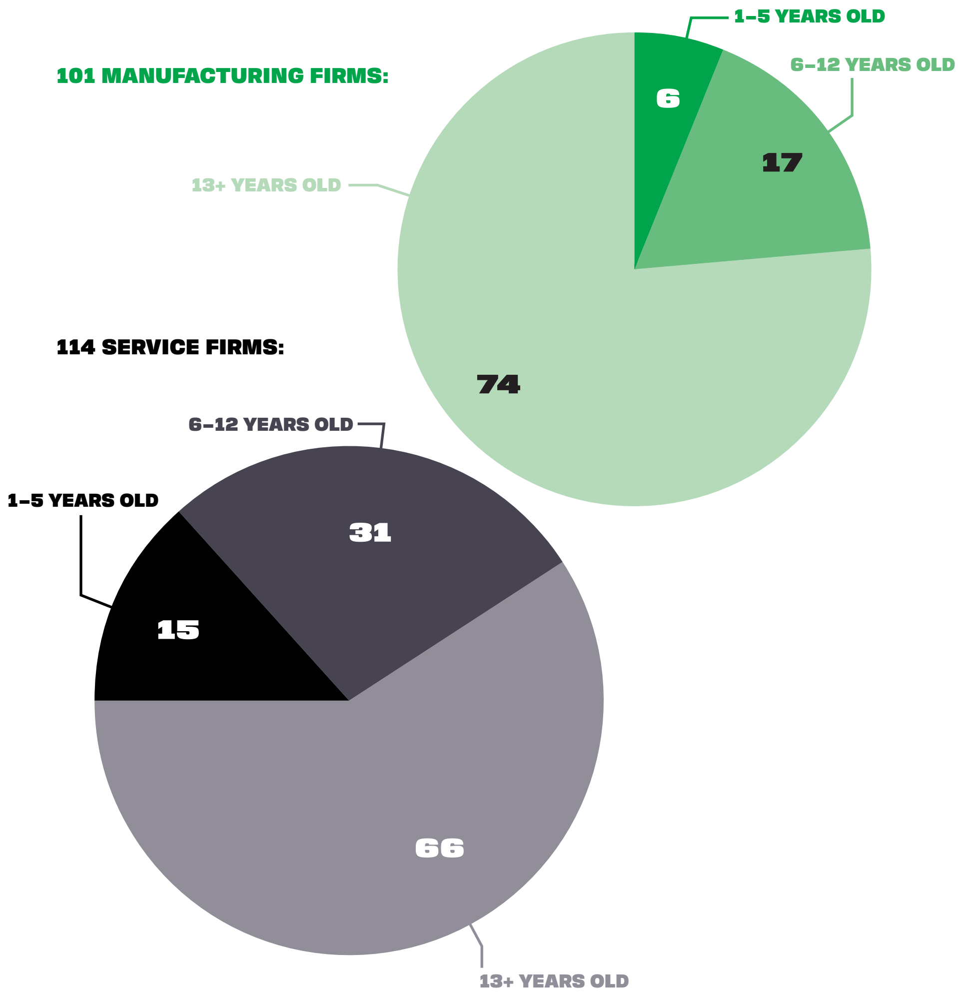


FIGURE 6. ANNUAL SALES, METHANE-RELEVANT MANUFACTURING AND SERVICE FIRMS



Most of the manufacturing firms we identified are mature firms (see Figure 7); 74 of 100 are at least 13 years old, and 12 — including National Oilwell Varco, Siemens Energy, and Gardner Denver — were founded before 1900. Only six of the manufacturing firms are startups. In contrast, the service firms we identified tend to be younger. Mature service firms constitute just 66 of the total of 114, and startups account for 15 firms. To meet demand for methane-related services, new service firms are emerging in states where the natural gas industry is prevalent. Since 2010, nine new firms have established headquarters in Texas alone, opening a total of 13 employee locations in the state.

FIGURE 7. MATURITY STAGE, METHANE-RELEVANT MANUFACTURING AND SERVICE FIRMS



Note: Founding year was unavailable for a few of the identified firms.

REGULATORY LANDSCAPE

FEDERAL REGULATIONS

A summary of federal methane LDAR regulations is found in Table 5. In 2016, the Environmental Protection Agency (EPA) adopted rules that serve to reduce methane emissions, local air pollution, and natural gas waste from new and modified oil and gas facilities. While these rules were weakened under President Trump, EPA's New Source Performance Standards[15] currently require new and modified non-low production well sites and gathering and boosting compressor stations to conduct semiannual leak detection and repair.[16] President Biden recently directed EPA to review these amendments and move forward with emission standards for older, existing oil and gas facilities.[17] Through agency action, EPA methane rules could be expanded and strengthened to reduce more emissions.

With strong federal emissions standards, operators would waste less product and generate greater economic returns for taxpayers, states and tribes, and royalty owners. At the same time, deep reductions of methane, a potent greenhouse gas, are critical to meeting the United States' climate goals.[18] Federal standards designed to achieve ambitious emissions reductions will necessitate large-scale investment in the methane mitigation industry.[19]

TABLE 5. FEDERAL METHANE LDAR REGULATIONS

JURISDICTION	REGULATORY AGENCY	REGULATION NAME	REGULATION STATUS	SOURCES ADDRESSED	LDAR TESTING FREQUENCY	REQUIRED LDAR TECHNOLOGY	PATHWAY FOR INNOVATIVE TECHNOLOGIES	NOTABLE EXCLUSIONS
Federal (All Lands)	Environmental Protection Agency	Oil and Natural Gas Sector: Emission Standards for New, Reconstructed, and Modified Sources[20]	In effect without methane regulation;[21] under agency review at time of report release	New and modified sources in production and gathering and boosting	Semi-annual for non-low production well sites, gathering and boosting compressor stations	OGI or portable analyzers	Yes, per agency approval; criteria and process provided	Low-production well sites; transmission and storage (exclusions new to Trump amendments)

STATE REGULATIONS

Various states established or improved their own methane LDAR standards while Federal rules were in a state of uncertainty. Leaders like Colorado and California expanded the scope of their regulations to include low-producing sources and the transmission segment, respectively. Pennsylvania took the significant step of proposing a rule for existing sources, while Ohio has started early stakeholder outreach to do the same. Maryland started requiring quarterly LDAR in late 2020 for the gathering and processing and transmission segments, with well sites to follow in a second phase of the rulemaking. And New York has begun the stakeholder outreach process for quarterly LDAR at new and existing sources.

STATE REGULATIONS CAN NOT ONLY PROVIDE AN OPPORTUNITY FOR THE METHANE MITIGATION INDUSTRY TO GROW AND INNOVATE, BUT ALSO TO SERVE AS CASE STUDIES FOR WHAT IS VIABLE ECONOMICALLY AND POLITICALLY AT THE FEDERAL LEVEL.

Most significantly, New Mexico has proposed its first regulation on fugitive emissions in the oil and gas industry. The proposal addresses both new and existing sources and focuses on areas with high reported ozone levels (although proposed exemptions have raised questions about stringency). Equipment leaks are the largest reported source of emissions in the state's oil and gas industry.[22] A summary of the status of state methane LDAR regulations is found in Table 6.

Currently, some states with methane LDAR regulations have included exemptions of some kind — often for low producers, even though the relationship between production levels and total fugitive methane emissions is not necessarily direct, meaning that small producers are still capable of large emissions. In fact, a September 2020 study in Ohio found that "oil and gas wells in this lowest production category emit approximately 11% of total annual CH_4 from oil and gas production in the EPA greenhouse gas inventory, although they produce about 0.2% of oil and 0.4% of gas in the US per year."[23] Exemptions based on good results in previous emissions are another vulnerability, as consistent and frequent inspections are key for catching new leaks.[24]

States can also help improve emissions reductions by allowing the use of alternative technological innovations and providing clear criteria and directions for the approval process. This can in turn reduce compliance costs for operators. Currently, Maryland, New York, New Mexico, and Colorado have such provisions. California has no such provision for most of its regulated facilities but has acknowledged that it may revise its rule in the future to do so.[25] Wyoming, Ohio and Pennsylvania have provisions for alternative monitoring methods, but without a clearly defined approval pathway. Such a pathway will make the regulatory landscape more inviting to investment.

Though a patchwork of LDAR requirements for fugitive methane emissions at the state level cannot substitute for a consistently defined and implemented federal policy, nor ensure the uniform conditions that would encourage large-scale investment, state regulations can not only provide an opportunity for the methane mitigation industry to grow and innovate, but also to serve as case studies for what is viable economically and politically at the federal level.

TABLE 6. STATE METHANE LDAR REGULATIONS

JURISDICTION	REGULATORY AGENCY	REGULATION NAME	REGULATION STATUS	SOURCES ADDRESSED	LDAR TESTING FREQUENCY	REQUIRED LDAR TECHNOLOGY	PATHWAY FOR INNOVATIVE TECHNOLOGIES	NOTABLE EXCLUSIONS
California	California Environmental Protection Agency	GHGs Emission Standards for Crude Oil and Natural Gas Facilities[26]	In effect	New and existing sources	Quarterly	OGI or portable analyzers (must use analyzers at least once)	No	Equipment already under local standards
California	California Public Utilities Commission	Natural Gas Leak Abatement Program	In effect	New and existing sources	Triennial, or more frequent for high-risk equipment	No specific technology required	Yes	
Colorado	Colorado Department of Public Health and Environment	Reg. 7 Control of Ozone via Ozone Precursors and Control of Hydrocarbons via Oil and Gas Emissions[27]	In effect	New and existing sources	Annual, semi-annual, quarterly or monthly based on facility type, output capability and emissions over previous year	OGI or portable analyzers based on facility type, output capability and emissions over previous year	Yes, per agency approval; process and criteria pending	
Maryland	Maryland Department of the Environment	Control of Methane Emissions from the Natural Gas Industry[28]	In effect	New and existing sources	Quarterly	OGI or portable analyzers	Yes, per agency approval; process and criteria pending	Well sites (to be addressed in Phase 2 rule)
New Mexico	New Mexico Environment Department	Oil and Natural Gas Regulation for Ozone Precursors[29]	Preliminary draft released at time of report release	New and existing sources in high-ozone areas	Annual, semi-annual, quarterly or monthly based on emissions potential	OGI or portable analyzers	Yes, per agency approval; process and criteria pending	Low producers and low projected emitters
New York	New York State Department of Environmental Conservation	Oil & Natural Gas Sector Emissions in New York[30]	Early stakeholder outreach in 2018	New and existing sources	Quarterly	OGI, or portable analyzers at a certain threshold level	Yes, per agency approval; process and criteria pending	

TABLE 6. STATE METHANE LDAR REGULATIONS, CONTINUED

JURISDICTION	REGULATORY AGENCY	REGULATION NAME	REGULATION STATUS	SOURCES ADDRESSED	LDAR TESTING FREQUENCY	REQUIRED LDAR TECHNOLOGY	PATHWAY FOR INNOVATIVE TECHNOLOGIES	NOTABLE EXCLUSIONS
Ohio	Ohio Environmental Protection Agency	General Permit 18.1[31]	In effect	New and modified major sources	Quarterly for one year with step-downs if <2% of equipment leaked over previous year	OGI or portable analyzers	No; option for individual has been requested	Conventional well sites, transmission and storage segment
Ohio	Ohio Environmental Protection Agency	New Rules Regulating Emissions from the Oil and Gas Industry[32]	Early stakeholder outreach in 2018	New and existing sources	Quarterly with stepdown for production sites if <2% of equipment leaked over last two inspections	OGI or portable analyzers	TBD	Transmission and storage segments
Pennsylvania	Pennsylvania Department of Environmental Protection	General Permit 5 and 5A[33]	In effect	New and modified sources	Quarterly with stepdown if <2% of equipment leaked over last two inspections	OGI or portable analyzers	Yes, per agency approval; process and criteria pending	Conventional well sites
Pennsylvania	Pennsylvania Department of Environmental Protection	Control of VOC Emissions from Oil and Natural Gas Sources[34]	Rule proposed	New and existing sources	Quarterly with stepdown if <2% of equipment leaked over last two inspections	OGI or portable analyzers	TBD	Transmission segment; low producers
Wyoming	Wyoming Department of Environmental Protection	Air Quality Standards and Regulations Ch. 6 Section 2[35]	In effect	New and modified sources, existing sources in Upper Green River Basin	Semi-annual or quarterly based on area, source type, previous emissions	OGI or portable analyzers, or AVO for existing sources in Upper Green River Basin	Yes, per EPA criteria; process not provided	Conventional sources, transmission and storage segment

JOBS

Reducing methane emissions from the oil and gas industry not only protects the climate and reduces product loss; it also creates jobs. These are good jobs that pay well and offer upward mobility. Many of them require on-site work, so they are not at risk of being offshored.

The manufacturing and service firms described in this study represent a large number of occupations, including engineers, designers, technicians, assemblers, fabricators, and many others (see Table 7 and Table 8). Compared to as recently as five years ago, software and data-related occupations are increasingly prominent, especially in the service firms. This is consistent with a digitalization process underway throughout the oil and gas industry.[37]

TABLE 7. U.S. MEDIAN WAGES OF KEY OCCUPATIONS IN METHANE MITIGATION MANUFACTURING[36]

OCCUPATION	MEDIAN ANNUAL SALARY ($US)
Chemical Engineers	$ 140,960
Electrical Engineers	$ 126,520
Civil Engineers	$ 119,500
Mechanical Engineers	$ 114,520
Software and Web Developers, Programmers, and Testers	$ 109,560
Computer Programmers	$ 108,280
Electronics Engineers, Except Computer	$ 104,110
Environmental Engineers	$ 102,680
Industrial Engineers, Including Health and Safety	$ 101,250
Industrial Engineers	$ 97,570
Occupational Health and Safety Specialists and Technicians	$ 84,740
Commercial and Industrial Designers	$ 82,470
Electrical and Electronic Engineering Technologists and Technicians	$ 73,050
Control and Valve Installers and Repairers	$ 71,510
Engineering Technologists and Technicians, Except Drafters	$ 70,780
Drafters, Engineering Technicians, and Mapping Technicians	$ 68,780
Industrial Machinery Mechanics	$ 68,290
Environmental Engineering Technologists and Technicians	$ 67,210
Industrial Machinery Installation, Repair, and Maintenance Workers	$ 67,020
Installation, Maintenance, and Repair Occupations	$ 64,560
Industrial Engineering Technologists and Technicians	$ 63,070
Drafters	$ 58,210
Assemblers and Fabricators	$ 37,150

TABLE 8. U.S. MEDIAN WAGES OF KEY OCCUPATIONS IN METHANE MITIGATION SERVICES[38]

OCCUPATION	MEDIAN ANNUAL SALARY ($US)
Computer and Information Research Scientists	$ 126,410
Chemical Engineers	$ 110,840
Computer Hardware Engineers	$ 108,140
Health and Safety Engineers	$ 104,740
Atmospheric and Space Scientists	$ 102,060
Electrical and Electronics Engineers	$ 99,800
Electrical Engineers	$ 96,600
Information Security Analysts	$ 95,830
Software and Web Developers, Programmers, and Testers	$ 95,610
Materials Engineers	$ 92,000
Mechanical Engineers	$ 90,560
Environmental Engineers	$ 88,420
Chemists and Materials Scientists	$ 86,810
Computer and Information Analysts	$ 85,290
Commercial and Industrial Designers	$ 84,990
Industrial Engineers	$ 84,700
Computer Systems Analysts	$ 83,640
Computer Programmers	$ 83,060
Geoscientists	$ 82,190
Management Analysts	$ 81,740
Environmental Scientists and Geoscientists	$ 75,240
Web Developers and Digital Interface Designers	$ 74,570
Physical Scientists	$ 71,170
Business and Financial Operations Occupations	$ 66,880
Designers	$ 63,240
Aircraft Mechanics and Service Technicians	$ 60,730
Precision Instrument and Equipment Repairers	$ 60,640
Drafters, Engineering Technicians, and Mapping Technicians	$ 54,290
Calibration Technologists and Technicians	$ 52,820
Computer Support Specialists	$ 52,640
Environmental Engineering Technologists and Technicians	$ 48,800
Environmental Science and Geoscience Technicians	$ 43,160
Installation, Maintenance, and Repair Occupations	$ 40,030
Drone operators	$ 40,000
Assemblers and Fabricators	$ 38,900

GEOGRAPHY

The distribution of jobs that comprise the methane emissions mitigation industry is robust, with at least 748 employee locations spread across 47 states, plus Puerto Rico and the District of Columbia. The only states without employee locations in our 2021 count are Hawaii, Idaho and Mississippi. In total, we identified 210 headquarters, 111 manufacturing/assembly locations, and 473 other employee locations (see map in Figure 8).

FIGURE 8. U.S. EMPLOYEE LOCATIONS OF FIRMS IN METHANE EMISSIONS MITIGATION INDUSTRY

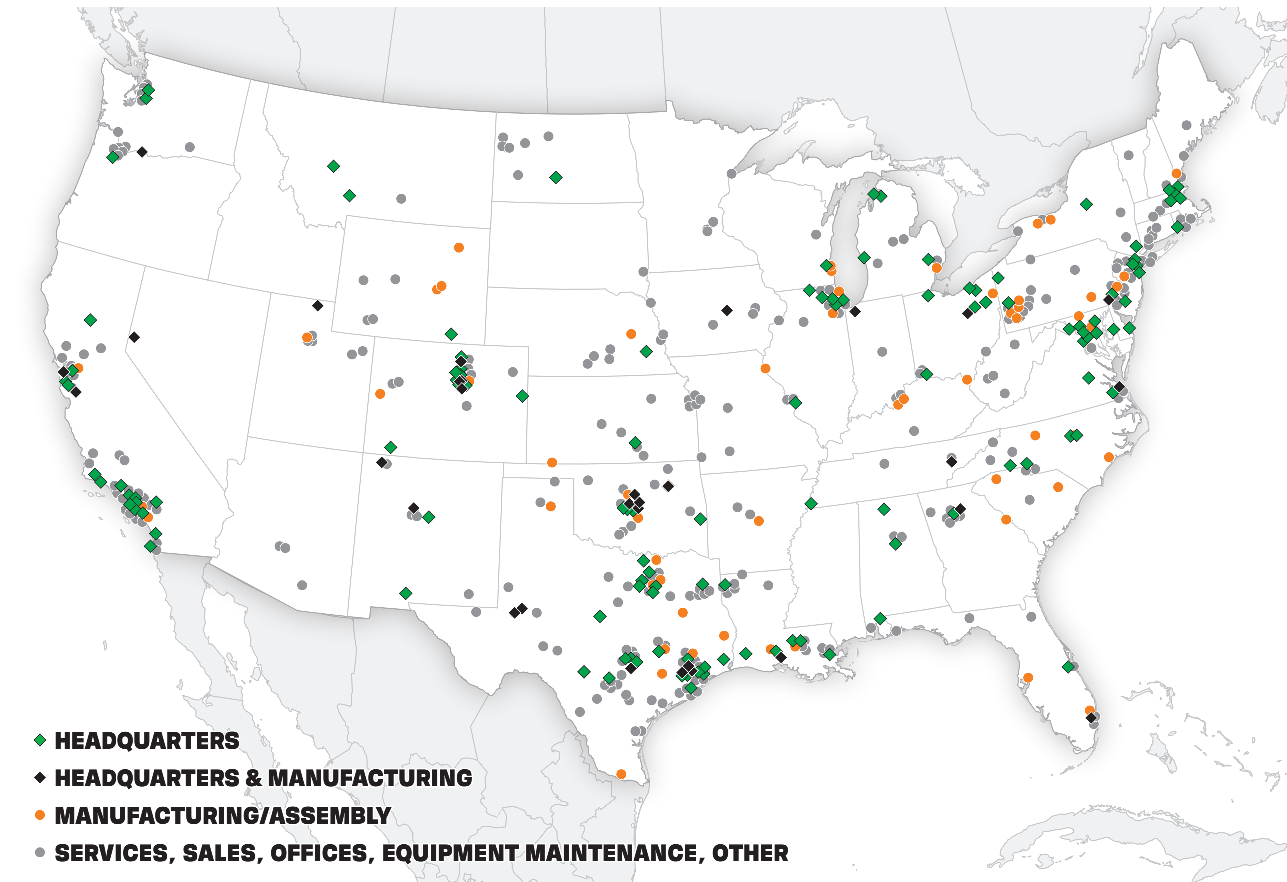
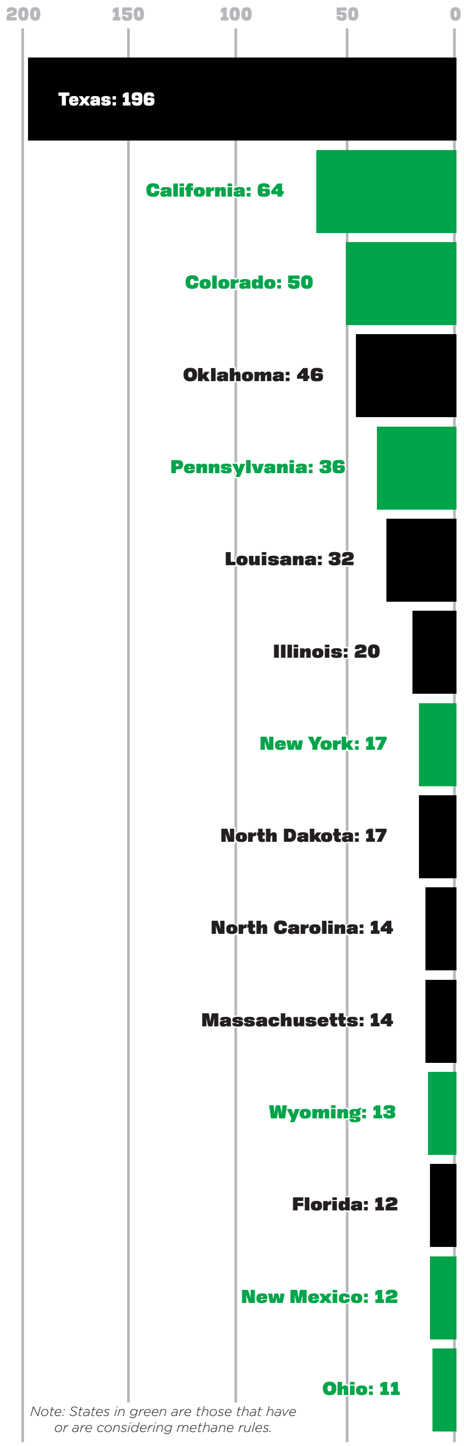


FIGURE 9. TOP 15 STATES IN US EMPLOYEE LOCATIONS, METHANE EMISSIONS MITIGATION, 2021



Unsurprisingly, the heaviest concentrations of employee locations are found in oil and gas-producing states (see Figure 9). Of the 748 locations identified nationwide, 392 of these sites, or 52 percent, are in the five states of Texas, California, Colorado, Oklahoma, and Pennsylvania. One state that has seen especially high growth is California — relevant employee locations in California have grown 167 percent since our previous counts — perhaps an indication of the fast-growing role of data and information technology firms in detecting and measuring methane emissions. Such California-headquartered firms include Kelvin, which uses AI for process control in order to predict future leaks; Orbital Sidekick, which builds and launches hyperspectral imaging satellites; and Planet, which builds satellites and operates a platform that downloads and processes 11+TB of data daily.

Also not surprising is that nearly half of the top 15 states (shown in Figure 9) are states that either have methane rules in place or are considering them. Of the eight such states, seven are in this top-state list, including California, Colorado, Pennsylvania, New York, Wyoming, New Mexico, and Ohio. This would suggest that employee locations are poised to grow if the federal government and/or states roll out new rules on methane emissions.

ANTICIPATED GROWTH

We reached out to all 215 identified firms with a brief survey in which we asked, "Do you feel that future state or federal methane emission rules would likely help grow your company — and if 'yes,' in what ways?" A total of 57 firms responded. Among manufacturing firms, 75 percent (18 out of 24) reported that if future state or federal methane emission rules were put in place, they would anticipate hiring more employees. For service firms, this figure was 88 percent (29 out of 33). Full survey results are found in Figure 10. A sample of comments by surveyed firms that reported anticipating future growth is found in Figure 11.

FIGURE 10. GROWTH ANTICIPATED BY METHANE EMISSIONS MITIGATION FIRMS
Manufacturing Firm Responses: 24 **Service Firm Responses: 33**

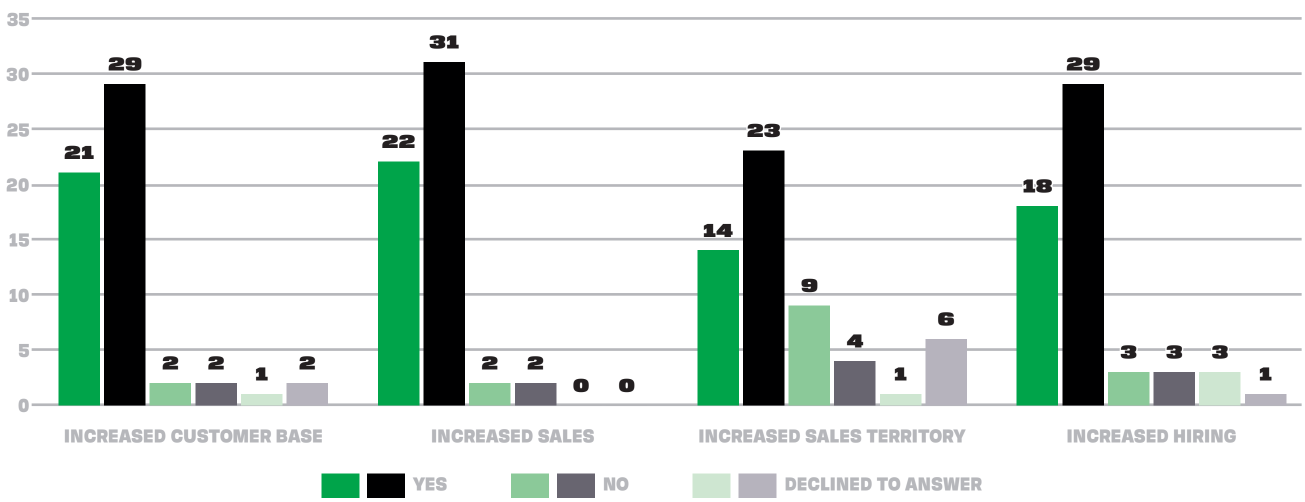


FIGURE 11. COMMENTS ON ANTICIPATED GROWTH, SELECTED METHANE EMISSIONS MITIGATION FIRMS

Yes – we would need to increase our engineering payload, payload operations, analysts/data processing, and flight operations teams.

Also, pressure from investors. Customers seem to be adopting wholesale (faster than anticipated). Currently hiring data positions.

Yes, we already feel the increase and phone calls. We are looking to add as many as 15 to 20 back for patrol and data processing.

With additional methane emissions rules we believe that there will be more companies looking for ways to provide disclosure and transparency. We would plan to hire and grow our teams to meet those needs.

Additional employees: perhaps in the long run depending on what the new rule requirements might be.

It is game on in the US now that methane emission reductions are back on the table. Canadian market is already taking off. Yes, we will more than triple in size if our sales forecasts are correct.

There are thousands upon thousands of valves and controls leaking natural gas today ... We would expand customer base, increase sales and expand our sales territory.

COMPANY PROFILE: LASEN

An extraordinarily sensitive laser technology mounted on a helicopter can survey hundreds of miles of pipeline in a day, detecting even the smallest of leaks.

THE LASEN SYSTEM IS THE ONLY ONE ON THE MARKET THAT WORKS IN THE MID-IR SPECTRAL REGION, A DISTINCTION THAT MAKES IT EXTREMELY SENSITIVE.

LaSen is a leak detection firm that provides precision remote sensing of pipelines using aerial LiDAR survey. Its unique system has detected more than 40,000 leaks along 500,000 miles of pipeline, preventing nearly 45 billion cubic feet of methane from escaping into the atmosphere.

Developed in-house, LaSen's differential absorption LiDAR system sends two laser beams down to the ground — one that's tuned to the methane spectrum, and a reference beam that's not tuned to anything. When the methane-spectrum beam passes through any amount of methane, its power is diminished, so when it bounces back to the sensor, it's much different from the reference beam, indicating the presence of methane. The amount of difference between the two beams is then used to determine the size of the leak.

The LaSen system is the only one on the market that works in the mid-IR spectral region, a distinction that makes it extremely sensitive; it can detect methane concentrations as low as four parts per million. LaSen president Tim Goolsby notes that, while competitors' technology finds only larger leaks, "Ours finds all of them."

BENEFITS TO OPERATORS AND COMMUNITIES

LaSen provides its clients the distinct advantage of much faster inspection than is possible with traditional methods. "Surveying on foot or by vehicle," says Goolsby, "they have issues with access to properties, safety issues, logistics. They can only cover, on a good day, maybe five or six miles of pipeline, where we cover about 400 miles a day." Goolsby notes that this time savings is crucial for managing emissions. "Instead of it leaking for two months while their technicians are out there looking for it, our clients can go straight to getting it fixed."

Along with the leak detection, LaSen's clients also receive photographs and video footage of each inspection flight, giving them a near-real-time view of their right-of-way. These aerial views help an operator identify construction activities that could potentially affect the pipeline. They also help locate fallen or outdated "pipeline markers," required indicators installed along the right-of-way that serve as a warning that a buried pipeline is nearby.

EMPLOYMENT OPPORTUNITIES

Because LaSen develops and manufactures its technologies in-house, it requires a wide range of job types and skill sets. These include a PhD researcher, software engineer, lab technicians, and "jacks of all trade" who can weld, do precision machining, create PCB boards, design laser packages, and do 3-D printing. The 12 pilots and 12 LiDAR sensor technicians fly pipelines seven days a week. One-quarter of the staff are military veterans, and one-quarter are of Hispanic origin.

"From 2017 until now," says Goolsby, "we've doubled the number of employees, revenue, and the number of miles we've inspected." He sees that trend continuing. The company's five-year plan calls for adding another 20 or 30

employees. To handle this growth, they will soon break ground on a new 37,000-square-foot facility with a full machine shop, a dedicated laboratory, and ample office space.

FUTURE DEVELOPMENTS

Innovating continuously to improve leak detection, LaSen plans to keep adding new technologies and services. It is now working to create an "active" pipeline marker. Markers currently in use are not always easy to see. They can fall or get knocked down, and on older pipelines, their recorded locations may be inaccurate. LaSen's marker will be capable of detecting and reporting whether it is up or down; it will have its GPS coordinates encoded in it; and a reflector, small light, and strobes will improve its visibility at night. In the second phase of development, it will include a methane sniffer.

As for new services, the company is adding drones so it can inspect facilities, well pads, and compressor stations, using a third-party methane sensor to pinpoint leaks and an OGI camera to help clients see them on video. Another new service is detecting leaks over water. LaSen is working with Pacific Gas & Electric (PG&E) to test a new drone-mounted sensor that will enable them to inspect all their waterways from the air — an efficient replacement for the current process, which is done by boat.

Perhaps most exciting, LaSen is expanding its footprint beyond the United States. The company recently received its Standard Type Certificate from the Federal Aviation Administration to fly in Canada, the European Union, and Australia.

COMPANY PROFILE: AVITAS SYSTEMS

Thanks to immense data sets collected via drones and continuous monitoring — combined with advanced data techniques such as machine learning and computer vision — operators can identify and mitigate emissions more safely and cost-effectively than ever before.

Avitas is a 100% Baker Hughes-owned company, created in 2017 on the expectation that oil and gas operators can vastly improve their inspection processes by taking a digital approach to what is currently done by hand. Drawing on Baker Hughes' industry expertise and scale, Avitas helps its clients maintain asset integrity, with a strong focus on detecting, localizing and quantifying greenhouse gas emissions.

IT IS PERHAPS THE GROWING NEED FOR CUTTING EDGE, DATA-RELATED SKILLS THAT EXPLAINS WHY AVITAS IS CONSISTENTLY STAFFING UP.

Avitas offers both continuous monitoring and unmanned aerial systems (drones) to detect and characterize emissions. Having invested considerable resources in cyber-physical technology, advanced data analytics, and a powerful cloud-based platform, the company can cover more extensive assets across a wider geography than before. It can also gather data reliably and safely in remote or high-risk locations. Once gathered, the monitoring data is ingested and analyzed using proprietary algorithms and analytics that enable the Avitas team to pinpoint fugitive emission sources and quantify them. The Avitas end-to-end digital approach can continually learn, making future inspections even more accurate.

Jennifer Stewart, Avitas Vice President of Strategic Growth, notes that the company shares all this information gathered by aerial surveys with each client via an easy-to-use, cloud-based platform that provides not only an emissions profile, but also a 3D digital twin of the asset, including a detailed inventory of the componentry. The client can at any time pull up a report that is refreshingly intuitive and actionable. "A lot of companies use tabular data," Stewart says, "but it's our visual analysis that makes it easy to grasp and act on. We can tell them, 'Hey, hatch number five is leaking, see that? Here's the outline of the plume, and here's the quantification.'"

BENEFITS TO OPERATORS

Clients find that Avitas' aerial survey technology enables them to focus their methane emission efforts cost-effectively. Stewart attributes this to the data analytics looking not just backward, but forward. To illustrate: after six months of monitoring a large commercial operation via aerial surveys, the Avitas team identified a clear trend of certain components being the biggest emitters. "So the client then realized, 'I don't need to focus over there, I need to focus right here, because it's where a leak is likely to develop,'" says Stewart.

Another benefit important to clients is timeliness. So, notes Stewart, if you're using continuous monitoring, you can find a leak and fix it very quickly, as opposed to not knowing about it until the next semi-annual inspection.

And, for operators interested in demonstrating they are actively controlling their emissions, the use of continuous monitoring and aerial inspection technologies can demonstrate — to investors, lenders, certifiers, and the general public — that they have a lower-emitting product.

In addition to benefiting its own clients, Avitas seeks to have a significant impact on the oil and gas industry as a whole. The company has developed an Emissions Reduction Potential (ERP) metric, which is used to assess the efficiency of an inspection program; it provides operators the information they need to more quickly reduce their emissions. “That’s what we want to deliver,” says Stewart, “whether or not we’re the one that’s going out there and closing the valve.” The team keeps this big picture in mind as it makes strategic decisions because the industry’s continued viability, access to capital, and public acceptance depend in large part on reducing its greenhouse gas emissions.

EMPLOYMENT OPPORTUNITIES

The company has two technical groups. The engineering group comprises electrical, mechanical, and robotics engineers. The software and analytics group includes data engineers (who extract, collect, and integrate data); data scientists (who analyze the data provided by the data engineers). Among the data scientists are those specializing in computer vision, machine learning, and other artificial intelligence techniques. All have very different skills, and much of the expertise they require for their jobs is evolving rapidly, as new technologies and methods emerge.

It is perhaps this growing need for cutting-edge, data-related skills that explains why Avitas is consistently staffing up. “I manage our LinkedIn site,” says Stewart, “and I keep posting, ‘We’re hiring, we’re hiring. We need data scientists. We need drone pilots. We need program managers.” The company expects to keep expanding its workforce as more and more oil and gas operators recognize the benefits of automating and improving how they manage their physical assets.

FUTURE DEVELOPMENTS

Avitas, and Baker Hughes as a whole, anticipate continuing to serve operators with new and better ways to ensure a smooth and profitable energy transition. IoT devices alone constitute a backbone for communications that has enormous potential for expansion, to monitor and improve nearly any aspect of a facility’s operations. Stewart notes that, as the push for reductions in methane emissions intensifies — not just from policymakers, but also from financial stakeholders and an increasingly vigilant public — more operators will choose to address their fugitive emissions. “I believe,” says Stewart, “that with or without regulation, our industry knows we have to do better.”

COMPANY PROFILE: BAUER COMPRESSORS

For methane mitigation, manufacturers can draw on valuable expertise from outside the oil and gas industry to find ways to reduce gas leaks and to capture gas for use on-site or distribution.

BAUER IS STRONGLY FOCUSED ON DEVELOPING A DIVERSE WORKFORCE, A PRIORITY THAT COMES THROUGH CLEARLY IN THE NUMBERS: THE STAFF IS 48 PERCENT NON-WHITE AND 52 PERCENT WHITE.

Since its founding in Germany in 1946, Bauer has been manufacturing high-pressure compressors for various uses, such as breathing apparatuses for firefighters, divers and others. Bauer compressors are used widely in animal agriculture, at over 200 biogas installations worldwide; they serve transportation fleets in 2,000 installations with compressed natural gas. Today, Bauer is increasingly serving oil and gas operators with cutting-edge application of technologies it pioneered in these other sectors.

As an alternative to venting and flaring, the company's gas recovery units capture well gas and flash gas and compress it into the sales pipeline. Every gas-capture system is equipped with IoT remote telemetry, so clients can control and monitor it from offsite, using computer, mobile phone, or any smart device. Bauer's instrument air systems provide oil and gas operators an alternative to methane-emitting pneumatic devices.

Bauer further benefits its oil and gas customers by providing a patented system for reducing oxygen content in storage tanks to below hazardous levels, an approach that improves safety and reduces gas leaks. Designed to each client's specific tank configuration, the technology uses nitrogen to displace air in the tanks' headspace. By limiting oxygen, it decreases rusting of the tanks and reduces leaks over time — and it keeps tanks safe in the event that lightning hits the location, a relevant risk in thunderstorm-prone regions such as the Permian Basin in Texas.

Among the larger opportunities for methane mitigation is pipeline maintenance. Every interstate pipeline is required to be tested every five years, explains Brice Jones, Vice President of Industrial Sales. If an issue is found, says Jones, you have to pull out that section and fix it. "Instead of venting all that gas to the atmosphere, we can pull it out of the pipeline at very low pressure and store it in high-pressure cylinders, usually mobile units." The client can then either use the gas onsite, or transport it for use or distribution elsewhere, avoiding methane emissions and saving product that would otherwise be lost.

EMPLOYMENT OPPORTUNITIES

Bauer is strongly focused on developing a diverse workforce, a priority that comes through clearly in the numbers: the staff is 48 percent non-white and 52 percent white. The company not only ensures diversity in its hiring practices but also emphasizes a corporate culture that reflects all the communities within its workforce. The diversity inclusion committee, known informally as "Bauer Strong," works to cultivate diverse leadership within the company.

Upward mobility is a priority; it is typical, for instance, for an employee to start as a service tech and within a few years become a customer service manager. The current director of manufacturing began on the line putting together compressors. Employee benefits include not only vacation time and health insurance, but also a hot lunch, on-site doctor, and gym facilities. Perhaps the clearest indicator that Bauer provides good jobs is employee anniversaries. Sales team members stay on average for 20 years. Recently, the company celebrated four people who each have worked at the company for 45 years.

COMPANY PROFILE: QUESTOR

Existing technologies enable operators to eliminate emissions from flaring and venting. The key is to guarantee clean combustion and to put the resulting waste heat to use.

Questor is a public, international cleantech firm with headquarters in Calgary and over 90 percent of its sales in the United States. President and CEO Audrey Mascarenhas says that since its founding in 1995, the company has relied on innovation and holistic thinking to help the oil and gas industry become more sustainable.

A chemical engineer who has worked in oil and gas in production, operations, joint venture, facilities, and corporate development, Mascarenhas noticed early on that most flares she encountered were "black and smoky," belying the industry's standard assumption that flares burn at 98 percent efficiency. "Research shows it's as low as 60 percent," says Mascarenhas. "And many flares don't even stay lit, so they vent 100 percent into the atmosphere."

IMPROVING FLARE COMBUSTION AND USING THE RESULTING WASTE HEAT

In 2020, Questor became the first company in North America to receive ISO 14034 Environmental Technology Verification, and the first one in the world to receive it for combustion efficiency. Questor's thermal oxidizer combusts gas in an enclosed chamber with no smoke, no odor, and no visible flame — at an efficiency of 99.99%.

This combustion process results in a clean stream of hot exit gases, which, if an operator chooses, can then be used to provide process heat, generate power, or purify wastewater. Questor's power generators transform high- and low-temperature heat into electricity that can be used on-site or sent to a power grid. Once the heat is extracted, the CO_2 can be easily captured from the stack. This arrangement enables clients to get to net-zero, or even net-negative, while also protecting communities from harmful pollutants.

ELIMINATING VENTING DURING MAINTENANCE

Inefficient flares aren't the only huge opportunity to reduce methane emissions, says Mascarenhas. Also neglected are the industry's frequent blowdowns, completions, and pipeline maintenance — activities that can easily become super emitters. "We've got thousands and thousands of engine-compressor combinations," notes Mascarenhas. "Just like your car, after so many hours, they need to be overhauled. And what are we doing? We're venting the entire stream at over 1,000 pounds pressure."

Instead of venting during such tasks, clients can turn to Questor's 120-unit rental fleet of 99.99-percent-efficiency combustors. Each unit is designed with no fans, blowers or moving parts. It arrives on a patented trailer and sets up in 10 minutes, ready to go, easy to move. The units seldom need maintenance; some have been in operation for 20 years and have hardly been touched. Clients use them for pipeline work, coil tubing jobs, well tests, and green completions, all with impressive results. So much so, in fact, that Dominion Energy, a utility provider in 16 states, wrote Questor's technology into its specifications.

BENEFITS TO OPERATORS AND COMMUNITIES

Steps to address venting and flaring take on greater urgency as communities increasingly voice their concerns about health, safety and the environment. One such concern is blowouts, especially at sites near residential neighborhoods. Questor's equipment has been on jobs where a well blew out and only the combustor people knew — because there was drilling mud in the unit. If that had happened with an open flare instead, the burst of mud, liquids and gases could have put the community at risk.

Clients also benefit in other ways by achieving zero methane hydrocarbon emissions. Regulators in Colorado and North Dakota now allow operators to assume that their Questor units achieve 100-percent efficiency, bringing the well-pad site below VOC limits. This is important to operators because it gives them permission to increase oil production under Title V of the Clean Air Act — welcome news for the operator and a win for the community.

Mascarenhas notes that clients seldom calculate the money saved through clean combustion; nor do they make a fair comparison with flaring. "They overlook the fact that you've got to space flares far away, you've got to have a bigger lease, you've got

to have a high-pressure flare and a low-pressure flare. Our one unit does both." To illustrate, at a typical site in Colorado, a client used to have 30 or 40 small combustors and 30 to 40 small vapor recovery units. By eliminating all of those, the Questor technology reduced the size of the lease by 30 percent and reduced the well-pad cost by 20 percent.

EMPLOYMENT OPPORTUNITIES

Questor is rapidly creating US jobs. The company was identified by SelectUSA, a US Department of Commerce program that searches for promising international firms with potential to create employment in the United States. In 2017, SelectUSA called Questor a success story for creating such jobs, an honor it has continued to earn. In fact, even this past year, despite the COVID-19 pandemic, the company has expanded its staff by 30 percent.

STEPS TO ADDRESS VENTING AND FLARING TAKE ON GREATER URGENCY AS COMMUNITIES INCREASINGLY VOICE THEIR CONCERNS ABOUT HEALTH, SAFETY AND THE ENVIRONMENT.

The company is remarkable for its diversity, with personnel from all over the world serving in engineering, management, technical sales, maintenance, accounting, and administration. A corporation whose president and CEO is a woman of color, Questor reports that 30 percent of its staff are women (compared with 15 percent across the oil and gas industry as a whole). "In this space, you need to be diverse, Mascarenhas explains. "Because you need to be innovative, you need to think on your feet, you need to shift, to persevere, and be resilient."

FUTURE DEVELOPMENTS

What is next for Questor? Mascarenhas envisions further innovations to help clients get to net-zero. Viewed from a whole-system perspective, she says, flaring is not just a problem, but an opportunity. She would like to turn the industry's attention to the vast potential for solving super emitters like flowbacks and completions and lack of pipeline takeaway capacity. These could be the biggest wins, especially if combined with waste heat to power. "We don't have to wait till 2050 to reach net zero. We can actually be there right now."

COMPANY PROFILE: SLR INTERNATIONAL

Climate change is altering the whole landscape of hydrocarbon energy, and many oil and gas operators need expert help in forging new paths to success.

SLR International is a traditional environmental consulting firm with deep expertise across seven key industry sectors, including a large practice in the oil and gas industry. Founded in 1994 in the U.K. as SECOR Ltd., the company now operates in five global regions. It changed its name to SLR in 2000, when U.S. operations opened.

Today, SLR helps its oil and gas clients set ESG goals and achieve them. As investors, regulators and the general public increasingly demand that operators commit to address climate change, a growing part of SLR's strategic advisory focuses on helping oil and gas operators reduce their methane emissions.

An important niche for SLR consists of mid-size operators that are now realizing they need to get onboard with what several of the major oil and gas companies have embraced: achieving net-zero greenhouse gas emissions by 2050. Unlike the BPs and Shells of the industry — which have internal staff devoted to planning for a net-zero future — some mid-size operators need professional advisory services. What is an ambitious, yet feasible, goal? What are the intermediate steps? Today, there is enough pressure coming from shareholders and stakeholders that many more companies — including those that are not necessarily in the public spotlight — are asking for SLR's help navigating complex choices so they can make informed decisions.

BENEFITS TO OPERATORS

SLR is particularly suited to helping clients keep up with rapidly changing technology, notes Tim Quarles, U.S. Air Program Manager. "We draw on a breadth of experience on the engineering side, and we take every opportunity to team with cutting-edge researchers, whether in field measurement, national studies, or pilots of new technologies." Matt Harrison, Senior Principal, agrees, adding that SLR enables its clients to benefit in a timely way from the newest developments. "Things are changing so fast," says Harrison, "if you take a week vacation, you've missed three critical papers that came out. Clients want help putting their arms around the quickly changing landscape of measurements, mitigations, and standards."

Detailed technical strategies to reduce methane emissions create value for SLR clients. For instance, when operators realize that periodic snapshots of fugitive emissions are not adequate, Harrison's team can help them find and test suitable ways to perform alternate monitoring or continuous monitoring, and do it affordably. But perhaps even greater value lies in helping clients design their overall climate strategies. "So you could say we're not only helping operators today," he notes. "We're also, in the big picture, helping them maintain the confidence of their stakeholders, investors and the general public, extending their social license to operate."

SLR IS PARTICULARLY SUITED TO HELPING CLIENTS KEEP UP WITH RAPIDLY CHANGING TECHNOLOGY.

EMPLOYMENT OPPORTUNITIES

SLR consistently hires scientists and engineers as well as positions in design, accounting, management, and administrative roles. Because of SLR's focus on research, the staff includes a number of graduate scientists. As with other environmental consulting firms, SLR finds it a continuing challenge to find talented candidates capable of embracing the oil and gas industry's increasingly high-level, complicated issues. Yet Harrison is seeing an encouraging trend at the universities it partners with on research projects. "What's interesting to me is the growing number of newly minted PhDs that I see coming on with a methane specialty," he says. "If you looked back even a few years ago, we didn't have anything like that."

FUTURE DEVELOPMENTS

Methane is a large growth opportunity, and the role of data is huge. Quarles notes that the public is demanding more and more data in real time. "We have more information on what is really happening, and there's more pressure for oil and gas operators to reduce their greenhouse gas emissions, so we are in a constant growth mode."

How can one company solve the large issues at stake? It can't, says Harrison. It's bigger than that, which is why SLR works hard to support the science, participate in research, and think collaboratively on the coming energy transition. "We are doing things in partnerships that couldn't be done just with one company or one institution."

COMPANY PROFILE: BALL AEROSPACE

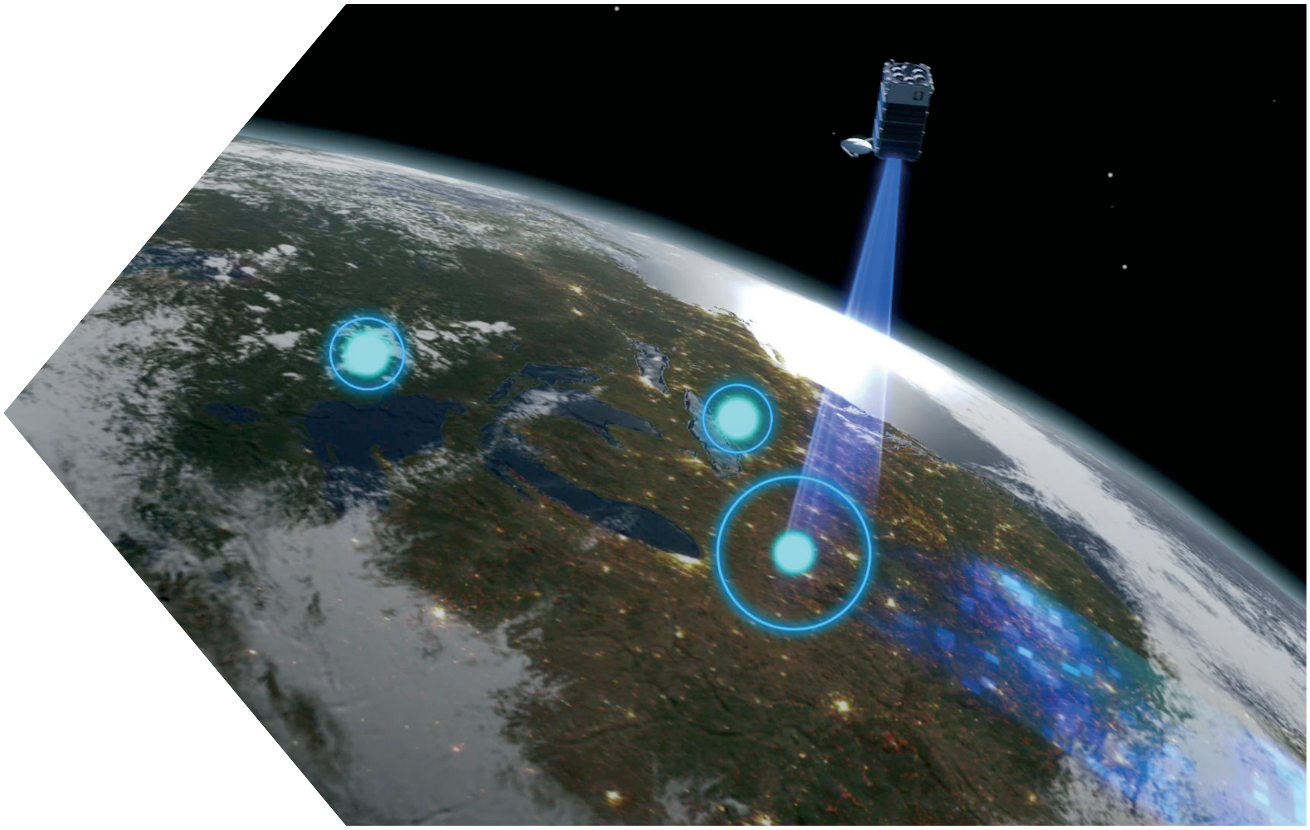
Drawing on NASA-mission expertise, an aerospace firm is building a remote sensing technology that will detect and measure methane emissions across the globe, doing so with unprecedented coverage and precision.

In 2018, the Environmental Defense Fund surprised a TED Talk audience by unveiling an ambitious undertaking: a new satellite that will locate and quantify sources of methane pollution worldwide. Data gathered by the mission, called MethaneSAT, will enable humanity to make the interventions needed to cut global methane emissions by 45 percent by 2025.

Dr. Makenzie Lystrup, an astrophysicist at Ball Aerospace & Technologies Corp., remembers being intrigued by the project's urgency.

"Space is not easy," she said. "You don't go there to measure something unless you have to."

Lystrup serves as Ball Aerospace's VP and General Manager of Civil Space. A wholly-owned subsidiary of Ball Corporation (a leading sustainable packaging company specializing in an infinitely recyclable material, aluminum), Ball Aerospace manufactures spacecraft, defense technologies, and instruments for scientific research. It has a long track record of performing remote sensing—of the Earth, of other planets, and bodies beyond our solar system.



After a 10-month competitive process, Ball Aerospace won a contract from MethaneSAT LLC, a newly-created branch of EDF. Lystrup's team set out to develop MethaneSAT's imaging spectrometer, the instrument that would identify and measure methane emissions across the planet.

GLOBAL COVERAGE, GREATER ACCURACY

Methane and other gases emit and absorb light at very specific wavelengths, what's known as their spectral signature. The MethaneSAT spectrometer will use the spectral signatures of methane and oxygen. Taking these two measurements simultaneously, on the same focal plane, generates a rich stream of data. This information, when combined with atmospheric data, will enable scientists to create a detailed global map of methane emissions and their sources.

MethaneSAT is a unique endeavor, says Lystrup. But Ball Aerospace is no stranger to complex, envelope-pushing challenges. She cites the company's work on the Hubble Telescope as an example. "When you think of a telescope, really, it's remote sensing. You're looking out, characterizing the light, looking for those spectral signatures, and then trying to understand the physics from them. With MethaneSAT, we're just looking for a different phenomenon."

Even within the realm of targeted methane-sensing efforts, MethaneSAT can do things no other satellite can. First, while other satellites can either detect emissions across large geographic areas or measure them at specific locations, MethaneSAT will do both. Second, it will do so with extraordinary precision (the Ball Aerospace instrument can pick up a methane concentration as low as three parts per billion), including large point sources as well as cumulative emissions from thousands of smaller sources across the globe. Third, the information it collects will be public and free, enabling citizens, government, and corporations to take action.

MEANINGFUL IMPACT

For nearly all of Ball Aerospace's 65-year history, it has been engaged in monitoring Earth. Increasingly, the company's clients are seeking to understand ways in which the planet is changing. These include record-breaking weather events such as hurricanes, floods, droughts, and heat waves—disasters that have profound effects on people's lives.

Everyone wants to do work that is meaningful, Lystrup notes, and methane presents an extraordinary opportunity to alter the course of climate change. "The team is really engaged. It's exciting to work on something that matters to people, and that has potential for real positive impact."

WHAT'S NEXT?

Does Ball Aerospace see more projects like MethaneSAT in its future? Hard to say, says Lystrup. As a private, non-profit venture, this one is unlike any of the company's numerous government and corporate clients.

At the same time, more and more decision makers are realizing that addressing climate change within our lifetime will require us to cut methane emissions. The first step is knowing where the sources are. Since the data from MethaneSAT will be free to the public, there will certainly be more opportunities to do so.

APPENDIX: 215 FIRMS IN THE U.S. METHANE EMISSIONS MITIGATION INDUSTRY

101 MANUFACTURING FIRMS

MANUFACTURING FIRM	FIRST YEAR	INDUSTRY CATEGORY	RELEVANT TECHNOLOGIES	EMPLOYEES RANGE	SALES RANGE (MILLIONS)	U.S. EMPLOYEE LOCATIONS (HQ APPEARS FIRST)
ABB Group*	1988	DMR, ADA	CR, FS, UAV, A, S	10,001+	$10,000+	NC, CA, OH, OK, PA, TX
A. W. Chesterton	1884	M	RPS, V	1,001-5,000	$501-$1,000	MA, GA, IL, LA, TX, WV
Advantage Midstream	2017	M	FM, GC	1-500	1-$38.5	TX
AESSEAL	1979	M	RPS	1,001-5,000	1-$38.5	TN, CA, IA, ME, WA
Ametek	1930	DMR, M	CR, APD	10,001+	$1,001-$10,001	PA
Baker Hughes*	1987	DMR, M, ADA	LDAR, OGI, CR, FS, MGL, UAV, RPS, V, APD, REC, PLVT, FM, GC	10,001+	$10,000+	TX, CA, CO, KS, LA, MA, MI, OK
Ball Corporation*	1880	DMR, ADA	A, S	10,001+	$10,000+	CO
Bauer Compressors	1946	M	RPS, VRU, GC	1-500	$38.6-$500	VA, CA
Bray	1986	M	V, APD	501-1,000	$501-$1,000	TX, AL, CA, IL, LA
Calscan	1995	DMR, M	FS, V, APD	1-500	1-$38.5	TX
Calvert Energy	2014	M	GC	1-500	1-$38.5	MD
Capstone Turbines	1988	M	GC	1-500	$38.6-$500	CA
Certarus	2012	M	GC	1-500	1-$38.5	TX, CO
CI Systems	1977	DMR	OGI	51-200	$15-$50	TX
Cimarron Energy*	1984	DMR, M	LDAR, OGI, FS, PLVT, VRU	1-500	$38.6-$500	TX, CO, KY, OH, OK
Circor Energy	1999	M	V, APD	1,001-5,000	$501-$1,000	MA, FL, KY, NC, NY, TX, UT
Clarke Valve	2011	M	V	1-500	1-$38.5	RI
ComAp	1991	M	GC	1-500	$38.6-$500	IL
COMM Engineering USA	1991	M	VRU, FM	1-500	1-$38.5	LA, CO, OK, TX
Compressor Engineering Corporation	1964	DMR, M	CR, RPS	1-500	1-$38.5	TX, AL, LA
Compressor Products International	1897	M	V	501-1,000	$38.6-$500	TX
Cook Compression	1888	DMR, M	CR, FS, RPS	1-500	1-$38.5	TX, CA, CO, IN, LA, OK, TN
CORKEN	1924	M	VRU	1-500	1-$38.5	OK
Crusoe Energy*	2018	SC, M	FM, GC	1-500	1-$38.5	CO

KEY TO RELEVANT TECHNOLOGIES

LDAR: Leak Detection & Repair | **MGL:** Mobile Ground Labs | **RPS:** Rod Packing & Dry Seals | **PLVT:** Plunger Lifts/Velocity Tubing | **OGI:** Optical Gas Imaging **UAV:** Unmanned Aerial Vehicles

V: Low-emission Valves | **VRU:** Vapor Recovery Units **CR:** Non-OGI Close Range | **A:** Aircraft **APD:** Alternatives to Pneumatics **FM:** Flare Mitigation | **FS:** Fixed Sensors

S: Satellites | **REC:** Reduced Emission Completions **GC:** Gas Capture For Use Or Distribution

** Firm offers relevant manufacturing and relevant services.*

MANUFACTURING FIRM	FIRST YEAR	INDUSTRY CATEGORY	RELEVANT TECHNOLOGIES	EMPLOYEES RANGE	SALES RANGE (MILLIONS)	U.S. EMPLOYEE LOCATIONS (HQ APPEARS FIRST)
Curtiss-Wright	1990	M	APD	1-500	1-$38.5	MN, NC
Custom Compression Systems	2010	M	VRU	1-500	1-$38.5	LA
Dresser Natural Gas Solutions	1879	M	APD	501-1,000	$38.6-$500	TX, PA
EagleBurgmann	1977	M	RPS	1-500	$1,001-$10,000	TX, CA, LA, MI, NC, NJ, OH
ECOTEC	2015	DMR	CR, FS, MGL	1-500	1-$38.5	CA
EcoVapor Recovery Systems	2010	M	VRU, FM, GC	1-500	1-$38.5	CO, TX
ElectraTherm	2005	M	FM, GC	1-500	1-$38.5	GA
Emerson	1890	DMR, M, ADA	OGI, CR, FS, RPS, V, APD, VRU	10,001+	$10,000+	MO, AK, FL, GA, IA, LA, MN, NC, NJ, NM, TX, WA, WI
Endurance Lift Systems	2014	M	PLVT	1-500	1-$38.5	TX, AR, CO, ND, NM, PA, TX, WY
Engineered Concepts	1959	M	VRU, GC	1-500	<$38.5	NM
Enovation Controls	2009	M	APD	1-500	$38.6-$500	OK, TX
Exterran	2007	M	VRU, GC	1,001-5,000	$501-$1,000	TX, CO, OK, PA
FCI-Fluid Components International	1964	DMR	CR, FS	1-500	$38.6-$500	CA
Flex Energy Solutions	2011	M	APD, VRU, FM, GC	1-500	$38.6-$500	CO, ND, NY, TX
FLIR Systems	1978	DMR	OGI, CR, FS, MGL, UAV	1,001-5,000	$1,001-$10,000	OR, CA, MA, MD, NH, VA
Flogistix*	1996	DMR, M	LDAR, OGI, CR, FS, UAV, VRU	1-500	$38.6-$500	OK, NM, TX, WY
Flowserve	1997	M	RPS, V, APD, VRU	10,001+	$1,001-$10,000	TX, KY, MD, NC, PA, SC, VA, WV
FLSmidth	1882	M	V, VRU	10,001+	$1,001-$10,000	PA, GA, UT
Galileo Technologies	1987	M	GC	1-500	1-$38.5	CA, NJ
Gardner Denver	1859	M	RPS	5,001-10,000	$1,001-$10,000	WI, AL, CA, CT, IL, LA, MO, ND, OK, PA, TX, WA
Garlock	1887	M	RPS, V, APD	1-500	$38.6-$500	TX, NY
GasTechno Energy & Fuels	2004	M	FM, GC	1-500	1-$38.5	MI
Generon	2006	M	VRU	501-1,000	$38.6-$500	TX, CA
GTUIT	2011	M	FM, GC	1-500	1-$38.5	MT, ND, TX
Hoerbiger	1895	M	RPS, V	501-1,000	$1,001-$10,000	FL, CA, IL, KS, LA, OH, OK, TX, WY
Honeywell*	1906	DMR	OGI, CR, FS	5,001-10,000	$1,001-$10,000	NC, GA, NJ, PA, SC, WA
Hycomp	1986	M	RPS	1-500	1-$38.5	UT

101 MANUFACTURING FIRMS, CONTINUED

MANUFACTURING FIRM	FIRST YEAR	INDUSTRY CATEGORY	RELEVANT TECHNOLOGIES	EMPLOYEES RANGE	SALES RANGE (MILLIONS)	U.S. EMPLOYEE LOCATIONS (HQ APPEARS FIRST)
ICI Infrared Cameras Inc	1995	DMR	OGI	1-500	1-$38.5	TX
InstrumentAir	2007	M	APD	1-500	1-$38.5	CO
John Crane	1917	M	RPS	5,001-10,000	$1,001-$10,000	IL, AK, AL, CA, CO, GA, IA, IL, IN, KS, LA, MI, MN, MO, ND, NE, NJ, NY, OK, OR, PA, RI, TX, UT, WI
Kaydon Ring & Seal	1986	M	RPS			MD
Kimray	1948	M	V, APD, GC	1-500	$38.6-$500	OK, PA, TX
KUVA	2015	DMR	OGI, FS, MGL	1-500	1-$38.5	MA
Mesa Natural Gas Solutions	2014	M	FM	1-500	$15-$50	CO, WY
Microdrones GmbH	2005	DMR, SC	CR, UAV	1-500	1-$38.5	NY, GA
MSA	1914	DMR	CR, FS	1,001-5,000	$1,001-$10,000	PA, CA, IL, NC, TX
National Oilwell Varco	1841	M	APD, PLVT, VRU	10,001+	$1,001-$10,000	TX, ND, OK
NevadaNano	2004	DMR	FS	1-500	1-$38.5	NV
Neway Valve	1997	M	V, APD	1,001-5,000	$38.6-$500	TX
Norriseal	1981	M	V, APD	1-500	1-$38.5	TX, LA, OK
Orbital Sidekick*	2016	DMR, ADA	S	0-50	$0-$15	CA
Pacific Advanced Technology	1988	DMR	OGI	1-500	1-$38.5	CA
PCS Ferguson	1985	M	PLVT	1-500	1-$38.5	CO, LA, NM, OK, PA, TX, UT, WY
Petrogas Environmental Systems	1975	M	VRU, GC	1-500	1-$38.5	TX
Pioneer Energy	2006	M	FM, GC	1-500	1-$38.5	CO
Planet*	2010	ADA	S	201-1,000	$51-$500	CA
Platinum Vapor Control	2012	M	VRU	1-500	1-$38.5	TX, NM
Primus Green Energy		M	FM, GC	1-500	1-$38.5	TX, NJ
Production Lift Systems	1989	M	PLVT	1-500	1-$38.5	TX
PSG Blackmer		M	VRU	1,001-5,000	$38.6-$500	IL, CA, CO, MI, PA, VA

KEY TO RELEVANT TECHNOLOGIES

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Questor Technology*	1995	SC, M	VRU	0-50	$0-$15	TX, CO, FL, ND, PA
Quincy Compressor	1920	M	RPS, VRU	1-500	$38.6-$500	AL, CT, MA, NJ, NY, PA
Remediation Service International		M	VRU, FM	1-500	1-$38.5	CA
Rotork	1957	M	APD	1,001-5,000	$501-$1,000	NC, CA, NY, PA, RI, TX, WI
SAFCell	2009	M	APD	1-500	1-$38.5	CA
Schlumberger*	1926	DMR, M, ADA	LDAR, CR, V, APD	10,001+	$10,000+	TX, AR, OK
SeekOps*	2017	DMR	LDAR, CR, UAV	1-500	1-$38.5	TX, CA
Sensit	1980	DMR	CR, FS, MGL	51-200	$15-$50	IN
Shore Pipeline Solutions	2020	M	GC	1-500	1-$38.5	MD
Siemens Energy	1847	M	RPS, APD	10,001+	$10,000+	DC
Sierra-Olympic Technologies	1995	DMR	OGI	1-500	1-$38.5	OR
Solar Injection Systems	1992	M	APD	1-500	1-$38.5	TX
Solar Turbines	1927	M	APD, FM	1,001-5,000	$1,001-$10,000	CA, FL, IL, LA, NJ, PA, TX, UT
Stewart & Stevenson	1902	M	APD	1-500	$38.6-$500	TX, CO, WY
Swagelok	1947	M	V, APD	5,001-10,000	$1,001-$10,000	OH, AK, CA, KS, OR, TX, WA
TCI USA	1988	M	FM	1-500	1-$38.5	CO
Tech Tool Ohio	1990	M	PLVT	1-500	1-$38.5	OH
TechnipFMC	2015	M	RPS, V, APD, REC	10,001+	$10,000+	TX, AK, CA, CO, LA, ND, OK, PA, TX, UT, WY
Tenaris	2001	M	PLVT	10,001+	$1,001-$10,000	TX, OK, PA
Tescorp	1987	M	VRU	1-500	1-$38.5	OK
TPE Midstream	2014	DMR, M	CR, FM	1-500	1-$38.5	OK
TXAM Pumps	1986	M	APD	1-500	1-$38.5	TX, AR, CO, ND, NM, OK, TX, WV, WY
Weatherford	1992	M	APD, PLVT	501-1,000	$38.6-$500	TX, CA, LA, OK, PA, UT, WY
Well Master	1984	M	PLVT	1-500	1-$38.5	CO, NM, TX
Whirlwind Methane Recovery Systems	2007	M	APD, VRU, FM	1-500	1-$38.5	OK
Zahroof Valves	2019	M	V	1-500	1-$38.5	TX
Zeeco	1979	M	VRU, FM, GC	1,001-5,000	$38.6-$500	OK, CT, KS, KY, TX

114 SERVICE FIRMS

SERVICE FIRM	FIRST YEAR	INDUSTRY CATEGORY	RELEVANT TECHNOLOGIES	EMPLOYEES RANGE	SALES RANGE (MILLIONS)	U.S. EMPLOYEE LOCATIONS (HQ APPEARS FIRST)
A.R.T. Aviation Services	2010	DMR	LDAR, CR, A	0-50	$0-$15	
ABB Group*	1988	DMR, ADA	CR, FS, UAV, A, S	10,001+	$10,000+	NC, CA, OH, OK, PA, TX
AECOM	1990	DMR, SA		10,001+	$10,000+	CA
Aerial Production Services	2014	DMR	LDAR, OGI, UAV	0-50	$0-$15	MD
Alliance Emission Monitoring	2020	DMR, SA	LDAR	51-200	$15-$50	AL, CA, TX
Altamira	1994	DMR	LDAR, OGI	51-200	$15-$50	OK, TX
American Aerospace Advisors	2002	DMR, ADA	UAV	0-50	$0-$15	PA
Amerigo	2012	DMR	LDAR, OGI	0-50	$0-$15	TX
AmeriTek Environmental Services	1999	DMR	LDAR, OGI, CR	51-200	$0-$15	TX
Antares Technology Solutions	1988	DMR, ADA		0-50	$0-$15	LA
Apex Companies	1988	DMR	LDAR, OGI, CR, UAV	201-1,000	$51-$500	MD
Apogee Scientific	1993	DMR	LDAR, CR, A	0-50	$0-$15	CO
Aster Global	2019	SA		0-50	$0-$15	OH
Atlas Technical Consultants	2006	DMR	LDAR, OGI, CR	51-200	$15-$50	TX
Atmosfir Optics	2011	DMR	LDAR, CR, FS	0-50	$0-$15	NC
Atmospheric Corrosion Specialists	2003	DMR	LDAR, CR, UAV	0-50	$0-$15	VA
Avitas	2017	DMR, ADA	LDAR, OGI, UAV	0-50		TX, CA, MA
Baker Consulting	2010	DMR	LDAR, OGI	51-200	$15-$50	ND
Baker Hughes Company*	1987	DMR, ADA, M	LDAR, OGI, CR, FS, MGL, UAV, RPS, V, APD, REC, PLVT, FM, GC	10,001+	$10,000+	TX, CA, CO, KS, LA, MA, MI, OK
Ball Corporation*	1880	DMR, ADA	A, S	10,001+	$10,000+	CO
Beacon Energy Services	2008	DMR	LDAR, OGI, CR	51-200	$15-$50	CA, UT

KEY TO RELEVANT TECHNOLOGIES

LDAR: Leak Detection & Repair | **MGL:** Mobile Ground Labs | **OGI:** Optical Gas Imaging | **UAV:** Unmanned Aerial Vehicles | **CR:** Non-OGI Close Range **A:** Aircraft | **FS:** Fixed Sensors | **S:** Satellites

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SERVICE FIRM	FIRST YEAR	INDUSTRY CATEGORY	RELEVANT TECHNOLOGIES	EMPLOYEES RANGE	SALES RANGE (MILLIONS)	U.S. EMPLOYEE LOCATIONS (HQ APPEARS FIRST)
Belmont Technology	2017	DMR, ADA		0-50	$0-$15	TX
Bison Engineering	1980	DMR	LDAR, OGI	0-50	$0-$15	MT, AZ
Bluefield Technologies	2017	DMR, ADA	S	0-50	$0-$15	NY, CA
Bridger Photonics	2006	DMR, ADA	LDAR, CR, UAV, A	51-200	$15-$50	MT
Business Technical Services	2010	DMR	LDAR, CR	0-50	$0-$15	OH
C3.ai	2009	DMR, ADA		51-200	$15-$50	CA, NY
Cameron-Cole	2001	SA	OGI, CR	51-200	$15-$50	CO, CA, FL, MA, TN
Cegal	2000	DMR, ADA		201-1,000	$51-$500	TX
Chem-Air	1973	DMR	A	0-50	$0-$15	LA
Chesapeake Bay Helicopters	1998	DMR	LDAR, CR, A	0-50	$0-$15	VA
Cimarron Energy*	1984	DMR, M	LDAR, OGI, FS, PLVT, VRU	1-500	$38.6-$500	TX, CO, KY, OH, OK
Colorado Heli-ops	2009	DMR	LDAR, CR, A,	0-50	$0-$15	CO
Corridor Field Services	2016	DMR	LDAR, OGI, UAV	0-50	$0-$15	AL
Crusoe Energy*	2018	SA, M	FM, GC	1-500	1-$38.5	CO
Custom Stack Analysis	1965	DMR	LDAR, CR, FM	0-50	$0-$15	OH, IL, NY, PR, SC
Cyberhawk	2008	DMR	LDAR, UAV	51-200	$15-$50	CO, TX
Dan Fitzgerald & Associates	1979	DMR	LDAR, CR, MGL	0-50	$0-$15	CA, IA, SD
Darbonne Services	1983	DMR	LDAR, OGI, CR	0-50	$0-$15	LA
Dataiku	2013	DMR, ADA		201-1,000	$51-$500	NY
DeNovo Global Technologies	2007	DMR	LDAR, CR	0-50	$0-$15	TX
DG Consulting	2014	DMR	OGI, CR	0-50	$0-$15	WV
EcoTest Energy Services	2014	DMR	LDAR, OGI, CR	0-50	$0-$15	OK, PA, TX
Emission Monitoring Service	1986	DMR	LDAR, OGI, CR	201-1,000	$51-$500	TX
ENCOS	1994	DMR	LDAR, OGI, CR	0-50	$0-$15	LA
Environmental Compliance & Testing	2014	DMR	LDAR, OGI, CR	0-50	$0-$15	TN
ERM	1971	DMR, SA	LDAR, OGI	5,001-10,000	$501-$1,000	CA

114 SERVICE FIRMS, CONTINUED

SERVICE FIRM	FIRST YEAR	INDUSTRY CATEGORY	RELEVANT TECHNOLOGIES	EMPLOYEES RANGE	SALES RANGE (MILLIONS)	U.S. EMPLOYEE LOCATIONS (HQ APPEARS FIRST)
Flogistix, LP*	1996	DMR, M	LDAR, OGI, CR, FS, UAV, VRU	1-500	$38.6-$500	OK, NM, TX, WY
Gas Detection Services	2017	DMR	LDAR, CR, MGL, UAV, A	0-50	$0-$15	CO
Gas Ops Leak Detectives	2014	DMR	LDAR, OGI, CR	0-50	$0-$15	CO
Gas Technology Institute	1941	DMR, M	APD	201-1,000	$51-$500	IL, CA, DC, TX
GHD	1928	DMR, SA	LDAR, OGI, CR	10,001+	$1,001-$10,000	NM
Heath Consultants	1933	DMR	LDAR, OGI, CR, FS, MGL, UAV	1,001-5,000	$501-$1,000	TX, AZ, PA
Honeywell*	1906	DMR	OGI, CR, FS	5,001-10,000	$1,001-$10,000	NC, GA, NJ, PA, SC, WA
Huco Consulting	2008	DMR		0-50	$0-$15	TX
HydroChemPSC	1977	DMR, M	LDAR, OGI, CR, VRU	5,001-10,000	$1,001-$10,000	TX
IBM Thomas J. Watson Research Center	1911	DMR, ADA		10,001+	$10,000+	NY, MA
Insight Environmental	2004	DMR	LDAR, OGI, CR, FS, UAV	51-200	$0-$15	TX, AK, MN, ND, WI
IRT Consult		DMR	LDAR, OGI	0-50	$0-$15	FL
K&K Services	2007	DMR	LDAR, CR	0-50	$0-$15	IL
Kairos Aerospace	2014	DMR, ADA	LDAR, OGI, A	0-50	$0-$15	CA
Kayrros	2016	DMR, ADA	S	51-200	$15-$50	NY, TX
Keitu Engineering	2001	DMR	LDAR, OGI	0-50	$0-$15	ND
Kelvin	2013	DMR, ADA		51-200	$15-$50	CA, CO, TX
L&M Environmental Response	2016	DMR	LDAR, OGI, CR	0-50	$0-$15	LA
LaSen	1989	DMR	LDAR, OGI, UAV, A	0-50	$0-$15	NM
Leak Finder	2009	DMR	LDAR, OGI	0-50	$0-$15	OH
Leak Imaging	2010	DMR	LDAR, OGI	0-50	$0-$15	TX
Leak Surveys	2004	DMR	LDAR, OGI, A			TX
Lesair Environmental	2000	DMR	LDAR, OGI, CR	0-50	$0-$15	CO
M&R Industrial Services	2005	DMR	LDAR, OGI	0-50	$0-$15	TX
Montrose Environmental	2012	DMR	LDAR, OGI, CR, FS, MGL, UAV	201-1,000	$51-$500	CA, CO, IL, PA, TX

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SERVICE FIRM	FIRST YEAR	INDUSTRY CATEGORY	RELEVANT TECHNOLOGIES	EMPLOYEES RANGE	SALES RANGE (MILLIONS)	U.S. EMPLOYEE LOCATIONS (HQ APPEARS FIRST)
My Drone Services	2016	DMR	LDAR, OGI, CR, FS, UAV	0-50	$0-$15	DE, FL
Olsson Associates	1956	DMR	LDAR, OGI, CR	1,001-5,000	$501-$1,000	NE, AR, AZ, CO, IA, KS, MO, NE, OK, TX
Omark Consultants	1987	DMR	LDAR, CR	51-200	$15-$50	MA
Orbital Sidekick*	2016	DMR, ADA	LDAR, A, S	0-50	$0-$15	CA
Otech Aerial Drone Service		DMR	LDAR, OGI, UAV	0-50	$0-$15	MI
Pergam Technical Services	2005	DMR	LDAR, CR, FS, UAV, A	1-500	<$38.5	WA
Picarro	1998	DMR, ADA	LDAR, CR, FS, MGL	1-500	<$38.5	CA
Planet*	2010	DMR, ADA	S	201-1,000	$51-$500	CA
Project Canary	2013	DMR, ADA, SA	FS, MGL	0-50	$0-$15	CO, TX
Questor Technology*	1995	DMR, ADA, SA, M	FM	0-50	$15-$50	TX, CO, FL, ND, PA
Ravan AIR	2018	DMR	LDAR, OGI, UAV	0-50	$0-$15	PA
Reces Environmental Consulting	2003	DMR	LDAR, CR	0-50	$0-$15	TX, CA
Red Hen Systems	1997	DMR	LDAR, OGI, CR, A	0-50	$0-$15	CO
Satelytics	2015	DMR, ADA	LDAR, FS, UAV, A, S	0-50	$0-$15	OH
Sceye	2015	DMR	LDAR, A	0-50	$0-$15	NM
Schlumberger *	1926	DMR, M, ADA	LDAR, CR, V, APD	10,001+	$10,000+	TX, AR, OK
Scientific Aviation	2010	DMR, ADA	LDAR, CR, FS, MGL, UAV, A	0-50	$0-$15	CO
SCS Engineers	1970	DMR	LDAR, OGI, CR, FS, MGL, UAV	201-1,000	$51-$500	CA
SEALTEC	1983	DMR	LDAR, CR	0-50	$0-$15	NJ
SeekOps Inc.*	2017	DMR	LDAR, CR, UAV	1-500	1-$38.5	TX, CA
SLR International	1994	SA		1,001-5,000	$501-$1,000	WA, AK, AZ, CA, CO, CT, GA, IL, IN, KY, LA, MA, ME, NH, NY, OK, OR, PA, SC, TN, TX, UT, VA, VT, WV
Southern Cross Corporation	1946	DMR	LDAR	201-1,000	$51-$500	GA
Southwest Research Institute	1947	DMR, ADA	LDAR, OGI, MGL, UAV, S	1,001-5,000	$501-$1,000	TX
Spectral Sensor Solutions	2012	DMR	LDAR, FS, UAV	0-50	$0-$15	IN, NM

114 SERVICE FIRMS, CONTINUED

SERVICE FIRM	FIRST YEAR	INDUSTRY CATEGORY	RELEVANT TECHNOLOGIES	EMPLOYEES RANGE	SALES RANGE (MILLIONS)	U.S. EMPLOYEE LOCATIONS (HQ APPEARS FIRST)
Spherical Analytics	2017	DMR, ADA	S	0-50	$0-$15	MA
Stantec	1954	SA		10,001+	$1,001-$10,000	FL
Stranded Solutions	2013	M	FM, GC	0-50	$0-$15	MI
Strata	1997	DMR	LDAR, OGI, CR	0-50	$0-$15	KS, OK
Team Inc	1973	DMR, M	LDAR, OGI	5,001-10,000		TX, CO, CT, IL, LA, NJ, WA
Tern Technologies	1984	DMR	LDAR, OGI	0-50	$0-$15	AK
The Sniffers	1991	DMR, SA	LDAR, OGI, CR, FS, MGL, UAV	51-200	$15-$50	TX
Think Environmental	1984	DMR	LDAR, OGI, CR	51-200	$15-$50	TX
Tricord Consulting	2013	DMR	LDAR, OGI, CR	0-50	$0-$15	TX, CA, IL, LA, NC
Trihydro	1984	DMR	LDAR, OGI, CR	201-1,000	$15-$50	WY
Trinity Consultants	1974	DMR		201-1,000	$51-$500	TX
UM Inspections	2015	DMR	LDAR, CR, UAV	0-50	$0-$15	TX
Urbint	2015	DMR, ADA	LDAR	51-200	$15-$50	NY
Viper Drones	2015	DMR	LDAR, OGI, UAV	0-50	$0-$15	FL, AL
Well Data Labs	2014	DMR, ADA		0-50	$0-$15	CO
Westshore Consulting	1982	DMR	LDAR, OGI, CR	0-50	$0-$15	MI
Wood	1912	SA		10,001+	$10,000+	GA, TX
WSP	1885	DMR	LDAR, OGI, CR, FS	10,001+	$10,000+	NY

KEY TO RELEVANT TECHNOLOGIES

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ABBREVIATIONS AND REFERENCES

ABBREVIATIONS

ABBREVIATION	NAME
ADA	Advanced Data Analytics
AI	Artificial Intelligence
bcm	billion cubic meters
CH_4	Methane
CO_2	Carbon dioxide
EPA	Environmental Protection Agency
ESG	Environmental, Social, and Governance
IEA	International Energy Agency
IoT	Internet of Things
IR	Infrared
ISO	International Organization for Standardization
LDAR	Leak Detection and Repair
LiDAR	Light Detection and Ranging
LNG	Liquified Natural Gas
ML	Machine Learning
OGI	Optical Gas Imaging
PCB	Printed Circuit Board
SA	Strategic Advisory
TB	Terabyte
UAV	Unmanned Aerial Vehicle (drone)
VRU	Vapor Recovery Unit

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ENDNOTES

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3 EPA, "Understanding Global Warming Potentials."
4 U.S. Environmental Protection Agency, "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2014."
5 IEA, "Methane Tracker 2020."
6 Fox et al., "A Review of Close-Range and Screening Technologies for Mitigating Fugitive Methane Emissions in Upstream Oil and Gas."
7 Fox et al.
8 Fox et al.
9 Fox et al.
10 Fernandez, "AI Makes Detecting Methane Leaks Less Confusing."
11 IEA, "Methane Tracker 2020." Estimate is based on 2019 natural gas prices.
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13 The World Bank, "Global Gas Flaring Reduction Partnership GGFR)."
14 Jacobs, "Innovators Seek To Transform Flaring Into Money and Power."
15 EPA, Oil and Natural Gas Sector: Emission Standards for New, Reconstructed, and Modified Sources.
16 Executive Order 13783 of March 28, 2017, Promoting Energy Independence and Economic Growth.
17 Executive Order 13390 of January 21, 2021, on Protecting Public Health and the Environment and Restoring Science to Tackle the Climate Crisis.
18 Executive Order 14008 of January 27, 2021, Tackling the Climate Crisis at Home and Abroad.
19 Lyon, Nowlan, and Paranhos, "Pathways for Alternative Compliance: A Framework to Advance Innovation, Environmental Protection, and Prosperity."
20 EPA, Oil and Natural Gas Sector: Emission Standards for New, Reconstructed, and Modified Sources.
21 EPA, Oil and Natural Gas Sector: Emission Standards for New, Reconstructed, and Modified Sources Reconsideration; EPA, Oil and Natural Gas Sector: Emission Standards for New, Reconstructed, and Modified Sources Review.
22 "Methane Mitigation Roadmap."
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24 Lyon, Nowlan, and Paranhos, "Pathways for Alternative Compliance: A Framework to Advance Innovation, Environmental Protection, and Prosperity."
25 Lyon, Nowlan, and Paranhos.
26 Subarticle 13: Greenhouse Gas Emission Standards for Crude Oil and Natural Gas Facilities.
27 Regulation 7: Control of Ozone via Ozone Precursors and Control of Hydrocarbons via Oil and Gas Emissions, 7.

28 Control of Methane Emissions from the Natural Gas Industry.
29 Draft Oil and Natural Gas Regulation Ozone Precursors.
30 Oil & Natural Gas Sector Emissions in New York Stakeholder Regulation Outline.
31 Equipment leaks from valves, flanges, pressure relief devices, open end valves or lines, pneumatic controllers, pump seals, compressor seals (except seals regulated under 40 CFR 60.5380a or 5385a) in natural gas service.
32 Early Stakeholder Outreach — New Rules Regulating Emissions from the Oil and Gas Industry.
33 Wolf and McDonnell, "Overview of GP-5A, GP-5, and Exemption 38"; "Energy Policies of IEA Countries."
34 Proposed Rulemaking, Control of VOC Emissions from Oil and Natural Gas Sources.
35 Permitting Requirements.
36 U.S. Bureau of Labor Statistics, "Occupational Employment Statistics."
37 EY, "Oil and Gas Digital Transformation and the Workforce Survey 2020."
38 U.S. Bureau of Labor Statistics. Salary for drone operators is from Glassdoor.

Datu
data for the big picture

EDF’S
EXHIBIT JJJ

REBUTTAL TESTIMONY OF HILLARY HULL

I. DOCUMENTS REVIEWED:

In preparing my rebuttal, I reviewed the following documents:

- John Smitherman testimony, NMOGA Appendix A.
- NMOGA redline, Appendix B.
- Valor EPC Study: NMAC 20.2.50.123, Storage Vessels, attachment to NMOGA Appendix A2.
- Kinder Morgan redline, Kinder Morgan Ex. X.
- IPANM proposed modifications, IPANM Ex. 1.
- Cost-Benefit Analysis, Colorado Department of Public Health and Environment ("CDPHE") (Feb. 7, 2014), EDF Ex. BB.
- Cost-Benefit Analysis, Regulation 7, CDPHE, EDF Ex. EE.
- API Comments on the 2016 Control Techniques Guidelines, NMOGA Ex. 24.
- Datu Research 2021 Report, EDF Ex, III.
- ERG-LDAR Reductions and Costs VOC Spreadsheet, NMED Ex. 69.
- Storage Tanks Reductions and Costs VOC Spreadsheet, NMED Ex. 100.

II. SUMMARY

My rebuttal testimony will discuss the following:

- The New Mexico Oil and Gas Association's (NMOGA) proposal to reduce the frequency of leak inspections at wellhead facilities will result in 23,000 additional tons of volatile organic compounds (VOCs) and 79,000 additional tons of methane (CH_4) being leaked to the atmosphere annually starting upon the effective date of the rule compared to the New Mexico Environment Department's (NMED) proposal for wellhead sites.

- NMOGA's proposal to reduce the frequency of leak inspections at compressor stations will result in a 20% decrease in emission reductions from gathering and boosting sites and a 12% decrease in emission reductions from transmission compressor stations compared to the NMED proposal for wellhead sites.
- NMOGA's estimate of the costs to comply with NMED's proposed instrument-based monitoring requirements contained in 20.2.50.116.C NMAC (leak detection and repair or "LDAR" requirements) are inflated. NMED's estimates of costs are conservative and in line with those estimated by the Colorado Air Pollution Control Division for its similar tiered LDAR program.
- NMOGA and Kinder Morgan's proposals to exempt compressor stations in the transmission segment from LDAR will result in 980 tons of unabated VOC pollution and 36,000 tons of unabated methane pollution each year using EDF's emission estimates.
- Kinder Morgan's proposal to allow for compliance with EPA LDAR requirements to replace NMED's proposed requirements will result in up to 1,600 additional tons of VOCs and up to 8,900 additional tons of methane leaked annually.
- NMED's estimate of the control costs for its storage tank provision is reasonable, and if anything, conservative.

III. NMOGA's WELLHEAD SITE LDAR PROPOSAL WILL RESULT IN SIGNIFICANT AMOUNTS OF ADDITIONAL POLLUTION TO THE ATMOSPHERE

I reviewed NMOGA's proposal to reduce the frequency of leak inspections at oil and gas wellhead sites. The proposal significantly weakens the NMED proposal and will result in thousands more tons of smog-forming VOCs and climate-warming CH_4 released to the atmosphere each year. NMOGA's proposal would result in 23,000 additional tons of VOCs and 79,000 additional tons of methane left unabated annually.

NMOGA's proposal requires annual LDAR at wellhead sites emitting less than 10 tons per year (TPY) of VOCs, semi-annual LDAR at wellhead sites emitting between 10 and 25 TPY of VOCs, and quarterly LDAR at wellhead sites emitting more than 25 TPY of VOCs. This increases the emission thresholds triggering each LDAR tier by fivefold compared to NMED's proposal. NMED proposes wellhead sites emitting less than 2 TPY of VOCs conduct annual LDAR, well sites emitting between 2 and 5 TPY of VOCs conduct semi-annual LDAR, and those emitting more than 5 TPY of VOCs conduct quarterly LDAR.

We used the same methodology described in my direct testimony regarding EDF's proposed LDAR proximity requirement to analyze the impact of NMOGA's LDAR proposal on air quality. Specifically, using the VOC bottom-up inventory as a proxy for potential to emit (PTE), we categorize each wellhead site depending on the VOC tier (<10 TPY VOC, between 10 and 25 TPY VOC, and >25 TPY VOC). We sum the methane and VOC emissions covered by the NMOGA proposal in each tier (using both the bottom-up and site-level methane emissions as lower and upper bounds). We then calculate emissions reductions for equipment leaks in each tier using the assumed reduction percentages of 40%/60%/80% for annual/semiannual/quarterly LDAR respectively. Due to the intermittent nature of abnormal process condition emissions we estimate LDAR emission reductions for these emissions using data from Cusworth et al., Ex. H. Cusworth et al. used airborne imaging spectrometers to measure CH_4 emissions from production facilities and additionally estimated the persistence of emissions from those sources. Using this data, we estimate the likelihood that abnormal process condition emissions would be detected by LDAR: ~25%/44%/68%/97% for annual/semiannual/quarterly/monthly LDAR, respectively. We assume that 100% of abnormal process condition emissions that are detected by LDAR are mitigated.

IV. NMOGA's COMPRESSOR STATION LDAR PROPOSAL WILL RESULT IN SIGNIFICANT AMOUNTS OF ADDITIONAL POLLUTION TO THE ATMOSPHERE

I reviewed NMOGA's proposal to reduce the frequency of leak inspections at compressor stations. NMED's proposal requires quarterly LDAR for compressor stations emitting less than 25 TPY of VOCs and monthly LDAR for compressor stations emitting equal to or greater than 25 TPY of VOCs. NMOGA's proposal decreases the inspection frequency from monthly to quarterly for compressor stations emitting 25 TPY of VOCs or more, and from quarterly to semi-annual for those emitting below 25 TPY of VOCs.

We calculated the additional tons of pollution that would be released by NMOGA's proposal using EDF and EPA emission estimates. NMOGA's proposal will result in up to 8,400 additional tons of VOCs and up to 34,000 additional tons of methane leaked annually, using EDF emission estimates. Using 2020 EPA emission estimates, NMOGA's proposal will result in ~680 additional tons of VOCs and ~ 2,700 additional tons of methane leaked annually. For this analysis, we started with NMED's Inventory of Compressor Stations from their LDAR Reductions and Costs spreadsheet. We applied station specific emission factors to first estimate methane emissions. We used two sets of emission estimates for comparison. In 2020, EPA released new emission estimates of 16.6 TPY of CH_4 for gathering and boosting (G&B) stations and 40.4 TPY of CH4 for transmission compressor stations. EDF used study data from Marchese et al (2015) and Zimmerle et al (2015) to recalculate baseline emissions factors at G&B and transmission compressor stations to 205.7 TPY of CH_4 and 553.9 TPY of CH4, respectively. We converted these emissions to VOCs using EPA ratios of methane to VOC (i.e., methane:VOC of 3.6:1 for G&B sites, and methane:VOC ratio of 36.1:1 for transmission compressor stations). We then calculate emissions reductions for equipment leaks in each tier using the assumed reduction percentages of 40%/60%/80%/90% for annual/semiannual/quarterly/monthly OGI LDAR respectively.

In sum, NMOGA's proposal will result in significantly more emissions of smog-forming VOCs and climate-warming methane than NMED's proposal.

V. NMED'S ESTIMATE OF THE COST EFFECTIVENESS OF ITS INSTRUMENT-BASED EQUIPMENT LEAK MONITORING PROVISIONS IS REASONABLE, AND IF ANYTHING UNDERSTATES THE COSTS OF INSPECTIONS.

I have reviewed NMED's estimate of the costs and VOC reductions associated with proposed 20.2.50.116.C. and D NMAC (i.e., the LDAR provisions). Per these provisions operators must inspect wellhead sites and compressor stations for leaks using optical gas imaging (OGI), EPA method 21 (M21), or an approved alternative leak monitoring plan.

For wellhead sites, NMED estimates the average cost per ton of VOC to conduct LDAR inspections at New Mexico facilities subject to its proposal to be $3,506. NMED Ex. 69. This average cost per ton is based on ERG's estimate of the expected emission reductions for each facility, assuming an annual, semi-annual, or monthly inspection requirement per the NMED proposal and an estimate of costs based on EPA 2015 costs.

I compared NMED's average cost per ton of VOC figure with that of a neighboring air pollution control agency, the Colorado Air Pollution Control Division. In 2014 Colorado adopted a similar tiered inspection program to that proposed by NMED. Colorado's program, like

NMED's proposal, requires operators to inspect well sites at various frequencies depending on the emissions from the well site, or particular equipment at the well site (i.e., storage tanks). Colorado's estimate of the cost effectiveness of its program is in line with NMED's. In the 2014 Cost-Benefit Analysis, Colorado Department of Public Health and Environment (“CDPHE”) (Feb. 7, 2014), the Colorado AQCC estimated the average cost-effectiveness of conducting inspections using an IR Camera or Method 21 for controlling VOC leaks to be $1,259 ($/ton) for well production facilities. This assumed annual, quarterly and monthly inspections. NMED's estimate of the cost effectiveness of its program is in line with Colorado's. If anything, a comparison of the NMED and Colorado estimates demonstrates NMED's estimate is conservative.

In its critique of the NMED LDAR technical analysis, NMOGA has grossly overestimated costs. NMOGA obscurely relies on the American Petroleum Institute’s (API) December 2015 comments on the draft 2016 CTGs, which increased the EPA estimate for cost effectiveness of proposed leak detection requirements from $2,230 per well site to over $6,400 per site. This number dramatically overstates the costs of LDAR and was notably rejected by EPA in their 2016 CTGs. My review of API's comments indicates API’s reasoning was critically flawed and NMOGA’s reliance upon this information is misplaced.

First, API presumed that all operators would create their own in-house LDAR survey program from scratch rather than employ third-party providers. This assumption inflates the cost of implementing an LDAR program for all but the largest operators. For small operators it is often more economical to hire a third-party contractor to conduct leak inspections than to purchase its own IR camera and other equipment necessary to conduct inspections. For example, when Colorado first adopted its LDAR program in 2014 it assumed that operators who have less than 500 wells would hire a third-party contractor to conduct LDAR as they would not be able to fully utilize an IR camera. EDF Ex BB. API also used basin-level averages to imply that for each survey, an operator would travel approximately 340 miles roundtrip. This estimate seems high. Moreover, API did not provide support for this estimate in its comments and NMOGA fails to provide evidence that this number is applicable to New Mexico operators.

Information from a new study demonstrates that the methane mitigation industry, including third party contractors who can conduct LDAR inspections, is growing. Indeed, many of these firms are using efficient screening methods, such as aerial surveys, that can screen multiple facilities for leaks in a much shorter timeframe than can be achieved using ground-based OGI methods. Per a recent report by Datu Research, the number of methane mitigation service firms nearly doubled in the last four years alone. EDF Ex. III. Per this report, Datu Research surveyed 98 firms between June 29 and July 21, 2021. More than half of the respondents stated they could serve at least 100 more well sites per day than they currently serve. Nearly half noted they could scale up to serve more than 500 well sites per day using advanced methane detection technologies such as fixed sensors, airplanes or satellites.

The rapid growth in advanced methane detection technologies is likely to significantly reduce the costs of LDAR compliance. NMED's proposal allows operators to obtain approval to use alternative equipment leak monitoring plans. Most likely, many of these plans will rely on a combination of fixed sensors, aerial surveys or satellites. NMED's estimate of the costs associated with conducting ground-based vehicle inspections is likely quite conservative, and NMOGA's estimate of costs wildly inflated.

VI. THE EIB SHOULD REJECT PROPOSALS TO ELIMINATE OR REDUCE THE FREQUENCY OF INSPECTIONS AT TRANSMISSION COMPRESSOR STATIONS

I reviewed and analyzed Kinder Morgan and NMOGA’s proposal to remove instrument-based LDAR requirements for transmission compressor stations. The removal of LDAR requirements for transmission compressor stations would result in 980 tons of additional VOC and 36,000 tons of additional methane emitted annually.

I also reviewed the alternative proposal to allow operators to comply with EPA 0000a requirements for compressor stations rather than the NMED proposed requirement. Per EDF's analysis, the alternative proposal to allow for compliance with OOOOa requirements would result in 1,600 additional tons of VOCs and up to 8,900 additional tons of methane leaked annually. These harmful pollutants threaten public health and contribute to the climate crisis.

Kinder Morgan’s proposal to defer promulgation of state standards to limit pollution from existing transmission compressor stations is equally flawed. First, EPA rules for existing sources are uncertain. EPA has yet to propose rules to address methane pollution from existing sources. Second, because EPA has yet to propose requirements, the EIB has no assurance that the EPA requirements will achieve comparable emission reductions as NMED's proposal. Third, at best, EPA's rules will not take effect for at least 1 year after the proposal whereas NMED's proposal, if adopted, will result in near-term pollution reductions. Fourth, EPA's rules for the oil and gas industry are often the subject of petitions for reconsideration and litigation which could weaken or further delay rules for existing compressor stations. Given the ozone concentrations measured in the counties subject to the rule, the likelihood that ozone pollution will worsen due to climate change, as Tammy Thompson discusses in her rebuttal testimony, and the significant methane emissions that contribute to near-term climate warming, I strongly counsel against deferring LDAR requirements for existing sources.

VII. NMED'S ESTIMATE OF THE COSTS TO CONTROL STORAGE VESSELS ARE REASONABLE, AND IF ANYTHING, CONSERVATIVE

I reviewed NMED's estimate of the costs to control pollution from storage vessels and compared those to costs estimated by the Colorado Air Pollution Control Division. Based on this review, NMED's estimated costs are reasonable and conservative. The EIB should reject the claims by NMOGA that NMED has overestimated costs.

The Colorado Air Pollution Control Division estimated the annualized cost of a flare equipped with an auto igniter to be $6,287 in 2014 (EDF Ex. BB) and $6,488 in 2019 (EDF Ex. EE). NMED, by contrast, estimates an annualized cost of $9,112. NMED Ex. 100. To derive this number, NMED used EPA's "Table 4-5. Total Capital Investment and Total Annual Costs of a Combustor," from EPA's Control Techniques Guidelines for the Oil and Natural Gas Industry, October 2016. EPA-453/B-16-001.

For background, in 2014, the Colorado Air Pollution Control Division lowered the uncontrolled VOC emission control threshold from 20 tpy down to 6 tpy for condensate storage tanks statewide. In the 2014 EIA for Proposed Revisions to AQCC Reg. 7, the Colorado AQCC estimated the annualized cost of installing 588 flare control devices to be about $3.7 million dollars with an average cost effectiveness of about $716 per ton of VOC reduced. For the smallest individual tank battery subject to controls (6 tons per year), the flare cost effectiveness was estimated to be $1,471 per ton of VOC reduced.

In 2019, Colorado transitioned to a 2 tpy tank control threshold. In the 2019 EIA for Reg. 7, the Colorado AQCC estimated the annualized cumulative cost of installing 65 flare control devices to be about $421,700 dollars with an average cost effectiveness of about $2,232 per ton of VOC reduced. For the smallest category of tanks (2-3 tpy) the incremental cost of controls on 36 tanks was estimated to be $2,843 per ton of VOC reduced.

Colorado's estimates are in line with what NMED has estimated, especially in comparing the NMED cost estimates to the 2019 Colorado EIA. If anything, NMED has overestimated the costs associated with installing control devices on tanks, as compared to the estimates by Colorado in their 2014 and 2019 rulemakings. Otherwise, I believe NMED's estimates to be fair and accurate.