# Addendum to Technical Support Document on Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866: Application of the Methodology to Estimate the Social Cost of Methane and the Social Cost of Nitrous Oxide

**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 the Interior
Department of Transportation
Department of the Treasury
Environmental Protection Agency
National Economic Council
Office of Management and Budget
Office of Science and Technology Policy

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**Addendum:**

**Valuing Methane and Nitrous Oxide Emission Changes in Regulatory Benefit-Cost Analysis**

## I. Introduction

While carbon dioxide ($CO_2$) is the most prevalent greenhouse gas (GHG) emitted into the atmosphere, other GHGs are also important contributors: methane ($CH_4$), nitrous oxide ($N_2O$), hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride.[1] The potential of these gases to change the Earth's climate relative to $CO_2$ is commonly represented by their 100-year global warming potential (GWP). GWPs measure the contribution to warming of the Earth's atmosphere resulting from emissions of a given gas (i.e., radiative forcing per unit of mass) over a particular timeframe relative to $CO_2$. As such, GWPs are often used to convert emissions of non-$CO_2$ GHGs to $CO_2$-equivalents to facilitate comparison of policies and inventories involving different GHGs.

While GWPs allow for some useful comparisons across gases on a physical basis, using the social cost of carbon dioxide (SC-$CO_2$)[2] to value the damages associated with changes in $CO_2$-equivalent emissions is not optimal. This is because non-$CO_2$ GHGs differ not just in their potential to absorb infrared radiation over a given time frame, but also in the temporal pathway of their impact on radiative forcing, which is relevant for estimating their social cost but not reflected in the GWP. Physical impacts other than temperature change also vary across gases in ways that are not captured by GWP. For instance, $CO_2$ emissions, unlike $CH_4$ and other GHGs, contribute to ocean acidification. Likewise, damages from $CH_4$ emissions are not offset by any positive effect of $CO_2$ fertilization on agriculture. Thus, transforming gases into $CO_2$-equivalents using GWP, and then multiplying the $CO_2$-equivalents by the SC-$CO_2$, is not as accurate as a direct calculation of the social costs of non-$CO_2$ GHGs.[3]

In light of these limitations and the paucity of peer-reviewed estimates of the social cost of non-$CO_2$ gases in the literature, the 2010 SC-$CO_2$ Technical Support Document (TSD)[4] did not include an estimate of the social cost of non-$CO_2$ GHGs and did not endorse the use of GWP to approximate the value of non-$CO_2$ emission changes in regulatory analysis. Instead, the Interagency Working Group (IWG) noted that more work was needed to link non-$CO_2$ GHG emission changes to economic impacts.

Since that time, new estimates of the social cost of non-$CO_2$ GHG emissions have been developed in the scientific literature, and a recent study by Marten et al. (2015) provided the first set of published estimates

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[1] See EPA Endangerment Finding: Endangerment and Cause or Contribute Findings for Greenhouse Gases under Section 202(a) of the Clean Air Act, 74 Fed. Reg. 66,496 (Dec. 15, 2009).

[2] Throughout this Addendum we refer to the estimates as "SC-$CO_2$ estimates" rather than the more simplified "SCC" abbreviation that was previously used by the IWG.

[3] For more detailed discussion of the limitations of using a GWP based approach to valuing non-$CO_2$ GHG emission changes, see, e.g., Marten et al. (2015) and recent EPA regulatory impact analyses (e.g., EPA 2016a).

[4] The 2010 SC-$CO_2$ TSD and subsequent updates are available at: https://www.whitehouse.gov/omb/oira/social-cost-of-carbon.

for the social cost of $CH_4$ and $N_2O$ emissions that are consistent with the methodology and modeling assumptions underlying the IWG $SC\text{-}CO_2$ estimates. Specifically, Marten et al. used the same set of three integrated assessment models (IAMs), five socioeconomic and emissions scenarios, equilibrium climate sensitivity distribution, three constant discount rates, and the aggregation approach used by the IWG to develop the $SC\text{-}CO_2$ estimates. This addendum summarizes the Marten et al. methodology and presents the $SC\text{-}CH_4$ and $SC\text{-}N_2O$ estimates from that study as a way for agencies to incorporate the social benefits of reducing $CH_4$ and $N_2O$ emissions into benefit-cost analyses of regulatory actions that have small, or "marginal," impacts on cumulative global emissions. As stated in the 2010 TSD, most federal regulatory actions can be expected to have impacts on global emissions that may be considered marginal in this context. In the future, this addendum may include values for the social cost of additional non-$CO_2$ greenhouse gases.

The $SC\text{-}CH_4$ and $SC\text{-}N_2O$ estimates presented in this addendum offer a method for improving the analyses of regulatory actions that are projected to influence $CH_4$ or $N_2O$ emissions in a manner consistent with how $CO_2$ emission changes are valued. The estimates are presented with an acknowledgement of the limitations and uncertainties involved and with a clear understanding that they should be updated over time to reflect increasing knowledge of the science and economics of climate impacts, just as the IWG has committed to do for $SC\text{-}CO_2$.

The methodology and estimates described in this addendum have undergone multiple stages of peer review and their use in regulatory analysis has been subject to public comment. With regard to peer review, the study by Marten et al. (2015) was subjected to a standard double-blind peer review process prior to journal publication. In addition, the application of these estimates to federal regulatory analysis was designated as Influential Scientific Information (ISI), and its external peer review was added to the EPA Peer Review Agenda for Fiscal Year 2015 in November 2014. The public was invited to provide comment on the peer review plan, though EPA did not receive any comments. The external peer reviewers agreed with EPA's interpretation of Marten et al.'s estimates; generally found the estimates to be consistent with the approach taken in the IWG $SC\text{-}CO_2$ estimates; and concurred with the limitations of the GWP approach, finding directly modeled estimates to be more appropriate. All documents pertaining to the external peer review, including a white paper summarizing the methodology, the charge questions, and each reviewer's full response is available on the EPA Science Inventory website.[5] For a discussion of public comments on the valuation of non-$CO_2$ GHG impacts in general and the use of the Marten et al. estimates for the $SC\text{-}CH_4$, see recent EPA regulations with $CH_4$ impacts (e.g., EPA 2012a, 2012b, 2016a, 2016b) and for the $SC\text{-}N_2O$, see recent EPA and DOT regulations with $N_2O$ impacts (e.g., EPA and DOT 2016). OMB has determined that the use of the Marten et al. estimates in regulatory analysis is consistent with the requirements of OMB's Information Quality Guidelines Bulletin for Peer Review and OMB Circular A-4.

## II. Overview of Methodology

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[5] The complete record for this review is available on the EPA Science Inventory website at:
http://cfpub.epa.gov/si/si_public_pra_view.cfm?dirEntryID=291976.

The social cost of non-$CO_2$ GHG emissions can be directly estimated using an IAM similar to the way in which the SC-$CO_2$ is estimated. As discussed at length in the 2010 SC-$CO_2$ TSD, IAMs couple simplified models of atmospheric gas cycles and climate systems with highly aggregated models of the global economy and human behavior to represent the impacts of GHG emissions on the climate and human welfare. Within IAMs, the equations that represent the influence of emissions on the climate are based on scientific assessments, while the equations that map climate impacts to human welfare are based on economic research that has studied the effects of climate on various market and non-market sectors. Estimating the social cost of emissions for a given GHG at the margin involves perturbing the emissions of that gas in a given year and forecasting the increase in monetized climate damages relative to the baseline. These incremental damages are then discounted back to the perturbation year to represent the marginal social cost of emissions of the specific GHG in that year.

Several researchers have directly estimated the social cost of non-$CO_2$ GHG emissions using IAMs. Among these published estimates there is considerable variation in the models and input assumptions. Fankhauser (1994) developed a simple IAM to estimate the average SC-$CH_4$ and SC-$N_2O$ for emissions in the 2010 and 2020 decades given a 100-year time horizon for climate change damages. Kandlikar (1995) and Hammitt et al. (1996) also developed simple models to estimate the social cost of $CH_4$, $N_2O$, and other gases for a single socio-economic-emissions scenario and using constant discount rates. Tol et al. (2003) and Hope (2005, 2006) developed estimates for the SC-$CH_4$ in 2000 using the FUND and PAGE models, respectively. Waldhoff et al. (2011) used a newer version of the FUND model to develop estimates of the social cost of marginal $CH_4$, $N_2O$, and sulfur hexafluoride ($SF_6$) emissions for the average year in the 2010-2019 decade. While they considered only a single emissions period, they conducted a wide range of sensitivity analyses including four socio-economic-emissions scenarios, in addition to the default FUND scenario.

These studies differ in the emission perturbation year, employ a wide range of constant and variable discount rate specifications, and consider a range of baseline socioeconomic and emissions scenarios that have been developed over the last 20 years. However, none of these published estimates of the SC-$CH_4$ and SC-$N_2O$ are consistent with the modeling assumptions underlying the IWG SC-$CO_2$ estimates, and most are likely underestimates due to changes in the underlying science since their publication. Therefore, Marten et al. (2015) provide the first set of direct estimates of the SC-$CH_4$ and SC-$N_2O$ that are consistent with the SC-$CO_2$ estimates currently used in federal regulatory analysis.

The estimation approach of Marten et al. (2015) used the same set of three IAMs, five socio-economic-emissions scenarios, equilibrium climate sensitivity distribution, and three constant discount rates used to develop the IWG SC-$CO_2$ estimates. Details on each of these inputs are provided in the 2010 SC-$CO_2$ TSD. Marten et al. also used the same aggregation method as the IWG to distill the 45 distributions of the SC-$CH_4$ and SC-$N_2O$ produced for each emissions year into four estimates for use in regulatory analysis. Three values are based on the average SC-$CH_4$ and the average SC-$N_2O$ from the three IAMs, at discount rates of 2.5, 3, and 5 percent. As discussed in the 2010 TSD, there is extensive evidence in the scientific and economic literature of the potential for lower-probability, but higher-impact outcomes from climate change, which would be particularly harmful to society and thus relevant to the public and policymakers. The fourth value is included to represent the marginal damages associated with these lower-probability,

higher-impact outcomes. Accordingly, this value is selected from further out in the tail of the distributions of SC-CH$_4$ and SC-N$_2$O estimates; specifically, the fourth value corresponds to the 95th percentile of the frequency distributions of SC-CH$_4$ and SC-N$_2$O estimates based on a 3 percent discount rate.

The IWG has determined that it is reasonable to use the same focus on global benefits for valuing emission reductions that was used to estimate the SC-CO$_2$. This is because anthropogenic climate change involves a global externality: emissions of most greenhouse gases (including CH$_4$ and N$_2$O) contribute to damages around the world even when they are emitted in the United States, and conversely, greenhouse gases emitted elsewhere contribute to damages in the United States. Consequently, to address the global nature of the problem, estimates of the social cost of CH$_4$ and N$_2$O must incorporate the full (global) damages caused by emissions. In addition, climate change presents a problem that the United States alone cannot solve. Other countries will also need to take action to reduce GHG emissions if significant changes in the global climate are to be avoided. Furthermore, adverse impacts on other countries can have spillover effects on the United States, particularly in the areas of national security, international trade, public health, and humanitarian concerns. Thus, consistent with the approach for the SC-CO$_2$, the IWG concluded that a global measure of the benefits from reducing U.S. CH$_4$ and N$_2$O emissions is preferable. Similarly, the IWG has determined that the range of discount rates used to estimate SC-CO$_2$ are appropriate for estimating SC-CH$_4$ and SC-N$_2$O as well. The rationale put forth in the 2010 TSD to use this set of discount rates because of the intergenerational nature of CO$_2$ impacts also applies to CH$_4$ and N$_2$O. Although the atmospheric lifetime of CH$_4$ is notably shorter than that of CO$_2$, the impacts of changes in contemporary CH$_4$ emissions are also expected to occur over long time horizons that cover multiple generations, and the lifetime of N$_2$O is almost 10 times as long as the lifetime of CH$_4$.[6] For additional discussion see the SC-CO$_2$ TSD.[7]

In order to develop SC-CH$_4$ and SC-N$_2$O 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$_2$O perturbation, and 2) add more specificity to the assumptions regarding post-2100 baseline CH$_4$ and N$_2$O emissions.

Regarding the climate modeling, both the DICE and PAGE models as implemented by the IWG to estimate SC-CO$_2$ use an exogenous projection of aggregate non-CO$_2$ radiative forcing, which prevents one from introducing a direct perturbation of CH$_4$ or N$_2$O emissions into the models and then observing its effects.[8]

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[6] The IPCC Fifth Assessment Report (AR5) estimates a central tendency for the e-folding time of CH$_4$ in the atmosphere to be 12.4 years (Myhre et al. 2013). This means that it is expected to take over 40 years for the perturbation resulting from a unit of CH$_4$ emitted today to decay to less than one percent of its initial size. The IPCC AR5 estimate of the perturbation lifetime of N$_2$O is 121 years. Impacts on temperature and other climatic variables will persist longer than the elevated concentrations due to the inertia of the climate system.

[7] See also the OMB Response to Comments on SC-CO$_2$, which elaborates on the use of global values (pp. 30-32) and the selection of discount rates (pp. 20-25), available at:
https://www.whitehouse.gov/sites/default/files/omb/inforeg/scc-response-to-comments-final-july-2015.pdf.

[8] The FUND model is the only one of the three IAMs that explicitly considers CH$_4$ and N$_2$O using a one-box atmospheric gas cycle models for these gases, with geometric decay towards pre-industrial levels, based on the

Therefore, to estimate the SC-$CH_4$ and SC-$N_2O$, Marten et al. (2015) applied a one-box atmospheric gas cycle model to explicitly consider the path of additional radiative forcing from a $CH_4$ or $N_2O$ perturbation, which is then added to the exogenous non-$CO_2$ radiative forcing projection to estimate the incremental damages compared to the baseline. The one-box atmospheric gas cycle model appended to DICE and PAGE used exponential decay functions to project atmospheric $CH_4$ and $N_2O$ concentrations from the $CH_4$ and $N_2O$ emissions projections, respectively, in the five socio-economic-emissions scenarios. They set the average lifetime of $CH_4$ and $N_2O$ to 12 and 114 years, respectively, following the findings of the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report (AR4) (Forster et al. 2007). The direct radiative forcing associated with the atmospheric $CH_4$ and $N_2O$ concentration was estimated using the functional relationships for each of these gases presented in the IPCC's Third Assessment Report (TAR) (Ramaswamy et al. 2001) and used in AR4. To account for the indirect effects of $CH_4$ as a precursor for tropospheric ozone and stratospheric water vapor, Marten et al. followed the approach of the IPCC in AR4 of increasing the direct radiative forcing of $CH_4$ by 40 percent.

The second modeling modification was needed because the SC-$CO_2$ modeling exercise assumed that overall radiative forcing from non-$CO_2$ sources remains constant past 2100 without specifying the projections for individual GHGs that were implicit in that assumption. This broad assumption was sufficient for the purposes of estimating the SC-$CO_2$; however, estimating the SC-$CH_4$ and SC-$N_2O$ requires explicit projections of baseline $CH_4$ and $N_2O$ emissions to determine the atmospheric concentration and radiative forcing off of which to compare the perturbation. Marten et al. (2015) chose to interpret the SC-$CO_2$ assumption for non-$CO_2$ radiative forcing past 2100 as applying to each gas individually, such that the emissions of each gas fall to their respective rate of atmospheric decay. This has the effect of holding global mean radiative forcing due to atmospheric $CH_4$ or $N_2O$ constant past 2100. Marten et al. showed that, due to the relatively short lifetime of $CH_4$, alternative methods for extrapolating $CH_4$ emissions past 2100 have only a negligible effect (less than 0.5 percent) on the SC-$CH_4$. For the longer-lived gas $N_2O$, Marten et al. found the difference in the SC-$N_2O$ estimates across the alternative methods to be less than 1 percent, even for emissions as far out as 2045, and found the projections to be equivalent to two significant digits.

## III. Results

The SC-$CH_4$ and SC-$N_2O$ estimates are presented in Table 1.[9] Following the same approach as with SC-$CO_2$, values for 2010, 2020, 2030, 2040, and 2050 are calculated by combining all outputs (10,000 estimates per model run) from all scenarios and models for a given discount rate. Values for the years in between

IPCC's Third Assessment Report (TAR) (Ramaswamy et al. 2001). FUND augments the TAR expression for the additional radiative forcing from $CH_4$ to account for the influences of stratospheric water vapor and tropospheric ozone changes.

[9] The Marten et al. (2015) estimates in this table and the remainder of the document have been adjusted to reflect the minor July 2015 technical corrections to the SC-$CO_2$ estimates. See Corrigendum to Marten et al. for more details, available at: http://www.tandfonline.com/doi/abs/10.1080/14693062.2015.1070550.

are calculated using linear interpolation. The full set of annual SC-CH$_4$ and SC-N$_2$O estimates between 2010 and 2050, and a detailed set of percentiles by model and scenario combination and additional summary statistics for 2020, are reported in Appendix Add-A. The full set of model results are available on the OMB website.[10]

Although a direct comparison of the estimates in Table 1 with all of the other published estimates is difficult, given the differences in the models and socioeconomic and emissions scenarios, results from three relatively recent studies offer a better basis for comparison (Hope 2006, Marten and Newbold 2012, Waldhoff et al. 2014). In general, the SC-CH$_4$ and SC-N$_2$O estimates in Table 1 are higher than previous estimates. The higher SC-CH$_4$ estimates are partially driven by the higher effective radiative forcing due to the inclusion of indirect effects from CH$_4$ emissions in the modeling. Similar to other recent studies, the directly modeled SC-CH$_4$ and SC-N$_2$O estimates in Table 1 are higher than the GWP-weighted SC-CO$_2$ estimates. A more detailed discussion comparing recent estimates of the SC-CH$_4$ and SC-N$_2$O can be found in Marten et al. (2015).

**Table 1: SC-CH$_4$ and SC-N$_2$O Estimates (in 2007 dollars per metric ton)[11]**

| Year | SC-CH$_4$ | | | | SC-N$_2$O | | | |
| | 5% Average | **3% Average** | 2.5% Average | High Impact (3% 95th) | 5% Average | **3% Average** | 2.5% Average | High Impact (3% 95th) |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 2010 | 370 | **870** | 1,200 | 2,400 | 3,400 | **12,000** | 18,000 | 31,000 |
| 2015 | 450 | **1,000** | 1,400 | 2,800 | 4,000 | **13,000** | 20,000 | 35,000 |
| 2020 | 540 | **1,200** | 1,600 | 3,200 | 4,700 | **15,000** | 22,000 | 39,000 |
| 2025 | 650 | **1,400** | 1,800 | 3,700 | 5,500 | **17,000** | 24,000 | 44,000 |
| 2030 | 760 | **1,600** | 2,000 | 4,200 | 6,300 | **19,000** | 27,000 | 49,000 |
| 2035 | 900 | **1,800** | 2,300 | 4,900 | 7,400 | **21,000** | 29,000 | 55,000 |
| 2040 | 1,000 | **2,000** | 2,600 | 5,500 | 8,400 | **23,000** | 32,000 | 60,000 |
| 2045 | 1,200 | **2,300** | 2,800 | 6,100 | 9,500 | **25,000** | 34,000 | 66,000 |
| 2050 | 1,300 | **2,500** | 3,100 | 6,700 | 11,000 | **27,000** | 37,000 | 72,000 |

The estimates in Table 1 suggest the social cost of CH$_4$ emissions in 2020 is 26-46 times higher than for CO$_2$, with the larger difference occurring at higher discount rates.[12] For emissions in 2050 the SC-CH$_4$ is 31-52 times higher than the SC-CO$_2$. These ratios can be directly compared to the GWP, for which the IPCC

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[10] https://www.whitehouse.gov/omb/oira/social-cost-of-carbon.
[11] To maintain consistency with the current SC-CO$_2$ TSD, values in this Addendum are presented in 2007 dollars. The SC-CH$_4$ estimates presented here are also rounded to two significant digits. The unrounded estimates (available on OMB's website) can be adjusted to current year dollars for use in RIAs using the GDP Implicit Price Deflator (available at http://www.bea.gov/iTable/index_nipa.cfm).
[12] This range of estimates of the global damage potential of CH$_4$ relative to CO$_2$ in 2020, and the same range for the N$_2$O results below, is calculated by dividing the (unrounded) SC-CH$_4$ estimate for each discount rate by the corresponding (unrounded) estimate of SC-CO$_2$.

AR4 100-year GWP of $CH_4$ was 25[13], to see how the GWP-based approach discussed above will likely provide an underestimate of the value of $CH_4$ emission changes particularly for higher discount rates and future emissions years in this application. Similarly, the estimates in Table 1 suggest the social cost of $N_2O$ emissions in 2020 is 318-399 times higher than for $CO_2$, with the larger difference occurring at higher discount rates. For emissions in 2050 the SC-$N_2O$ is 339-416 times higher than the SC-$CO_2$. Similar to the case for $CH_4$, these ratios can be directly compared to the GWP, for which the IPCC AR4 100-year GWP of N2O was 298, to see how the GWP-based approach discussed above will likely provide an underestimate of the value of $N_2O$ emission changes particularly for higher discount rates and future emissions years in this application.

As was the case with SC-$CO_2$, the SC-$CH_4$ and SC-$N_2O$ increase over time because future emissions are expected to 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 gross GDP. Table 2 illustrates how the growth rate for the SC-$CH_4$ and SC-$N_2O$ estimates varies over time.

**Table 2: Average Annual Growth Rates of SC-CH₄ and SC-N₂O Estimates between 2010 and 2050**

| Average Annual Growth Rate (%) | SC-CH₄ | | | | SC-N₂O | | | |
|---|---|---|---|---|---|---|---|---|
| | 5% Average | **3% Average** | 2.5% Average | High Impact (3% 95th) | 5% Average | **3% Average** | 2.5% Average | High Impact (3% 95th) |
| 2010-2020 | 4.6% | **3.8%** | 3.3% | 3.3% | 3.8% | **2.5%** | 2.2% | 2.6% |
| 2020-2030 | 4.1% | **3.3%** | 2.5% | 3.1% | 3.4% | **2.7%** | 2.3% | 2.6% |
| 2030-2040 | 3.2% | **2.5%** | 3.0% | 3.1% | 3.3% | **2.1%** | 1.9% | 2.2% |
| 2040-2050 | 3.0% | **2.5%** | 1.9% | 2.2% | 3.1% | **1.7%** | 1.6% | 2.0% |

The application of direct estimates of the SC-$CH_4$ and SC-$N_2O$ to benefit-cost analysis of a regulatory action is analogous to the use of the SC-$CO_2$ estimates. The future monetized value of emission reductions in each year (the SC-$CH_4$ or SC-$N_2O$ in year $t$ multiplied by the change in emissions in year $t$) must be discounted to the present to determine its total net present value for use in regulatory analysis. As discussed in the SC-$CO_2$ TSD, damages from future emissions should be discounted to the base year of the analysis at the same rate as that used to calculate the SC-$CO_2$ estimates themselves to ensure internal consistency – i.e., future damages from climate change, whether they result from emissions today or emissions in a later year, should be discounted using the same rate. The SC-$CH_4$ and SC-$N_2O$ estimates would be applied in the same way to calculate climate-related costs of a rulemaking that leads to an increase in $CH_4$ or $N_2O$ emissions, respectively.

## IV. Treatment of Uncertainty

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[13] The Marten et al. (2015) estimates are based on the conclusions presented in IPCC AR4 (Forster et al. 2007), which was the latest assessment available when they conducted their modeling and analysis, and therefore GWP estimates based on the same assumptions would provide the most consistent comparison.

Given the consistency with the SC-CO$_2$ methodology, the IWG considered various sources of uncertainty in the SC-CH$_4$ and SC-N$_2$O through a combination of a multi-model ensemble, probabilistic analysis, and scenario analysis. The outcome of accounting for various sources of uncertainty using these approaches is a frequency distribution of the SC-CH$_4$ and SC-N$_2$O 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.

Figure 1 presents the frequency distribution of the SC-CH$_4$ estimates for emissions in 2020 for each of the three discount rates.[14] Figure 2 presents the frequency distribution of the SC-N$_2$O estimates for emissions in 2020 for each of the three discount rates.[15] Each distribution in Figures 1 and 2 represents 150,000 estimates based on 10,000 simulations for each combination of the three models and five socioeconomic and emissions scenarios. As with the SC-CO$_2$, in general the distributions are skewed to the right and have long right tails, which tend to be even longer for lower discount rates. To highlight the difference between the impact of the discount rate on the estimates and other quantified sources of uncertainty, the bars below the frequency distributions provide a symmetric (5$^{th}$ to 95$^{th}$ percentile) representation of quantified variability in the SC-CH$_4$ and SC-N$_2$O estimates conditioned on each discount rate. The full set of SC-CH$_4$ and SC-N$_2$O results through 2050 is available on OMB's website. This may be useful to analysts in situations that warrant additional quantitative uncertainty analysis. See OMB Circular A-4 for guidance and discussion of best practices in conducting uncertainty analysis in RIAs.

**Figure 1: Frequency Distribution of SC-CH$_4$ Estimates for 2020 (in 2007$ per metric ton CH$_4$)**

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[14] Although the distributions in Figure 1 are based on the full set of model results (150,000 estimates for each discount rate), for display purposes the limits of the horizontal axis are truncated, such that 0.02 to 0.11 percent of the SC-CH$_4$ frequency distribution lies below the lowest bin presented and 0.34 to 3.1 percent of the frequency distribution lies above the highest bin presented, depending on the discount rate.

[15] Although the distributions in Figure 2 are based on the full set of model results (150,000 estimates for each discount rate), for display purposes the limits of the horizontal axis are truncated, such that 0.03 to 0.10 percent of the SC-N$_2$O frequency distribution lies below the lowest bin presented and 0.04 to 3.00 percent of the frequency distribution lies above the highest bin presented, depending on the discount rate.
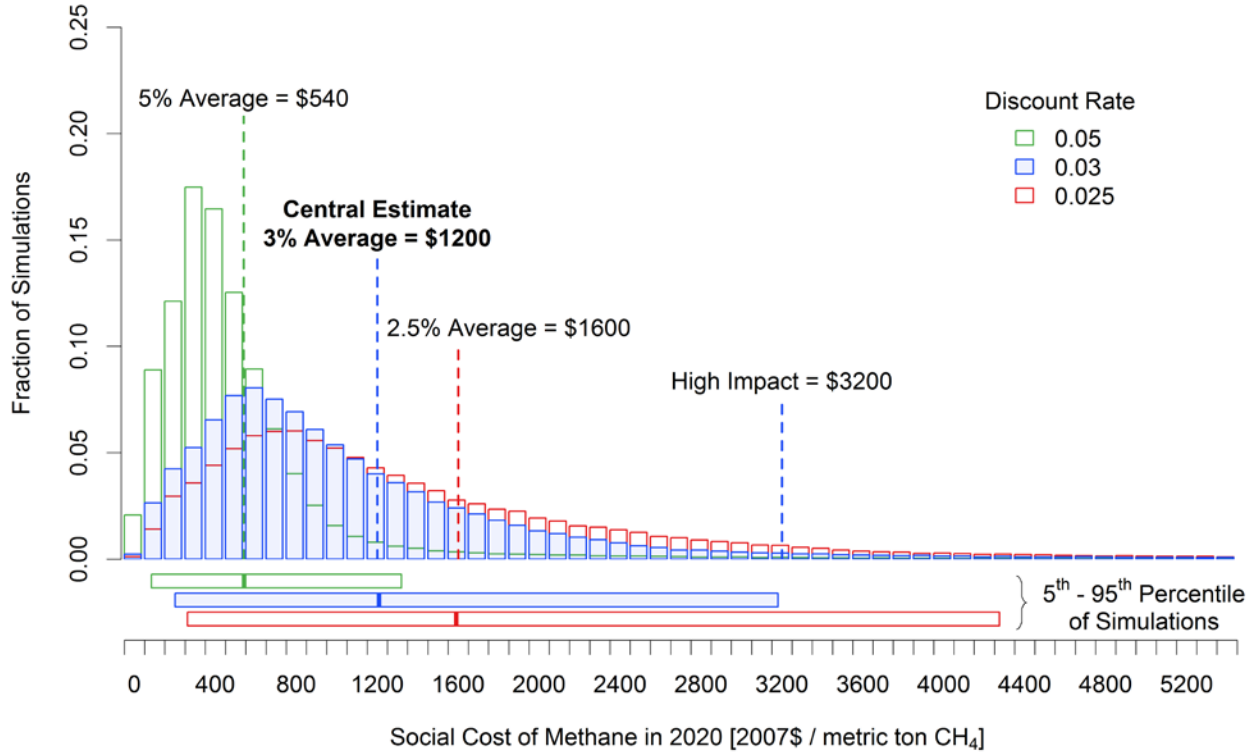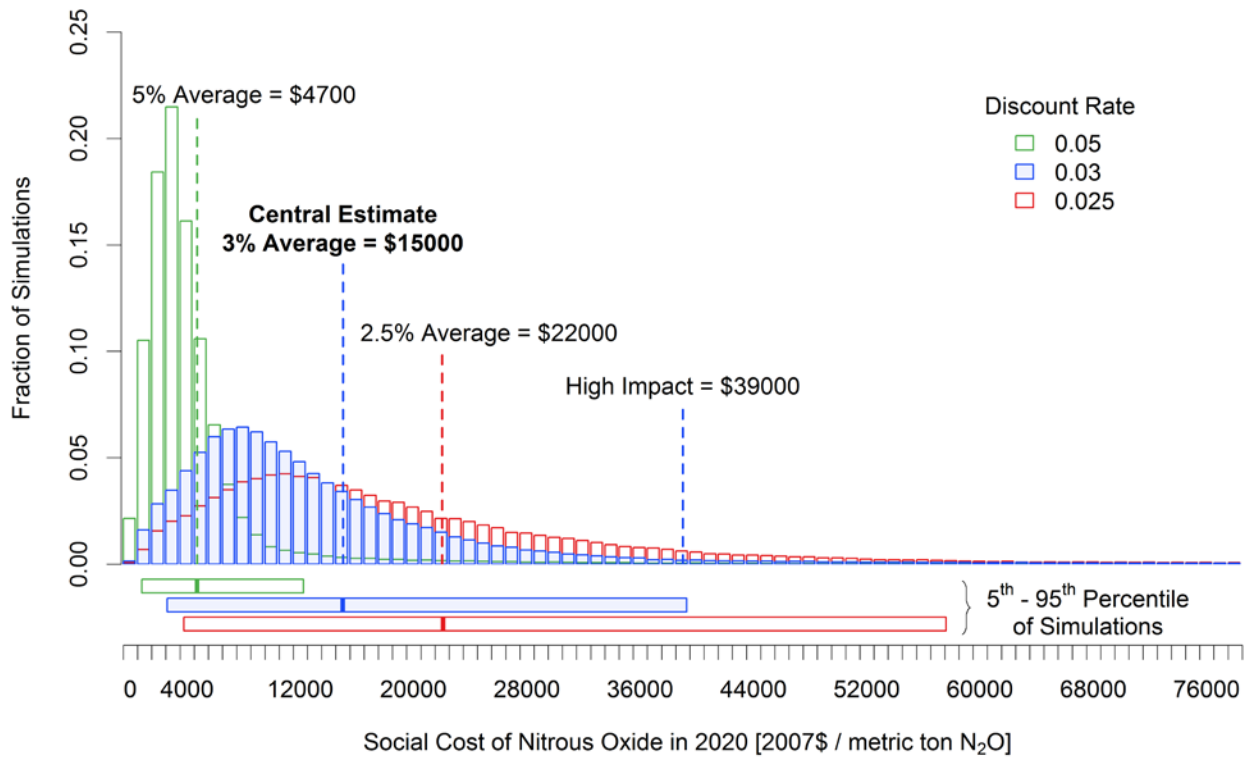
Figure 2: Frequency Distribution of SC-N$_2$O Estimates for 2020 (in 2007$ per metric ton N$_2$O)



## V. Limitations and Research Gaps

Given the consistency in underlying modeling methods and inputs, the SC-CH$_4$ and SC-N$_2$O estimates presented above share many of the same uncertainties and limitations as the SC-CO$_2$ estimates. Thus, they are presented with a clear understanding that they should be updated over time to reflect increasing knowledge of the science and economics of climate impacts. A number of areas where additional research is needed are discussed in the SC-CO$_2$ TSD. Here we discuss a few additional limitations that are specific to the SC-CH$_4$ and SC-N$_2$O estimates.

First, as discussed above, the one-box atmospheric gas cycle model used to explicitly consider the path of additional radiative forcing from CH$_4$ and N$_2$O perturbations in DICE and PAGE followed the findings of IPCC AR4, which was the latest assessment report at the time of the study. Updating the approach to include new findings from the IPCC Fifth Assessment Report (AR5) is expected to increase the SC-CH$_4$ estimates, such that the relationship between the direct SC-CH4 estimates and the GWP-based approach, as discussed in Section 3, are expected to hold. Updating the approach for the SC-N$_2$O is expected to either reduce the SC-N$_2$O estimates or to leave them nearly unchanged, depending on which approach to including climate-carbon feedbacks is used. The AR5 update most relevant for the SC-CH$_4$ is the increase of the adjustment factor to account for tropospheric ozone and stratospheric water vapor from 40 to 65 percent. Additionally, AR5 updated the perturbation lifetime of CH$_4$ from 12 years to 12.4 years and also presented GWPs that included the CO$_2$ oxidation product of fossil-fuel derived CH$_4$. For N$_2$O, the AR5 analysis included the effects of a reduction in CH$_4$ of 0.36 molecules for every additional N$_2$O molecule in the atmosphere because of N$_2$O impacts on stratospheric ozone, UV fluxes, and hydroxyl radical levels, and updated the perturbation lifetime of N$_2$O from 114 to 121 years. In addition, the AR5 assessment updated CH$_4$, N$_2$O, and CO$_2$ radiative efficiencies by less than 3 percent (due mainly to changes in background concentrations), presented an additional GWP that included an adjustment for climate-carbon feedbacks, and updated the impulse response function used for approximating CO$_2$ lifetimes. These updates led to GWPs for CH$_4$ presented by AR5 ranging from 28-36, compared to a GWP of 25 in AR4, and GWPs for N$_2$O ranging from 265-298 compared to a GWP of 298 in AR4 (Myhre et al. 2013).

Second, the direct health and welfare effects of tropospheric ozone production resulting from CH$_4$ emissions are not captured in the IAM damage functions and, thus, are not included in the SC-CH$_4$ estimates presented above. The global monetized benefit of the health effects resulting from ozone reduction due to CH$_4$ mitigation have been estimated in several studies (e.g., Anenberg et al. 2012, Shindell et al. 2012). A recent paper published in the peer-reviewed scientific literature presented a range of estimates of the monetized ozone-related mortality benefits of reducing CH$_4$ emissions using a methodology consistent in some (but not all) aspects with the modeling underlying the SC-CO$_2$ and SC-CH$_4$ estimates discussed above (Sarofim et al. 2015). Similar to previous studies, under their base case assumptions using a 3 percent discount rate, Sarofim et al. find global ozone-related mortality benefits of CH$_4$ emissions reductions to be $790 per metric ton of CH$_4$ in 2020, with 10.6 percent, or $80, of this amount resulting from mortality reductions in the United States. Additional welfare impacts of ozone, not included in this estimate, stem from damage to plants, which can lead to reductions in both crop yield and carbon sequestration by natural systems (Felzer et al. 2005, Shindell et al. 2012). Both of these impacts would suggest additional damages associated with CH$_4$ emissions that are not included in the SC-CH$_4$ estimates.

Third, the SC-CH$_4$ estimates do not reflect that CH$_4$ emissions lead to a reduction in atmospheric oxidants such as hydroxyl radicals. These oxidants are important for the conversion of sulfur dioxide into sulfates. Therefore, CH$_4$ emissions can suppress sulfate formation, leading to an increase in radiative forcing but a decrease in particulate matter and resulting health impacts (Shindell et al. 2009, Fry et al. 2012). The net effect of these offsetting impacts is not clear.

Fourth, the SC-CH$_4$ estimates do not account for impacts associated with CO$_2$ produced from CH$_4$ oxidizing in the atmosphere (Boucher et al. 2009); the inclusion of these impacts would increase the SC-CH$_4$ estimates.

Finally, in addition to the climate impacts of N$_2$O on radiative forcing due to changes in CH$_4$ concentrations resulting from effects on stratospheric ozone, UV fluxes, and hydroxyl radical levels discussed above, these changes may also have effects on the atmospheric behavior of other pollutants as well as direct effects on human health. These effects are not currently included in the calculation of the SC-N$_2$O.

## VI. Concluding Remarks

As directed by Executive Orders 12866 and 13563, federal agencies must use the best available scientific, technical, economic, and other information to quantify the costs and benefits of regulatory actions. Rigorous evaluation of costs and benefits has been a core tenet of the rulemaking process for decades. The estimates presented in this addendum offer a tool for improving the analyses of regulatory actions that are projected to influence CH$_4$ or N$_2$O emissions without introducing inconsistency with the manner in which CO$_2$ emission changes are valued. These estimates can and should be updated if and when the modeling assumptions underlying the SC-CO$_2$ estimates are updated to reflect the conclusions of IPCC AR5 or other evolving scientific and economic knowledge.

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## Table A1: Annual SC-CH₄ and SC-N₂O Values: 2010-2050 (2007$/metric ton)

| Year | SC-CH$_4$ | | | | SC-N$_2$O | | | |
|------|-----------|------|------|------|-----------|------|------|------|
| | 5% Average | **3% Average** | 2.5% Average | High Impact (3% 95th) | 5% Average | **3% Average** | 2.5% Average | High Impact (3% 95th) |
| 2010 | 370 | **870** | 1.200 | 2.400 | 3.400 | **12.000** | 18.000 | 31.000 |
| 2011 | 380 | **910** | 1,200 | 2,500 | 3,500 | **12,000** | 18,000 | 32,000 |
| 2012 | 400 | **940** | 1,300 | 2,600 | 3,700 | **12,000** | 19,000 | 33,000 |
| 2013 | 420 | **970** | 1,300 | 2,700 | 3,800 | **13,000** | 19,000 | 34,000 |
| 2014 | 440 | **1,000** | 1,300 | 2,700 | 3,900 | **13,000** | 20,000 | 34,000 |
| 2015 | 450 | **1,000** | 1,400 | 2,800 | 4,000 | **13,000** | 20,000 | 35,000 |
| 2016 | 470 | **1,100** | 1,400 | 2,900 | 4,200 | **14,000** | 20,000 | 36,000 |
| 2017 | 490 | **1,100** | 1,500 | 3,000 | 4,300 | **14,000** | 21,000 | 37,000 |
| 2018 | 510 | **1,100** | 1,500 | 3,000 | 4,400 | **14,000** | 21,000 | 38,000 |
| 2019 | 520 | **1,200** | 1,500 | 3,100 | 4,600 | **15,000** | 22,000 | 38,000 |
| 2020 | 540 | **1,200** | 1,600 | 3,200 | 4,700 | **15,000** | 22,000 | 39,000 |
| 2021 | 560 | **1,200** | 1,600 | 3,300 | 4,900 | **15,000** | 23,000 | 40,000 |
| 2022 | 590 | **1,300** | 1,700 | 3,400 | 5,000 | **16,000** | 23,000 | 41,000 |
| 2023 | 610 | **1,300** | 1,700 | 3,500 | 5,200 | **16,000** | 23,000 | 42,000 |
| 2024 | 630 | **1,400** | 1,800 | 3,600 | 5,400 | **16,000** | 24,000 | 43,000 |
| 2025 | 650 | **1,400** | 1,800 | 3,700 | 5,500 | **17,000** | 24,000 | 44,000 |
| 2026 | 670 | **1,400** | 1,900 | 3,800 | 5,700 | **17,000** | 25,000 | 45,000 |
| 2027 | 700 | **1,500** | 1,900 | 3,900 | 5,900 | **17,000** | 25,000 | 46,000 |
| 2028 | 720 | **1,500** | 2,000 | 4,000 | 6,000 | **18,000** | 26,000 | 47,000 |
| 2029 | 740 | **1,600** | 2,000 | 4,100 | 6,200 | **18,000** | 26,000 | 48,000 |
| 2030 | 760 | **1,600** | 2,000 | 4,200 | 6,300 | **19,000** | 27,000 | 49,000 |
| 2031 | 790 | **1,600** | 2,100 | 4,300 | 6,500 | **19,000** | 27,000 | 50,000 |
| 2032 | 820 | **1,700** | 2,100 | 4,500 | 6,800 | **19,000** | 28,000 | 51,000 |
| 2033 | 850 | **1,700** | 2,200 | 4,600 | 7,000 | **20,000** | 28,000 | 52,000 |
| 2034 | 880 | **1,800** | 2,200 | 4,700 | 7,200 | **20,000** | 29,000 | 54,000 |
| 2035 | 900 | **1,800** | 2,300 | 4,900 | 7,400 | **21,000** | 29,000 | 55,000 |
| 2036 | 930 | **1,900** | 2,400 | 5,000 | 7,600 | **21,000** | 30,000 | 56,000 |
| 2037 | 960 | **1,900** | 2,400 | 5,100 | 7,800 | **21,000** | 30,000 | 57,000 |
| 2038 | 990 | **2,000** | 2,500 | 5,200 | 8,000 | **22,000** | 31,000 | 58,000 |
| 2039 | 1,000 | **2,000** | 2,500 | 5,400 | 8,200 | **22,000** | 31,000 | 59,000 |
| 2040 | 1,000 | **2,000** | 2,600 | 5,500 | 8,400 | **23,000** | 32,000 | 60,000 |
| 2041 | 1,100 | **2,100** | 2,600 | 5,600 | 8,600 | **23,000** | 32,000 | 61,000 |
| 2042 | 1,100 | **2,100** | 2,700 | 5,700 | 8,800 | **23,000** | 33,000 | 62,000 |
| 2043 | 1,100 | **2,200** | 2,700 | 5,800 | 9,100 | **24,000** | 33,000 | 64,000 |
| 2044 | 1,200 | **2,200** | 2,800 | 5,900 | 9,300 | **24,000** | 34,000 | 65,000 |
| 2045 | 1,200 | **2,300** | 2,800 | 6,100 | 9,500 | **25,000** | 34,000 | 66,000 |
| 2046 | 1,200 | **2,300** | 2,900 | 6,200 | 9,800 | **25,000** | 35,000 | 67,000 |
| 2047 | 1,300 | **2,400** | 2,900 | 6,300 | 10,000 | **26,000** | 35,000 | 68,000 |
| 2048 | 1,300 | **2,400** | 3,000 | 6,400 | 10,000 | **26,000** | 36,000 | 69,000 |
| 2049 | 1,300 | **2,500** | 3,000 | 6,500 | 10,000 | **26,000** | 36,000 | 71,000 |
| 2050 | 1,300 | **2,500** | 3,100 | 6,700 | 11,000 | **27,000** | 37,000 | 72,000 |

**Table A2: 2020 Global SC-CH₄ Estimates at 2.5 Percent Discount Rate (2007\$/metric ton CH₄)**

| Percentile | 1st | 5th | 10th | 25th | 50th | Avg | 75th | 90th | 95th | 99th |
|---|---|---|---|---|---|---|---|---|---|---|
| Scenario[16] | | | | | PAGE | | | | | |
| IMAGE | 120 | 220 | 300 | 520 | 1100 | 2200 | 2500 | 5500 | 8300 | 14000 |
| MERGE Optimistic | 90 | 160 | 220 | 380 | 790 | 1600 | 1900 | 4200 | 6400 | 11000 |
| MESSAGE | 110 | 190 | 260 | 450 | 940 | 2000 | 2200 | 5100 | 7900 | 14000 |
| MiniCAM Base | 100 | 190 | 260 | 450 | 940 | 1900 | 2200 | 4900 | 7300 | 13000 |
| 5th Scenario | 64 | 120 | 170 | 290 | 590 | 1400 | 1500 | 3600 | 5900 | 12000 |

| Scenario | | | | | DICE | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| IMAGE | 460 | 580 | 670 | 880 | 1200 | 1400 | 1800 | 2600 | 3000 | 3500 |
| MERGE Optimistic | 330 | 420 | 490 | 640 | 890 | 1000 | 1300 | 1800 | 2100 | 2400 |
| MESSAGE | 420 | 540 | 630 | 820 | 1100 | 1300 | 1700 | 2300 | 2600 | 3100 |
| MiniCAM Base | 400 | 520 | 600 | 790 | 1100 | 1300 | 1700 | 2400 | 2800 | 3300 |
| 5th Scenario | 360 | 460 | 530 | 680 | 920 | 1100 | 1300 | 1900 | 2200 | 2600 |

| Scenario | | | | | FUND | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| IMAGE | 170 | 450 | 610 | 980 | 1600 | 1900 | 2400 | 3600 | 4400 | 6500 |
| MERGE Optimistic | 230 | 500 | 650 | 990 | 1500 | 1800 | 2300 | 3300 | 4100 | 6400 |
| MESSAGE | 180 | 430 | 580 | 920 | 1400 | 1700 | 2200 | 3100 | 3700 | 5500 |
| MiniCAM Base | 230 | 480 | 640 | 1000 | 1600 | 1800 | 2400 | 3500 | 4300 | 6500 |
| 5th Scenario | -10 | 260 | 390 | 670 | 1100 | 1300 | 1700 | 2400 | 3000 | 4400 |

**Table A3: 2020 Global SC-CH₄ Estimates at 3 Percent Discount Rate (2007\$/metric ton CH₄)**

| Percentile | 1st | 5th | 10th | 25th | 50th | Avg | 75th | 90th | 95th | 99th |
|---|---|---|---|---|---|---|---|---|---|---|
| Scenario | | | | | PAGE | | | | | |
| IMAGE | 86 | 160 | 220 | 380 | 800 | 1700 | 1900 | 4200 | 6500 | 12000 |
| MERGE Optimistic | 64 | 120 | 160 | 280 | 590 | 1300 | 1400 | 3300 | 5100 | 8900 |
| MESSAGE | 77 | 140 | 200 | 350 | 720 | 1600 | 1700 | 4000 | 6300 | 12000 |
| MiniCAM Base | 74 | 140 | 190 | 330 | 690 | 1500 | 1600 | 3700 | 5700 | 10000 |
| 5th Scenario | 44 | 91 | 130 | 230 | 470 | 1100 | 1100 | 2800 | 4700 | 9400 |

| Scenario | | | | | DICE | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| IMAGE | 360 | 460 | 530 | 690 | 940 | 1100 | 1400 | 1900 | 2100 | 2500 |
| MERGE Optimistic | 270 | 340 | 400 | 510 | 700 | 790 | 1000 | 1300 | 1500 | 1800 |
| MESSAGE | 350 | 440 | 510 | 660 | 900 | 1000 | 1300 | 1700 | 2000 | 2300 |
| MiniCAM Base | 310 | 400 | 460 | 600 | 830 | 960 | 1200 | 1700 | 2000 | 2300 |
| 5th Scenario | 290 | 370 | 420 | 540 | 720 | 820 | 1000 | 1400 | 1600 | 1900 |

| Scenario | | | | | FUND | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| IMAGE | 160 | 370 | 490 | 760 | 1200 | 1400 | 1800 | 2500 | 3100 | 4600 |
| MERGE Optimistic | 200 | 400 | 520 | 770 | 1200 | 1400 | 1700 | 2400 | 3000 | 4700 |
| MESSAGE | 160 | 370 | 470 | 720 | 1100 | 1300 | 1600 | 2200 | 2700 | 4000 |
| MiniCAM Base | 200 | 400 | 510 | 770 | 1200 | 1300 | 1700 | 2500 | 3000 | 4600 |
| 5th Scenario | 41 | 240 | 340 | 540 | 840 | 980 | 1200 | 1700 | 2100 | 3000 |

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[16] See 2010 SC-CO₂ TSD for a description of these scenarios.

**Table A4: 2020 Global SC-CH₄ Estimates at 5 Percent Discount Rate (2007$/metric ton CH₄)**

| Percentile | 1st | 5th | 10th | 25th | 50th | Avg | 75th | 90th | 95th | 99th |
|---|---|---|---|---|---|---|---|---|---|---|
| Scenario | PAGE | | | | | | | | | |
| IMAGE | 26 | 58 | 85 | 160 | 330 | 770 | 810 | 2000 | 3100 | 6200 |
| MERGE Optimistic | 18 | 42 | 61 | 110 | 240 | 570 | 600 | 1400 | 2300 | 4600 |
| MESSAGE | 23 | 53 | 79 | 150 | 310 | 740 | 770 | 1900 | 3000 | 6100 |
| MiniCAM Base | 20 | 47 | 68 | 130 | 270 | 640 | 670 | 1600 | 2600 | 5100 |
| 5th Scenario | 11 | 34 | 53 | 100 | 220 | 560 | 550 | 1400 | 2300 | 4900 |

| Scenario | DICE | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| IMAGE | 200 | 250 | 290 | 360 | 460 | 490 | 610 | 770 | 850 | 950 |
| MERGE Optimistic | 160 | 200 | 220 | 270 | 350 | 380 | 470 | 590 | 650 | 730 |
| MESSAGE | 210 | 260 | 290 | 360 | 460 | 500 | 610 | 760 | 840 | 940 |
| MiniCAM Base | 170 | 210 | 240 | 300 | 390 | 420 | 520 | 660 | 740 | 830 |
| 5th Scenario | 170 | 210 | 240 | 290 | 370 | 400 | 490 | 610 | 680 | 760 |

| Scenario | FUND | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| IMAGE | 110 | 200 | 250 | 350 | 500 | 570 | 700 | 950 | 1100 | 1700 |
| MERGE Optimistic | 110 | 200 | 250 | 350 | 500 | 570 | 700 | 960 | 1200 | 1800 |
| MESSAGE | 110 | 200 | 240 | 340 | 490 | 550 | 680 | 910 | 1100 | 1600 |
| MiniCAM Base | 120 | 200 | 250 | 340 | 490 | 550 | 680 | 920 | 1100 | 1600 |
| 5th Scenario | 73 | 150 | 200 | 280 | 390 | 430 | 540 | 700 | 820 | 1100 |

**Table A5: 2020 Global SC-N₂O Estimates at 2.5 Percent Discount Rate (2007$/metric ton N₂O)**

| Percentile | 1st | 5th | 10th | 25th | 50th | Avg | 75th | 90th | 95th | 99th |
|---|---|---|---|---|---|---|---|---|---|---|
| Scenario | PAGE | | | | | | | | | |
| IMAGE | 2100 | 3900 | 5300 | 9300 | 20000 | 36000 | 44000 | 92000 | 130000 | 200000 |
| MERGE Optimistic | 1400 | 2500 | 3500 | 6100 | 13000 | 24000 | 30000 | 62000 | 91000 | 140000 |
| MESSAGE | 1400 | 2600 | 3600 | 6400 | 14000 | 28000 | 32000 | 71000 | 110000 | 180000 |
| MiniCAM Base | 1700 | 3100 | 4300 | 7600 | 16000 | 30000 | 37000 | 77000 | 110000 | 170000 |
| 5th Scenario | 650 | 1300 | 1900 | 3400 | 7500 | 18000 | 19000 | 47000 | 75000 | 150000 |

| Scenario | DICE | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| IMAGE | 8900 | 11000 | 13000 | 17000 | 23000 | 26000 | 33000 | 43000 | 49000 | 56000 |
| MERGE Optimistic | 5600 | 7100 | 8100 | 10000 | 14000 | 15000 | 19000 | 25000 | 28000 | 32000 |
| MESSAGE | 6400 | 8000 | 9200 | 12000 | 16000 | 18000 | 23000 | 30000 | 34000 | 40000 |
| MiniCAM Base | 7500 | 9600 | 11000 | 14000 | 20000 | 22000 | 28000 | 38000 | 43000 | 49000 |
| 5th Scenario | 4800 | 6100 | 7000 | 8900 | 12000 | 14000 | 18000 | 25000 | 29000 | 34000 |

| Scenario | FUND | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| IMAGE | 3300 | 6300 | 8200 | 13000 | 20000 | 24000 | 31000 | 44000 | 54000 | 75000 |
| MERGE Optimistic | 3600 | 6400 | 8200 | 12000 | 18000 | 21000 | 27000 | 37000 | 44000 | 65000 |
| MESSAGE | 2700 | 5500 | 7100 | 11000 | 16000 | 19000 | 24000 | 34000 | 40000 | 56000 |
| MiniCAM Base | 3500 | 6500 | 8200 | 12000 | 19000 | 22000 | 29000 | 41000 | 49000 | 71000 |
| 5th Scenario | 790 | 3300 | 4500 | 7300 | 12000 | 14000 | 18000 | 27000 | 32000 | 44000 |

**Table A6: 2020 Global SC-N$_2$O Estimates at 3 Percent Discount Rate (2007\$/metric ton N$_2$O)**

| Percentile | 1st | 5th | 10th | 25th | 50th | Avg | 75th | 90th | 95th | 99th |
|---|---|---|---|---|---|---|---|---|---|---|
| Scenario | | | | | | PAGE | | | | |
| IMAGE | 1400 | 2500 | 3500 | 6200 | 13000 | 25000 | 30000 | 65000 | 95000 | 150000 |
| MERGE Optimistic | 910 | 1700 | 2300 | 4100 | 8900 | 17000 | 21000 | 45000 | 67000 | 100000 |
| MESSAGE | 930 | 1800 | 2500 | 4400 | 9600 | 20000 | 23000 | 51000 | 78000 | 140000 |
| MiniCAM Base | 1100 | 2000 | 2800 | 4900 | 11000 | 21000 | 25000 | 54000 | 79000 | 130000 |
| 5th Scenario | 440 | 910 | 1300 | 2400 | 5400 | 13000 | 14000 | 34000 | 54000 | 110000 |

| Scenario | | | | | | DICE | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| IMAGE | 6000 | 7600 | 8700 | 11000 | 15000 | 17000 | 21000 | 28000 | 31000 | 35000 |
| MERGE Optimistic | 3900 | 5000 | 5600 | 7200 | 9500 | 10000 | 13000 | 17000 | 19000 | 21000 |
| MESSAGE | 4600 | 5700 | 6600 | 8400 | 11000 | 12000 | 16000 | 20000 | 23000 | 26000 |
| MiniCAM Base | 5000 | 6400 | 7300 | 9400 | 13000 | 14000 | 18000 | 24000 | 27000 | 30000 |
| 5th Scenario | 3400 | 4300 | 4900 | 6200 | 8300 | 9600 | 12000 | 16000 | 19000 | 22000 |

| Scenario | | | | | | FUND | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| IMAGE | 2400 | 4500 | 5700 | 8400 | 13000 | 15000 | 19000 | 28000 | 33000 | 47000 |
| MERGE Optimistic | 2600 | 4500 | 5600 | 8100 | 12000 | 14000 | 17000 | 24000 | 29000 | 43000 |
| MESSAGE | 2000 | 4000 | 5000 | 7300 | 11000 | 13000 | 16000 | 22000 | 26000 | 37000 |
| MiniCAM Base | 2600 | 4500 | 5700 | 8300 | 12000 | 14000 | 18000 | 26000 | 31000 | 45000 |
| 5th Scenario | 790 | 2500 | 3300 | 5200 | 7900 | 9100 | 12000 | 17000 | 20000 | 28000 |

**Table A7: 2020 Global SC-N$_2$O Estimates at 5 Percent Discount Rate (2007\$/metric ton N$_2$O)**

| Percentile | 1st | 5th | 10th | 25th | 50th | Avg | 75th | 90th | 95th | 99th |
|---|---|---|---|---|---|---|---|---|---|---|
| Scenario | | | | | | PAGE | | | | |
| IMAGE | 330 | 680 | 950 | 1700 | 3800 | 8300 | 9200 | 21000 | 33000 | 61000 |
| MERGE Optimistic | 220 | 450 | 640 | 1200 | 2600 | 5700 | 6300 | 15000 | 23000 | 42000 |
| MESSAGE | 250 | 530 | 750 | 1400 | 3100 | 6900 | 7500 | 18000 | 28000 | 54000 |
| MiniCAM Base | 250 | 520 | 730 | 1300 | 3000 | 6500 | 7200 | 17000 | 26000 | 48000 |
| 5th Scenario | 110 | 290 | 440 | 830 | 1900 | 4700 | 4800 | 12000 | 20000 | 42000 |

| Scenario | | | | | | DICE | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| IMAGE | 2100 | 2600 | 2900 | 3600 | 4600 | 4900 | 6000 | 7500 | 8200 | 9200 |
| MERGE Optimistic | 1500 | 1800 | 2000 | 2500 | 3200 | 3400 | 4200 | 5100 | 5600 | 6200 |
| MESSAGE | 1800 | 2200 | 2500 | 3100 | 3900 | 4200 | 5100 | 6300 | 7000 | 7700 |
| MiniCAM Base | 1700 | 2100 | 2300 | 2900 | 3700 | 4000 | 4900 | 6100 | 6800 | 7500 |
| 5th Scenario | 1400 | 1700 | 1900 | 2300 | 2900 | 3200 | 3900 | 4900 | 5400 | 6100 |

| Scenario | | | | | | FUND | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| IMAGE | 890 | 1500 | 1900 | 2600 | 3700 | 4200 | 5200 | 7000 | 8400 | 12000 |
| MERGE Optimistic | 900 | 1500 | 1800 | 2500 | 3500 | 4100 | 5000 | 6800 | 8200 | 12000 |
| MESSAGE | 830 | 1400 | 1800 | 2400 | 3400 | 3800 | 4700 | 6300 | 7500 | 11000 |
| MiniCAM Base | 980 | 1500 | 1800 | 2500 | 3500 | 3900 | 4800 | 6500 | 7800 | 12000 |
| 5th Scenario | 540 | 1100 | 1300 | 1800 | 2500 | 2800 | 3500 | 4600 | 5300 | 7200 |

**Table A8: Additional Summary Statistics of 2020 Global SC-CH₄ Estimates**

| Discount rate: | 5.0% | | | | 3.0% | | | | 2.5% | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Statistic: | Mean | Variance | Skewness | Kurtosis | Mean | Variance | Skewness | Kurtosis | Mean | Variance | Skewness | Kurtosis |
| DICE | 440 | 28000 | 1 | 0 | 930 | 210000 | 1 | 1 | 1200 | 420000 | 1 | 1 |
| PAGE | 650 | 1200000 | 4 | 26 | 1400 | 4400000 | 3 | 15 | 1800 | 6700000 | 3 | 13 |
| FUND | 530 | 160000 | 44 | 5900 | 1300 | 7800000 | 36 | 12000 | 1700 | 29000000 | -4 | 11000 |

**Table A9: Additional Summary Statistics of 2020 Global SC-N₂O Estimates**

| Discount rate: | 5.0% | | | | 3.0% | | | | 2.5% | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Statistic: | Mean | Variance | Skewness | Kurtosis | Mean | Variance | Skewness | Kurtosis | Mean | Variance | Skewness | Kurtosis |
| DICE | 3900 | 2300000 | 1 | 0 | 13000 | 40000000 | 2 | 13 | 19000 | 110000000 | 4 | 67 |
| PAGE | 6400 | 97000000 | 4 | 17 | 19000 | 690000000 | 3 | 9 | 27000 | 1300000000 | 3 | 8 |
| FUND | 3700 | 5400000 | -2 | 260 | 13000 | 120000000 | -1 | 360 | 20000 | 370000000 | -2 | 540 |