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Technical Update to Environment and Climate Change Canada’s Social Cost of Greenhouse Gas Estimates

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Executive Summary

The Government of Canada requires departments and agencies to conduct cost-benefit analysis of regulatory proposals as part of Regulatory Impact Analysis Statements. In considering regulations that would affect greenhouse gas (GHG) emissions, it is necessary to develop an appropriate monetary benefit (or cost) value for the consequences of reducing (increasing) GHG emissions in terms of altered impacts of climate change.

Climate change is a global problem. This is true both in terms of the causes of climate change and its impacts. Therefore, a global perspective is fundamental to adequately evaluating the benefits of reducing GHG emissions.

In 2010 and 2011, Environment and Climate Change Canada led an interdepartmental review of approaches to valuing GHG emissions, which recommended the adoption of Social Cost of Carbon (SCC) values based on research and analysis conducted by the U.S. Interagency Working Group on Social Cost of Carbon in 2010. The SCC is a monetary measure of the global damage expected from climate change from the emissions of an additional tonne of carbon dioxide (CO_2) in the atmosphere in a given year.

The SCC is a measure of the incremental additional damages that are expected from a small increase in CO_2 emissions (or conversely, the avoided damages from a decrease in CO_2 emissions). Estimates of the SCC therefore provide a way to value CO_2 emission changes in cost-benefit analysis where the goal is to provide informed analysis to decision makers that quantifies the incremental mitigation benefits associated with a policy action and compares them to the incremental costs of abatement. However, it would not necessarily be appropriate to use the estimates in another context or infer that the SCC as it is developed here should be considered as a potential carbon price for Canada.

Sophisticated models have been developed in the academic community that draw on economic and scientific knowledge to estimate the SCC. However, given that the models forecast both natural and economic outcomes centuries into the future, there is inherent uncertainty associated with the estimates, and a wide range of SCC values are reported in the literature. The SCC approach was preferred to the U.K.'s shadow price of carbon because it was well suited to Environment and Climate Change Canada's regulatory context, the Government of Canada approach to cost-benefit analysis, and aligned with the interdepartmental working group's objective to use credible, robust values.

The U.S. Interagency Working Group relied on three peer-reviewed, global, integrated assessment models developed by leading academic experts in the field to produce estimates of the SCC in a given year. The U.S. Working Group chose to develop four different sets of values to reflect uncertainty with respect to the discount rate, which determines how future costs are valued today, and the risk of severe catastrophes under low-probability scenarios. The SCC values increase over time, as emissions accumulate in the atmosphere and the cost associated with an additional tonne of CO_2 emissions increases.

Canada's interdepartmental working group recommended the adoption of the U.S. values in 2011, with a few minor adjustments. Instead of four different values, the group recommended two estimates using the same discount rate. The 3% discount rate selected is the central rate used in the U.S. and reflects the 3% social discount rate recommended by Canada's Treasury Board Secretariat Analysis Guide. The first estimate is the average central tendency estimate of the three models considered in U.S. SCC estimation (FUND, PAGE and DICE). The second estimate reflects lower probability, high-cost climate change impacts and is referred to as the 95th percentile of the SCC probability distribution. With the second estimate, the interdepartmental group recommended the exclusion of one of the models from the calculation, given that it does not include low-probability, high-cost impacts. As well, all of the estimates were transferred from US$ 2007 to US$ 2009 using the U.S. Gross Domestic Product (GDP) deflator and then converted into 2009 Canadian dollars. The use of the estimates in Canada was also extended to all GHGs (multiplying the SCC by the CO_2 equivalent of other GHGs[1]) because it was a greater issue to place no value on non-CO_2 GHG emissions than to use the SCC as a conservative (lower end) estimate when direct modelling of damages from a given GHG is unavailable.

The U.S. Interagency Working Group has acknowledged the limitations of the analysis related to developing SCC estimates given the current state of scientific knowledge, model capabilities and ongoing debates regarding appropriate discount rates. They committed to regularly updating the SCC estimates to reflect model updates and new economic or scientific insight.

In May 2013, the U.S. Interagency Working Group released a Technical Update Document with new SCC estimates. The revised estimates only reflect model updates to capture new insights from scientific and economic research. None of the original assumptions regarding discount rate, emissions scenarios or climate sensitivity have been revisited. Among many other changes, the DICE model now features an explicit representation of sea-level dynamics that is much more in line with actual sea-level variation. The FUND model now features an improved level of detail in land loss potential from sea-level rise, and the PAGE model features damage functions that are constrained by GDP, making it more realistic. While some of the changes made would reduce estimates of the SCC on their own, the overall effect of all of the changes considered is an increase in estimates. In November 2013 and July 2015, the U.S. Interagency Working Group released revised versions of its Technical Update Document with corrections, addressing minor issues in the modelling. Details on these corrections are included in Annex 2.

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[1] Based on the Global Warming Potentials (100 year) of GHGs from the IPCC's Fourth Assessment Report (AR4).

Following the publications of the updated U.S. estimates in May 2013 and the technical corrections of November 2013 and July 2015, Environment and Climate Change Canada reunited its interdepartmental working group to review and assess the changes. The group concluded that the updates are technical in nature, and provide a better reflection of the modeling exercise that was undertaken.

The table below shows the previous and updated central and 95th percentile SCC estimates for the Government of Canada, over the period from 2010–2050. The update, which incorporates the same adjustments to the U.S. values described above, results in a central SCC value of $41/tonne CO_2 in 2016 (C$ 2012)—an increase of 30% from the previous $31/tonne CO_2 (C$ 2012)—and an upper bound (95th percentile) value of $167/tonne CO_2 (C$ 2012) for sensitivity analysis—an increase of 34% from the previous $125/tonne CO_2.

Previous and Updated Canadian SCC Estimates for Period 2010 2050 (in C$ 2012[2] per tonne CO_2, discounted at 3%)[3]

Year	Previous central	Updated central	Previous 95th percentile	Updated 95th percentile
2010	27.6	34.1	108.6	131.5
2013	29.4	37.4	116.5	149.3
2015	30.7	39.6	121.8	161.1
2016	**31.3**	**40.7**	**124.5**	**167.0**
2020	33.9	45.1	135.1	190.7
2025	38.1	49.8	151.2	213.3
2030	42.2	54.5	167.4	235.8
2035	46.4	59.6	183.6	258.9
2040	50.5	64.7	199.6	281.9
2045	54.2	69.7	213.9	300.9
2050	57.8	74.8	228.0	319.8

In August 2015, the U.S. Environmental Protection Agency (USEPA) published two proposed regulations, both of which incorporated recently published, peer-reviewed estimates of the Social Cost of Methane ($SCCH_4$) in the central analysis of the cost-benefit analyses associated with these regulations. The USEPA also used these $SCCH_4$ (and analogous estimates for the Social Cost of Nitrous Oxide (SCN_2O)) in sensitivity analysis in an earlier proposed regulation in July 2015. Details on these estimates are included in Annex 3. The $SCCH_4$ and SCN_2O

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[2] The U.S. GDP deflator was used to bring the estimates from US$ 2007 to US$ 2012, which were then converted to C$ 2012.

[3] Estimates were modeled for years 2010, 2020, 2030, 2040, and 2050. To obtain estimates for years in between, one needs to linearly interpolate based on the estimates which are above and below the year desired.

estimates from the USEPA were adapted for the Canadian context by using the same process and methodology as was used for the SCC. The tables below show the Canadian estimates that have been established for both the $SCCH_4$ and the SCN_2O. These estimates will continue to be refined and updated with new developments in scientific and economic knowledge.

Canadian $SCCH_4$ Estimates for Period 2010–2050 (in C$ 2012 per tonne CH_4, discounted at 3%)

Year	Central	95th percentile
2010	946	2,857
2015	1,129	3,394
2016	**1,165**	**3,501**
2020	1,312	3,931
2025	1,519	4,735
2030	1,726	5,539
2035	1,971	6,480
2040	2,215	7,421
2045	2,462	8,233
2050	2,709	9,046

Canadian SCN_2O Estimates for Period 2010–2050 (in C$ 2012 per tonne N_20, discounted at 3%)

Year	Central	95th percentile
2010	12,847	42,476
2015	14,551	48,483
2016	**14,892**	**49,684**
2020	16,255	54,490
2025	18,185	61,839
2030	20,115	69,188
2035	22,287	77,356
2040	24,460	85,525
2045	26,798	94,118
2050	29,135	102,711

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1. Introduction

Government of Canada departments and agencies are required to conduct cost-benefit analysis of regulatory proposals as part of their Regulatory Impact Analysis Statements (RIAS). Cost-benefit analysis helps to inform decision-makers, stakeholders and the general public of potential positive and negative impacts of regulations on health, safety, the environment and the economy.

Cost-benefit analysis is an analytical process whereby impacts are quantified and summed with positive impacts (benefits) being assigned positive values and negative impacts (costs) being assigned negative values. Benefits accrued and costs incurred over time as a result of the proposed regulatory initiative are converted to present-day dollar values.

The process for quantifying these values is different for different types of impacts. While the financial costs of a regulation to businesses would already be quantified in monetary terms, other benefits or costs need to be converted into a monetary value. In order to undertake cost-benefit analysis related to greenhouse gas (GHG) regulations, it is necessary to develop a monetary value associated with reducing GHG emissions.

In 2010 and 2011, Environment and Climate Change Canada led the Canadian Interdepartmental Working Group (Canadian Group) in its review of approaches to valuing GHG emissions that recommended the use of values based on research and analysis undertaken by a U.S. Interagency Working Group (U.S. Group) in 2010.[4] The U.S. Group developed a set of values based on what is known as the "Social Cost of Carbon." Details regarding the approach taken by the U.S. Group were outlined in a 2010 Technical Support Document.[5] The U.S. Group published an update to this work in May 2013, with new recommended values (and has issued minor technical corrections twice since then – in November 2013 and July 2015).[6] Highlights of both of these documents are provided later in this paper.

The Social Cost of Carbon (SCC) is a term used to describe an estimate of the monetary value in a given year of worldwide damage that will occur over the coming decades and centuries from emitting one additional tonne of carbon dioxide (CO_2) emissions. Specifically, the SCC represents the marginal damage of an additional tonne of CO_2 emitted into the atmosphere in a given year, expressed in dollars, based on an assumed global CO_2 emissions path.

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[4] Environment Canada's Economic Analysis Directorate, *Selecting a Value for CO_2 Emissions of Government of Canada Regulatory Impact Analysis Statements*, 2011.

[5] Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866

[6] Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866

To calculate the SCC, it is necessary to project the impacts of the assumed global CO_2 path on the climate (e.g., temperature, precipitation and weather events). It is then necessary to determine the physical impacts associated with those climate impacts (e.g., sea levels, agriculture, forests, water availability, pests). An economic value then needs to be placed on the physical impacts to generate a monetary value for the emission.

Once the SCC values are generated, multiplying the appropriate SCC value for a given year by the total expected CO_2 emissions reductions (or increases) for that year, and then summing the discounted values over the time period considered for analysis, allows these GHG benefits (or costs) to be considered within cost-benefit analysis.

SCC values are generated using a specific subset of integrated assessment models (IAMs) developed by the academic community. Given that the exercise involves forecasting both natural and economic outcomes 50 to 300 years into the future, it is inherently uncertain. The U.S. approach recognizes this uncertainty and tries to capture a range of possibilities with varying assumptions.

Since the 2011 interdepartmental review, Environment and Climate Change Canada has used the SCC in all RIAS that involve GHG emissions. Natural Resources Canada and Transport Canada have also used the values in cost-benefit analysis. The Canadian Group recently revised its recommended SCC values for the Government of Canada based on the spring 2013 U.S. update (and the two minor technical corrections that have since been published).

The purpose of this paper is to present Environment and Climate Change Canada's revised values, describe the approach taken to establish SCC values and the rationale for following the U.S. in their recent update. The report is structured as follows:

- Section 2 discusses the U.S. Group's approach to the SCC;
- Section 3 presents the U.S. Group's SCC estimates;
- Section 4 outlines Environment and Climate Change Canada's approach to developing values for GHG emissions;
- Section 5 presents Environment and Climate Change Canada's adaptation of U.S. SCC estimates;
- Section 6 provides an overview of acknowledged model limitations and critiques;
- Section 7 presents the Technical Update of the SCC values; and
- Section 8 outlines revised Environment and Climate Change Canada recommended SCC values and concludes with a discussion concerning uncertainty, the utility of the SCC and next steps.
- Annex 1 shows the U.S. estimates of the SCC, expressed in Canadian dollars.
- Annex 2 describes the November 2013 and July 2015 technical corrections to the SCC.
- Annex 3 outlines the developments around the use of estimates for non-CO_2 GHG emissions.

2. The U.S. Interagency Working Group Approach to Social Cost of Carbon[7]

In order to describe how Environment and Climate Change Canada arrived at recommended SCC values, it is first necessary to outline the U.S. Group Approach, based on their 2010 Technical Support Document.

Estimating the SCC is made possible by the use of a particular subset of IAMs developed by the academic community, which bring together several different lines of research, including:

- GHG emissions forecasting, which includes consideration of demographic, economic and political variables;
- Climate change science (i.e., the study of the biogeochemical cycles and atmospheric processes that determine the fate of the GHG emissions, and the resulting changes in climate);
- The effect of the changes in climate on agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services; and
- The determination of impacts based on these changes and the valuation or monetization of these impacts.

The three IAMs selected by the U.S. Group are the three most commonly used peer-reviewed IAMs for estimating the SCC: PAGE, FUND and DICE. These models generally come in three parts: (1) emissions; (2) atmospheric composition and climate change; and (3) climate damages.

For each year, the U.S. SCC estimates are derived by running each of the selected three IAMs 10,000 times with random draws from the equilibrium climate sensitivity (ECS) probability distribution (and other model-specific uncertain parameters), for each of five sets of Gross Domestic Product (GDP), population and emissions trajectories over a period extending from the present day to 2300, for each of three discount rates. The outputs yield a frequency distribution of SCC estimates (\$/tonne CO_2) conditional on each discount rate for a given year. The models are run for each year over the time horizon considered to be relevant for policy and/or regulatory analysis.

For each of the IAMs, the basic computational steps (in general terms) for calculating the SCC in a particular year, *t,* are:

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[7] This section draws from the content of the U.S. Interagency Working Group Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866. Please refer to this document (p. 24) for a more specific and detailed description (Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866).

1. Select and input the path of emissions, GDP and population from the selected reference/baseline scenarios (generated from a separate modelling exercise);
2. Calculate the temperature effects and damages/benefits in each year resulting from the baseline path of emissions;
3. Create a new scenario by adding an additional tonne of CO_2 emissions in year *t*;
4. Recalculate the temperature effects and damages (benefits) across the economy expected in all years beyond *t* resulting from this adjusted emissions pathway;
5. Subtract the damages computed in Step 2 from those in Step 4 in each year;
6. Discount the resulting path of marginal damages back to the year of emissions using the agreed-upon fixed discount rates; and
7. Calculate the SCC as the net present value of the discounted path of damages computed in Step 6, divided by the unit of carbon/CO_2 emissions used to shock the models in Step 3.

To produce a range of plausible estimates to use in regulatory analysis, the SCC estimates were averaged across models and scenarios (each having equal weight), implicitly defining a frequency distribution of the SCC conditional on each discount rate in a given year. This approach helps to capture some of the key uncertainties associated with forecasting socio-economic and emissions scenarios, the climate system response to increased GHG concentrations, and balances out the strengths and weaknesses of the different IAMs.

The U.S. Group decided to select four values from the SCC distributions to reflect two key areas of uncertainty. The first is the discount rate, which determines how future costs are valued today. Lower discount rates place a greater value on future costs, resulting in higher SCC values. The U.S. Group selected the average SCC value conditional on the three discount rates chosen to represent a range of views in the academic literature (2.5%, 3%, and 5%).

The second uncertainty is with regard to lower probability, high-cost damages. This is intended to reflect the risk of higher-than-expected impacts from temperature change under low-probability scenarios. The U.S. Group felt this risk justified placing more weight on the tail of the distribution and selected the 95th percentile of the SCC frequency distribution corresponding to a 3% discount rate as a fourth value to use in regulatory analysis.

2.1 Integrated Assessment Models

As noted previously, three IAMs are used in the development of SCC estimates: PAGE, FUND and DICE. These models are commonly used for developing SCC estimates in the literature. Each model is weighed equally in the generation of central SCC estimates, balancing their respective strengths and weaknesses.

Each model has a different approach to estimating the economic damage resulting from changes in CO_2 emissions. For instance, PAGE measures damages as a percentage of GDP, based on the temperature difference between the given period and the pre-industrial average for the region where damage is to be measured. In FUND, the damage functions also consider the speed at which the temperature has increased from the last period to the present time. In DICE, temperature affects consumption as well as investment levels.

The PAGE model, developed by Chris Hope (University of Cambridge), features exogenous GDP growth, along with damages being split into the economic, non-economic and catastrophic categories, all of which are calculated separately for eight different regions. The model considers catastrophic damage in a separate damage function, attributing a stronger probability with increased temperature levels.[8]

The FUND model, developed by David Anthoff (University of California, Berkeley) and Richard Tol (University of Sussex), also features exogenous GDP growth as well as separately calibrated damage functions for 8 market and non-market sectors, which have different functional forms to calculate damage over 16 regions. The model does not account for the possibility of catastrophic events. Adaptation is included both implicitly and explicitly in the model, depending on the sector.[9]

The DICE model, developed by William Nordhaus (Yale), is an optimal growth production model that is based on a global production function with atmospheric CO_2 concentrations incorporated as an extra variable. This model perceives GHG emissions reductions as an investment in natural capital, implying that investing today (lower consumption) will enable higher future consumption. Technological progress is represented in the model by a declining carbon intensity of production over time. Adaptation is not included explicitly in the model, although it is implicitly included through the damage function. DICE differs from other models in that (1) GDP is endogenous, and (2) damages in a given period will reduce investment at that time, increasing damages in the future.[10]

2.2 Modelling Assumptions

The key modelling assumptions harmonized across models in the U.S. Group's approach include climate sensitivity, socio-economic and emissions trajectories, and discount rate.

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[8] HOPE, Chris, *The Marginal Impact of CO_2 from PAGE2002: An Integrated Assessment Model Incorporating the IPCC's Five Reasons for Concern*, Integrated Assessment 6, no. 1, 2006. The Marginal Impact of CO2 from PAGE2002: An Integrated Assessment Model Incorporating the IPCC's Five Reasons for Concern

[9] ANTHOFF, David, TOL, Richard, *The Climate Framework for Uncertainty, Negotiation and Distribution (FUND), Technical Description, Version 3.5*, 2010. The Climate Framework for Uncertainty, Negotiation and Distribution (FUND), Technical Description

[10] NORDHAUS, William, *The Challenge of Global Warming: Economic Models and Environmental Policy*, Vol. 4. New Haven: Yale University, 2007. The Challenge of Global Warming: Economic Models and Environmental Policy

2.2.1 Equilibrium Climate Sensitivity

Equilibrium climate sensitivity (ECS or climate sensitivity) is a metric used to describe how temperature responds to increases in atmospheric GHG concentrations. ECS is defined by the Intergovernmental Panel on Climate Change (IPCC) as the global annual mean surface air temperature change experienced by the climate system after it has attained a new equilibrium in response to a doubling of atmospheric CO_2 concentration relative to pre-industrial levels (or stabilization at a concentration of approximately 550 parts per million [ppm]).[11]

The U.S. Group uses the IPCC Fourth Assessment Report (AR4) as the basis for climate sensitivity assumptions.[12] This assumes a *likely* increase in temperature (greater than 66% probability) from a doubling of CO_2 concentrations of between 2°C and 4.5°C, with a best estimate of about 3°C. It further assumes that it is *very likely* (greater than 90% probability) that ECS is larger than 1.5°C.

The assessment translates into two modelling constraints around the distributions used for climate sensitivity:

1. A median equal to 3°C, to reflect the judgment of "a most likely value of about 3°C"; and
2. Two-thirds probability that the ECS lies between 2 and 4.5°C.

Four probability distributions that fit these constraints were considered, with the Roe and Baker distribution[13] being selected as it was the only distribution that was based on a theoretical understanding of the climate system response to increased GHG concentrations. The U.S. Group also felt it best reflected the IPCC judgment that values above 4.5°C cannot be excluded.[14]

The most recent IPCC Assessment Report (AR5) Working Group I updates conclusions relating to ECS, stating that the *likely* (greater than 66% probability) range is between 1.5°C and 4.5°C, that it is *extremely unlikely* (less than 5% probability) to be less than 1°C and *very unlikely* (less than 10% probability) to be greater than 6°C. The Summary for Policy Makers further notes that "No best estimate for equilibrium climate sensitivity can now be given because of a lack of agreement on values across assessed lines of evidence and studies." While a median (representing the most likely estimate suggested by the IPCC) ECS of 3°C from the AR4 was used as a constraint

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[11] *Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, p. 14, 2013. Climate Change 2013: The Physical Science Basis

[12] Intergovernmental Panel on Climate Change, *Climate Change 2007: Synthesis Report*. Climate Change 2007: Synthesis Report

[13] ROE, G., and BAKER, M., *Why is climate sensitivity so unpredictable?,* Science 318:629-632, 2007.

[14] *Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, p. 14, 2013. Climate Change 2013: The Physical Science Basis

in the U.S. Group Report, a substantially different median would be inconsistent with the AR5 assessment that ECS is *very unlikely* to be more than 6°C and *extremely unlikely* less than 1°C. For this reason, no change was made to the ECS parameter in this update.

2.2.2 Socio-economic and Emissions Trajectories

To estimate and monetize damages resulting from future climate change, it is necessary to construct forecasts of global population, GDP, and CO_2 emissions and non-CO_2 radiative forcing. Typically, higher population and greater wealth tend to result in higher GHG emissions, as well as a higher willingness to pay to avoid climate impacts.

The U.S. Group sought to identify a reliable, internally consistent set of policy scenarios for future global emissions, selecting five scenarios from a Stanford Energy Modelling Forum (EMF) exercise titled "EMF-22."[15] The EMF—an international forum for sharing and facilitating discussions on energy policy and global climate issues among experts—undertook the EMF-22 exercise to develop climate change control scenarios that reflect recent technological developments in their assessment of the costs of stabilizing CO_2 concentrations in the atmosphere, leading to a variety of scenarios of future emissions paths. The EMF-22 scenarios were chosen because they were recent (2009), peer-reviewed, published and publicly available.

In selecting scenarios, the U.S. Group aimed to include scenarios that spanned plausible ranges of outcomes. Among the 10 IAMs[16] used for EMF-22, 4 (MiniCAM, MESSAGE, IMAGE and MERGE) were selected, and their business-as-usual trajectories were used as scenarios with a resulting range of CO_2 atmospheric concentrations from 612 ppm to 889 ppm in 2100. These scenarios are considered to be representative of a broad spectrum of outcomes absent significant global mitigation action. The fifth scenario[17] represented stabilization at 550 ppm carbon dioxide equivalent (CO_2e) (425–484 ppm CO_2 only) in 2100, implying a greater level of global action to reduce GHG emissions. Scenarios that achieved lower GHG concentrations were not considered.

Probability distributions of SCC values are calculated in all three IAMs, under the five different EMF scenarios. Final values are determined using the average across models and scenarios.

2.2.3 Discount Rate

The effects of climate change occur over very long time horizons, making it necessary to consider how to value future costs today. A positive discount rate gives a lower weight to future costs. A zero discount rate would value them equally. The discount rate is meant to

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[15] For more information on the EMF-22 scenarios and their use in SCC calculations by the U.S. Group, please refer to the SCC Technical Support Document. Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866

[16] The IAMs used for the EMF-22 scenarios are different from the ones used for evaluating the SCC. Every other occurrence where IAMs are mentioned in this paper refers to the models used in the SCC estimation.

[17] For the 550 ppm CO_2e scenario, the U.S. Group averaged the GDP, population, and emission trajectories implied by the same four models used in the business-as-usual scenarios.

reflect both a rate of time preference and relative risk aversion. Discount rate selection is frequently controversial particularly in the intergenerational context, and while it is recognized that the choice of discount rate has a significant influence on the resulting SCC estimates, there is no consensus position in the literature on the “correct” discount rate to use. Some advocate discount rates based on observed market rates of return. Others argue that it is unethical to value costs to future generations less than those to current generations.

The U.S. Group selected three different discount rates to reflect varying views in the economic literature (2.5%, 3% and 5%). The central rate at 3% is recommended by the U.S. Office of Management and Budget when a regulation primarily affects private consumption. The U.S. Group developed SCC values for each of the three discount rates.

3. Initial U.S. SCC Estimates

The U.S. Group developed four sets of annual values from 2010 to 2050. The first three sets consist of averages of the three IAM outputs for each of the three discount rates: 2.5%, 3% and 5%. The fourth set of values represents an average of the results at the 95th percentile of the probability distribution, with a 3% discount rate. The 95th percentile value is meant to represent low-probability, high-cost impacts of climate change. In U.S. cost-benefit analyses presented in regulatory impact analysis, each of the four resulting SCC values is given consideration. This means that four sets of results for each year are produced to reflect the various potential outcomes depending on the SCC value retained. Tables 1, 2 and 3 below contain the sets of values developed in 2010 by the U.S. Group, the average annual growth rate for each decade of each set of values, as well as the distribution of values estimated by the models for each discount rate considered. The SCC estimates grow over time because future emissions are expected to produce larger incremental damages as the economy grows and physical and economic systems become more stressed in response to greater climatic change.

Table 1: U.S. SCC Estimates for Period 2010–2050 as published in 2010 (in US$ 2007/tonne of CO_2)

Discount rate	5%	3%	2.5%	3%
Year	**Average**	**Average**	**Average**	**95th percentile**
2010	4.7	21.4	35.1	64.9
2015	5.7	23.8	38.4	72.8
2016	**6.0**	**24.3**	**39.1**	**74.4**
2020	6.8	26.3	41.7	80.7
2025	8.2	29.6	45.9	90.4
2030	9.7	32.8	50.0	100.0
2035	11.2	36.0	54.2	109.7
2040	12.7	39.2	58.4	119.3
2045	14.2	42.1	61.7	127.8
2050	15.7	44.9	65.0	136.2

Source: United States Government[18]

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[18] United States Government, *Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866*, February 2010. Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866

Table 2: Average Annual Real Growth Rates of U.S. SCC Estimates Between 2010 and 2050*

Discount rate	5%	3%	2.5%	3%
Average annual real growth rate	**Average**	**Average**	**Average**	**95th percentile**
2010–2020	3.6%	2.1%	1.7%	2.2%
2020–2030	3.7%	2.2%	1.8%	2.2%
2030–2040	2.7%	1.8%	1.6%	1.8%
2040–2050	2.1%	1.4%	1.1%	1.3%

Source: United States Government[19]

*This table shows the real growth rate of each set of values of the U.S. SCC values issued in the 2010 Technical Support Document (Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866). Two factors explain the differences in growth paths of each set of values. First, as time passes, there is economic growth, and atmospheric concentrations of GHGs are higher. While the average temperature increase associated with each tonne of CO_2 emitted declines with increased atmospheric carbon concentrations, incremental damages increase with increased carbon concentrations as the economy grows to a greater degree, meaning that marginal damages increase through time. Second, as the damages of climate change get closer in time, they will be discounted less and therefore have a higher value.

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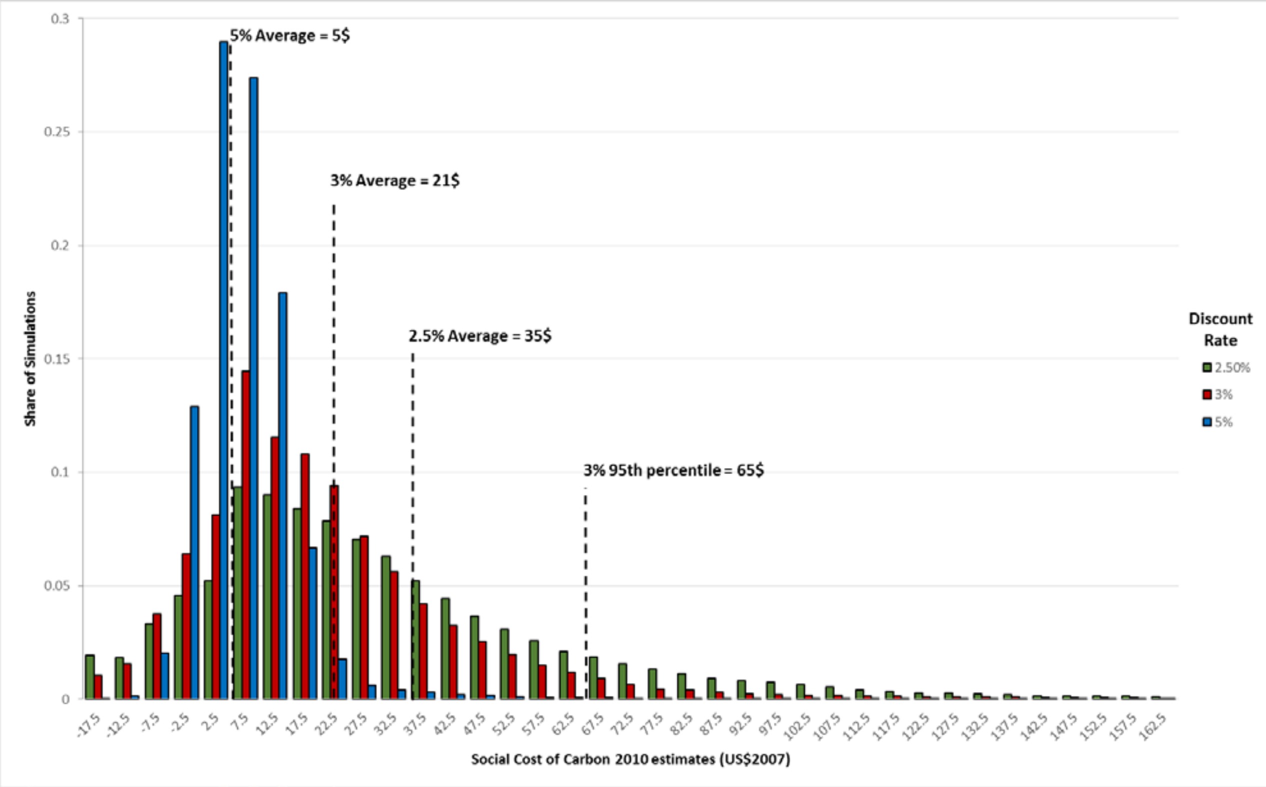
[19] *Ibid.*

Figure 1: Histogram of Global U.S. SCC Estimates in 2010 by Discount Rate, as published in 2010* (in US$ 2007/tonne of CO_2)**



Data Source: United States Government[20]

*The estimates used to produce this graph were taken from the 2010 Technical Support Document produced by the Interagency Working Group on the Social Cost of Carbon
**The distribution of SCC values ranges from -$5,192 to $66,116, but the X-axis has been truncated at approximately the 1st and 99th percentiles to better illustrate the data.

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[20] *Ibid.*

4. Canada's Approach to Developing Values for Greenhouse Gas Emissions

Over the course of 2010 and 2011, Environment and Climate Change Canada led a Government of Canada interdepartmental working group (Canadian Group) to determine how best to value GHG emissions in cost-benefit analysis. Two sets of values were explored: (1) the shadow price of carbon (or marginal abatement cost) used by the U.K. and France; and (2) the SCC used by the U.S. There are advantages and disadvantages to the use of each in different contexts. The Canadian Group determined that the U.S. SCC was the most appropriate estimate for the Canadian regulatory context for several reasons:

1. Following the U.K. approach would require estimating the marginal abatement costs associated with attaining a given emission reduction target, necessitating assumptions regarding federal, provincial and territorial policy choices (e.g., sector coverage, compliance flexibility);
2. The SCC is consistent with other approaches to valuation used in cost-benefit analysis, where values are based on an estimation of marginal damages;
3. The U.S. approach represents a robust attempt to capture the uncertainty in SCC estimates by using three different IAMs, five different emissions scenarios, and a higher value to represent lower probability, higher cost impacts;
4. The estimates derived by the U.S. Group are based on the work of a number of highly respected academic and government experts, and have been thoroughly vetted and reviewed; and
5. Key decisions of the U.S. Group, such as the use of global values and inclusion of a value to reflect the possibility of low probability, high impact events, were consistent with insights from climate science.

The Canadian Group agreed to recommend Canadian SCC values based on the work of the U.S., with a few minor adjustments to reflect recommendations of the group.

5. Canada's Adaptation of U.S. SCC Estimates

The Canadian Group considered how best to adapt the U.S. SCC work for Canada over the course of 2011. While alternative parameters, such as declining discount rates, were discussed, it was ultimately determined that it was more practical to adopt the U.S. results. Revisiting core parameters would have required a significant investment by the Government of Canada to acquire and run the IAMs used in the analysis. Given the extensive amount of work undertaken by the U.S. Group, and the substantial expertise involved in the effort, it was determined that it would be most effective to adopt the U.S. values as produced by the U.S. Group, with a few minor adjustments. Given the integrated nature of the Canadian and U.S. economies, alignment of regulatory and analytical approaches, which includes the Social Cost of Carbon, can be mutually beneficial. As major trading partners, alignment on the SCC ensures consistent communication of impacts to stakeholders and facilitates regulatory cooperation by incorporating common metrics to assess policies. Although both countries will feel the impacts of climate change differently, the costs included in the Social Cost of Carbon are global in nature. As such, estimates of climate change impacts for regulatory policies should be very similar. The approach recommended by the Canadian Group therefore uses the U.S. model results to estimate the SCC, with three minor adjustments:

1. Instead of using three discount rates, the Canadian group recommended using only the 3% central rate. Treasury Board Secretariat guidance recommends a social discount rate of 3% in circumstances where environmental and human health impacts are involved, as is the case for the SCC.[21] Following Treasury Board Secretariat guidance helps ensure consistency across federal departments. There was also a preference among Canadian Group members to limit the number of SCC values considered, as it was felt that it would be challenging to present four sets of cost-benefit results to decision-makers.
2. For the Canadian calculation of the 95th percentile estimates, the results of the FUND model are not included, as the model does not incorporate the low-probability, high-cost events that the 95th percentile value is meant to address. In Environment and Climate Change Canada cost-benefit analysis, the 95th percentile SCC values are used to estimate the sensitivity of the results to higher SCC values.
3. U.S. SCC estimates are then updated to reflect inflation through to 2012 using the U.S. GDP deflator and then converted into Canadian dollars. The Canadian values are updated regularly with the Canadian GDP deflator in order to correct for ongoing inflation.

While the use of the 95th percentile provides a more fulsome consideration of the possible range of impacts associated with climate change, it does not represent the extreme high end of SCC

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[21] Where relevant and applicable, the analysis can also be accompanied by the use of a shadow price of investment applied to all the costs of the intervention that results in a postponement or reduction of investment activity, estimated to be 7%.

estimates in the literature. Some studies have produced estimates exceeding \$1000/tCO_2 when considering more extreme scenarios, which include parameters such as very high climate sensitivity.[22]

At the time of the review, the Canadian Group acknowledged that estimation of the SCC was a complex and evolving field of study. Environment and Climate Change Canada committed to monitor research and analysis related to the SCC and to consider adjustments as appropriate.

The Canadian Group also recognized that cost-benefit analysis was only one analytical tool available to analyze GHG regulations, and recommended supplementary cost-effectiveness analysis.

Another distinction between Canadian and U.S. approaches relates to the use of the SCC for valuing emissions of non-CO_2 GHGs. To our knowledge, the U.S. has not used the SCC for non-CO_2 GHGs within their main analysis of any cost-benefit analyses[23], given that their global warming potential and lifespan are different (e.g., methane, or CH_4, has a much stronger warming potential, and its effects are felt in a much shorter timeframe).

However, Environment and Climate Change Canada concluded that it was likely a greater error to place no value on non-CO_2 emissions than to use the SCC, given the significant contributions of non-CO_2 GHG emissions to climate change impacts over the time period used in the analysis (2010–2050). Marten and Newbold (2012) confirmed this finding, showing that estimates of the social costs of methane and nitrous oxide would likely be higher than applying the SCC estimates to the emissions changes adjusted for global warming potential.[24] Environment and Climate Change Canada determined that using the SCC values for non-CO_2 GHGs is a conservative approach and has used the SCC in its cost-benefit analysis to value emission reductions from non-CO_2 GHGs for which no direct estimation consistent with the methodology and modelling framework underlying the SCC estimates are available. However, it was noted that if credible, peer-reviewed alternative methodologies to valuing non-CO_2 GHGs were developed, this approach would be reassessed.

Such methodologies have emerged and the U.S. EPA has since developed and used a Social Cost of Methane in the central case of the cost-benefit analysis for two proposed regulations[25]. It has

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[22] Ceronsky *et. al.* (2005) estimate the SCC for various catastrophic scenarios and estimate the SCC around \$1132/tCO_2 (in C\$ 2012) when considering a climate sensitivity of 9.3°C.

[23] The U.S. Environmental Protection Agency has used estimates of the SCC multiplied with the Global Warming Potential for methane, in the sensitivity analysis of regulations as an indication of what these impacts could look like.

[24] For more details, please see Marten, A. L.,& Newbold, S. C., *Estimating the social cost of non-CO_2 GHG emissions: Methane and nitrous oxide*, Energy Policy, 51, 957–972, 2012. Estimating the social cost of non-CO2 GHG emissions: Methane and nitrous oxide

[25] U.S. Environmental Protection Agency (EPA). 2015a. *Regulatory Impact Analysis for the Proposed Revisions to the Emission Guidelines for Existing Sources and Supplemental Proposed New Source Performance Standards in the Municipal Solid Waste Landfills Sector*. Office of Air Quality Planning and Standards, Health and Environmental Impacts Division. August.
U.S. Environmental Protection Agency (EPA). 2015b. *Regulatory Impact Analysis of the Proposed Emission Standards for New and Modified Sources in the Oil and Natural Gas Sector*. Office of Air Quality Planning and Standards. August.

also developed a Social Cost of Nitrous Oxide. Following a similar approach to the one used for the SCC, Environment and Climate Change Canada has developed a Canadian version of these estimates. Please see Annex 3 for more details around these developments. ECCC will continue to monitor developments on the valuation of non-CO_2 GHGs and will reassess its approach as further credible, peer-reviewed work emerges, whether it seeks to refine the Social Costs of Methane and Nitrous Oxide, or develop an approach for other GHGs.

Table 3 contains the previous Canadian estimates for the SCC for the 2010–2050 timescale in 2009 Canadian dollars. These values have been used by Environment and Climate Change Canada, Natural Resources Canada and Transport Canada for cost-benefit analyses to support regulatory processes since 2011. Environment and Climate Change Canada has, since then, used the SCC in all RIAS with a noticeable impact on GHG emissions, including light and heavy-duty vehicle, coal-fired electricity and renewable fuel regulations. The metric has also been used by Environment and Climate Change Canada to support policy development in other areas, such as environmental assessments and analysis of protected areas.

Table 3: Previous Canadian SCC Estimates for Period 2010–2050 as established in 2011 (in C$ 2009, discounted at 3%)

Year	Central estimate	95th percentile estimate
2010	25.6	100.9
2013	27.3	108.3
2015	28.5	113.2
2016	**29.1**	**115.7**
2020	31.5	125.5
2025	35.4	140.5
2030	39.2	155.5
2035	43.1	170.6
2040	46.9	185.5
2045	50.4	198.7
2050	53.7	211.8

6. Model Limitations and Critiques in the Literature

While the approach used by the U.S. to estimate the SCC is the most suitable method of placing a value on GHG emissions for Canada, the process of developing estimates of the SCC is by nature highly uncertain.

In its 2010 technical support document, the U.S. Group acknowledged a number of limitations of the analysis associated with SCC estimates, including incomplete treatment of non-catastrophic and potential catastrophic damages; uncertainty in extrapolation of damages to high temperatures; incomplete treatment of adaptation and technological change; and risk aversion to high-impact outcomes. Many critiques in the literature focus on these same areas, and these critiques form the basis for efforts to improve the estimation of the SCC. A short description of each of the main limitations/areas of critique is provided below.

Parameter uncertainty and model transparency: Uncertainty in the specification of parameters is one of the most common critiques of the IAMs. Parameters can either come from published, peer-reviewed scientific or economic literature or, where there is disagreement in the literature, reflect modellers' assumptions. Critics argue that parameter selection should be more carefully documented in order to increase transparency, and that uncertainties associated with parameter specification should be better identified and measured.[26] The U.S. Group provided significant detail on key parameters involved in the development of its SCC values in its Technical Support Document.

Inadequate representation of (non-catastrophic) damages: The treatment of damages in the IAMs has been criticized for not sufficiently reflecting the current state of knowledge concerning climate impacts. The U.S. Group acknowledged the limitations of the analysis, stating: "Current IAMs do not assign value to all the important physical, ecological and economic impacts recognized in the climate change literature because of [a] lack of precise information on the nature of the damages and because the science incorporated into these models understandably lags behind the most recent research."[27] Critics argue that more complex models are required to run low-mitigation scenarios to test the behaviour of the carbon cycle and climate system under these policy-relevant conditions and that the IAMs should be calibrated to these more advanced models. In addition, while impacts are estimated for a number of sectors such as agriculture and fisheries, the coverage of economic sectors is not comprehensive.[28]

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[26] NORDHAUS, William D., *Estimates of the Social Cost of Carbon: Background and Results from the RICE-2011 Model*, No. w17540, National Bureau of Economic Research, 2011, p. 25.

[27] United States Government, *Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866*, February 2010. Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866

[28] DOWNING, Thomas E. et. al., *Social Cost of Carbon: A Closer Look at Uncertainty*, Department for Environment, Food and Rural Affairs, U-K Government, 2005, p. iii.

Furthermore, regional representation of damages is limited, affecting the capture of potential regional variability and inter-regional interactions. Different models include a different number of regions, which result in different damage estimations.

Lastly, the IAM damage functions are calibrated to moderate temperature increases, with damages associated with higher temperatures being determined by extrapolation (as a power of the temperature range). Damage estimation under more extreme climate change scenarios is therefore subject to substantial uncertainty.[29]

The critiques regarding damage functions highlight the importance of continually updating both the IAMs and the SCC values used by governments. As outlined in Section 7, the recent U.S. update in SCC values is based on updates to the three IAMs to reflect developments in scientific and economic literature.

Catastrophic events: A common critique of the models is the degree to which they address low-probability, high-impact—or *catastrophic*—outcomes. Specifically, the models may not adequately capture potentially discontinuous abrupt or catastrophic[30] changes in the climate system.[31] The science around this issue remains under development, and there is a lack of consensus as to how best to capture the associated risk and risk premiums in the estimation of the SCC. The three IAMs used consider potential catastrophic outcomes to varying degrees: FUND does not include potentially catastrophic outcomes; DICE assesses catastrophic damages deterministically (by adding the expected value of the damage from a catastrophic event to the aggregate damage function); and PAGE treats the possibility of a catastrophic event probabilistically (by measuring damage as perceived change in welfare associated with the probability of a catastrophic event, accounting for risk aversion). While not explicitly the intent of the U.S. Group, the Canadian Group determined that the use of the 95th percentile of the SCC distribution in Environment and Climate Change Canada's regulatory and policy analysis is one way to try to capture a more fulsome sense of the higher costs associated with higher than expected impacts including potential catastrophic impacts of climate change.

Inter-sector and inter-regional interactions: At higher levels of global warming, some inter-sector and inter-regional interactions gain importance and are the underlying source of climate-induced national and economic security concerns. It is argued that these potential interactions such as changes in food supply or climate-induced migration from flooding or water scarcity are unevenly captured and frequently not represented in the models used to estimate the SCC.

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[29] KOPP, Robert E., MIGNONE, Bryan K., *The U.S. Government's Social Cost of Carbon Estimates after Their First Two Years: Pathways for Improvement*, Economics: The Open-Access, Open-Assessment E-Journal 6, 2012, p. 18.

[30] In the IAMs, a catastrophe is a low-probability environmental change with a high economic impact.

[31] United States Government, *Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866*, February 2010. Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866

Imperfect substitutability of environmental amenities: The three IAMs used to estimate the SCC assume that natural system losses can be compensated through increased consumption of non-climate goods. While this assumption is common to many economic models, and has a basis in theory, it is possible that in the context of climate change this substitutability is limited—damages to natural systems could become so great that no increase in non-climate goods could compensate. Critics argue that the limited nature of this substitutability could have significant implications for IAM outputs.

Risk aversion: A related critique is that the IAMs inadequately consider risk aversion with respect to high-impact outcomes.[32] Model calculations do not factor in that individuals may have a higher willingness to pay to avoid low-probability, high-impact outcomes, than for higher-probability, low-impact outcomes with the same estimated aggregate cost (the U.S. Group's inclusion of the 95th percentile estimate was largely motivated by this concern). While the U.S. Group further put forward the question as to whether regulatory assessments should consider such willingness to pay, they did not land conclusively on one side or the other, noting that the issue is important and that further investigation is warranted.[33]

Equity weights: There may also be a relationship between damages and willingness to pay. It is argued that the use of equity weights (where costs to low-income regions are given more weight than costs to high-income regions) would allow for greater or lesser economic importance to be ascribed to damages in certain world regions, thereby more accurately capturing the "true" economic impact.[34] In their 2010 work, the U.S. Group specifically excluded consideration of equity weights in part due to the significant challenges associated with developing an appropriate equity weight framework.[35] The U.S. Group further noted that even if it were appropriate, equity weights should not be used in developing the SCC for use in regulatory policy at this time.

Discount rate (intra- or inter-generational effect): As discussed earlier, the choice of discount rate is a highly contentious issue and has seen significant coverage in the literature[36]. The Stern Review

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[32] DIETZ, Simon, *The Treatment of Risk and Uncertainty in the US Social Cost of Carbon for Regulatory Impact Analysis*, Economics: The Open-Access, Open-Assessment E-Journal, 6.2012-18, 2012

[33] United States Government, *Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866*, February 2010. Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866

[34] DOWNING, Thomas E. *et. al.*, *Social Cost of Carbon: A Closer Look at Uncertainty*, Department for Environment, Food and Rural Affairs, U-K Government, 2005, p. 11.

[35] United States Government, *Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866*, February 2010, p. 11. Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866

[36] The literature on discount rates in the context of climate change economics and intergenerational impacts more broadly is extensive and divided. Beyond the Stern Review itself, see Goulder and Williams (2012), Beckerman and Hepburn (2007), and Ackerman (2007), for initial overviews of Stern's approach and summaries of the various critiques. Arrow et. al. (2012) summarizes the views of a recent expert panel on discounting benefits and costs in an intergenerational context.

(2007) employed a low value (1.4%)[37] for the discount rate, resulting in a substantially higher SCC estimate.[38] Weitzman has argued that given the large uncertainties concerning catastrophic events, the discount rate should decline over time, to represent a risk-adjusted discount rate.[39] Others have also looked into the idea of discount rates that decline over time in order to better take into consideration uncertainty in the discount rate over time. This literature suggests that the use of a declining discount rate does not have to be exclusively justified using ethical arguments. A recent article by Arrow et al. (2014) reviews the economic theory that points to the appropriateness of a declining discount rate when the future is uncertain.[40] The U.S. Technical Support Document outlines their consideration of discount rates in significant detail, and notes that in light of disagreement in the literature and uncertainty about how discount rates may change over time the U.S. Group decided to use three different constant rates to span (2.5%, 3% and 5%) to span a plausible range of intergenerational rates.

Adaptation response: Adaptation measures have been included in models to varying degrees. What counts as adaptation and the extent to which adaptation reduces impacts is variable between models. The literature argues that a better understanding of these impacts is needed, given the large uncertainties that remain. Another related source of uncertainty is the degree to which the IAMs capture technological changes and how these changes would impact both mitigation and adaptation at a regional or sub-national level, potentially altering emissions and adaptation pathways. Given uncertainty, the incomplete treatment of adaptation and technological change may under- or overestimate associated damages.[41]

Global SCC values: Some critics have argued that it is inappropriate to use a global measure of climate change benefits, given that the standard practice for cost-benefit analysis is normally domestic costs and benefits.[42] However, there are two unique aspects to climate change that justify the use of global values: (1) it involves a global externality, where emissions anywhere in the world contribute to global damages; and (2) the only way to address climate change is through global action. A majority of SCC estimates in the literature consider the global costs of climate change for these reasons.[43]

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[37] Stern used a pure rate of time preference of 0.1% and assumed an elasticity of marginal utility of 1. The PAGE model used by Stern had an average growth rate of consumption of 1.3%. Overall, this led to a discount rate of about 1.4%.

[38] STERN, Nicholas, *Stern Review on the Economics of Climate Change*, Cambridge University press, 2007, p. 41.

[39] WEITZMAN, Martin, *Rare Disasters, Tail-Hedged Investments, and Risk-Adjusted Discount Rates*, Working Paper 18496, National Bureau of Economic Research, October 2012, p. 28.

[40] ARROW, Kenneth, et al. (2014), *Should Governments Use a Declining Discount Rate in Project Analysis?*, Review of Environmental Economics and Policy, 8(2): 145-163.

[41] TOL, Richard S.J., *The Social Cost of Carbon: Trends, Outliers and Catastrophes,* Economics: The Open-Access, Open-Assessment E-Journal 2.2008-25, 2008, p. 2.

[42] HEYES, Anthony, MORGAN, Dylan, RIVERS, Nicholas, *The Use of a Social Cost of Carbon in Canadian Cost-Benefit Analysis*, Canadian Public Policy 39, 2013, p. 68.

[43] ROSE, Stephen K., *The role of the social cost of carbon in policy*, WIREs Climate Change, 3: 195–212, 2012, p. 205.

Finally, while the significant uncertainty associated with SCC estimates is openly acknowledged, reviews in both the U.S. and Canadian federal governments have concluded that the current approach to estimating the SCC is the most credible available at this time.

In its 2010 Technical Support Document, the U.S. Group on the SCC committed to continue to support research in this area and recommended that SCC estimates be revisited on a regular basis or as model updates become available. The intent was that the SCC estimates consistently reflect the most up-to-date scientific and economic knowledge, particularly to the extent that this knowledge is reflected in the models used in the estimation of the SCC; i.e., where model updates better reflect the state of knowledge and therefore improve the resulting estimates, new estimates should be generated.

In July 2015, the U.S. Group announced alongside a detailed summary and formal response to public comments (and minor technical correction to the SCC estimates), that it had requested that the National Academies of Sciences undertake a review of the latest research available on modeling the economic impacts of climate change in order to inform future changes to the SCC estimates developed by the U.S. Group. The study is being conducted in two phases, the first of which has been completed, and has led to the publication of an interim report. Focused on the tradeoffs associated with potential near-term narrow updates to the SCC, the report recommended that no short-term update be undertaken.[44] In early 2017, the final report is expected to be published, which will look into a range of alternative approaches to updating the SCC estimates, in order for these estimates to reflect the best science available, and will recommend research priorities for the future.

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[44] For more information on this process, please consult Assessing Approaches to Updating the Social Cost of Carbon - Project Description.

7. Technical Update of the SCC

On May 31, 2013, the U.S. Group publicly released updated SCC estimates. The update was based on new versions of each of the three IAMs used in the 2010 estimates. The updates reflect new insights from scientific and economic research. They do not revisit core assumptions made in 2010 regarding the discount rate, socio-economic and emission scenarios or climate sensitivity. The following sections describe the various relevant refinements to the three models.[45]

7.1 PAGE[46]

There are numerous changes between PAGE2002 and PAGE2009. The changes that have a direct impact on SCC estimates include the explicit modelling of the impacts of sea-level rise, a revision to the damage function to constrain damages to GDP, revised treatment for the probability of a discontinuity in the damage function, and revised assumptions on adaptation.

Sea-level rise damages have been added as a new category of damages, while the two other categories, economic and non-economic damages, have been adjusted to account for this change in scope of damages (i.e., to avoid double-counting). PAGE2009 also adds a new feature to ensure that potential damages cannot exceed total GDP; this limit was not present in PAGE2002.

The probability of a discontinuity (a non-linear extreme event, or a *catastrophic* event) is also significantly altered. Whereas in PAGE2002 a discontinuity was modelled as an expected value (i.e., the probability of a discontinuity was multiplied by the associated damages to obtain an expected value that was added to the economic and non-economic impacts), in PAGE2009 a discontinuity is modelled as a discrete event for each year; the damages are estimated either with or without a discontinuity occurring.

In addition, the temperature threshold for a possible discontinuity is lower than in PAGE2002, and both the level of damage from a discontinuity and its likelihood to increase as a function of temperature are higher. The model assumes that only one discontinuity can occur, and that when it does, it is permanent. Finally, adaptation assumptions are modified to reflect a smaller assumed reduction in vulnerability resulting from adaptation as well as a longer expected time period over which the vulnerability would be reduced (i.e., individual adaptation measures take longer to take effect). Both these changes would be expected to result in increased SCC estimates.

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[45] For a more comprehensive discussion of the model updates, please see the U.S. Government's technical support document from July 2015. Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866 All SCC related documents can be found at: Office of Management and Budget – Social Cost of Carbon.

[46] This section draws mainly from the U.S. Government's technical update document, as the evolution of the model is not well-described in the literature.

7.2 FUND[47]

FUND 3.8 features many changes compared with version 3.5 of the model. The changes that have significance with respect to SCC estimation include adjustments to the calculation of energy needs in relation to space heating, adjustments to the sea-level rise function, changes to the transient temperature response function, and the addition of indirect effects from methane emissions.

As the temperature increases, space heating needs decrease. The adjustments to the space heating calculation ensure that energy benefits relating to reduced space heating requirements are not overstated. Whereas FUND 3.5 allowed for the possibility of unbounded scaling of the space heating benefit as a function of increased temperature, FUND 3.8 ensures that the estimate of the benefit resulting from a reduction in space heating needs at no time exceeds twice the benefit accrued from a one degree increase in temperature (i.e., the benefit scaling function approaches a value of two in the limit of large temperature anomalies).

Changes to the sea-level rise and land loss calculations improve the level of detail of the land loss potential by considering that slopes of shorelines increase moving inland, as opposed to the initial approach, which assumed constant slopes. This reduces the modelled vulnerability of land to sea-level rise.

The transient temperature response function translates a change in global levels of radiative forcing into an expected corresponding change in temperature. In FUND, the change in temperature for a given year is determined based on a mean reverting function where the mean is the equilibrium temperature that would eventually be reached were that year's level of radiative forcing sustained. This function has been modified to better reflect research that demonstrates that the ECS has a more muted influence on the rate of the transient response, resulting in the temperature response typically being faster than estimated using the previous version of the model. In general, this results in a higher damage estimate, as while the same damages occur, they occur earlier (higher temperatures are reached earlier) and are therefore subject to a lower discount factor, increasing the value of the SCC.

Finally, FUND 3.8 incorporates indirect effects from methane emissions as detailed in the IPCC's AR4. These include setting the average atmospheric lifetime of methane to 12 years to account for the feedback of methane emissions on its own lifetime, and increasing the radiative forcing associated with atmospheric methane by 40% to account for the net impact of methane on ozone

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[47] This sections draws mainly from the U.S. Government's technical update document on the SCC from July 2015. Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866 For more detailed information on the model, please refer to FUND - Climate Framework for Uncertainty, Negotiation and Distribution.

production and stratospheric water vapour. Both changes result in higher temperature estimates and corresponding higher SCC estimates.

7.3 DICE

The 2010 DICE model incorporates a number of changes to the previously used 2007 version. Among these changes, the ones particularly pertinent to the estimation of SCC values are the updated parameter values for the carbon cycle model, the inclusion of an explicit representation of sea-level dynamics, and a re-calibrated damage function that features an explicit representation of economic damages from sea-level rise.

The update to the carbon cycle model reflects the weakening of the ocean as a carbon sink, which leads to higher concentrations of carbon in the atmosphere for the same emissions pathway. The inclusion of an explicit representation of sea-level dynamics in DICE2010 estimates sea-level rise as a function of thermal expansion of the oceans, melting glaciers and small ice caps, melting of the Greenland ice sheet, and melting of the Antarctic ice sheet. The re-calibrated damage function featured in DICE2010 generally has the effect of reducing damage in most of the early periods, while raising the damages in later periods, overall resulting in larger global damages.[48]

7.4 Updated U.S. Values

As was the case in the 2010 methodology, each of the three IAMs were run 10,000 times with random draws from the equilibrium climate sensitivity (ECS) probability distribution (and other model-specific uncertain parameters), for five different socio-economic and emissions scenarios using three different discount rates. The results were pooled (and weighted equally) across models and scenarios to produce three separate frequency distributions for the SCC in a given year, one for each of the three discount rates. As in 2010, from the 3 distributions, the U.S. Group selected 4 values: the average SCC at each discount rate (2.5%, 3%, and 5%) and the 95th percentile at a 3% discount rate. The fourth value is meant to represent low-probability, high-cost impacts. Tables 5, 6 and 7 provide the previous and updated U.S. SCC values for years 2010–2050, the average annual growth rate for each decade of each set of values, as well as a distribution of the values produced by the IAMs presented for each discount rate used. The estimates that follow include minor technical corrections published in November 2013 and July 2015. For more detail about these technical corrections, please consult Annex 2.

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[48] NORDHAUS, William D., *Integrated Economic and Climate Modeling*, No. 1839, Cowles Foundation for Research in Economics, Yale University, 2011.

Table 4: Previous and Updated U.S. SCC Estimates for Period 2010–2050 (US$ 2007/tonne of CO_2)[49]

Year	Previous 5% average	Updated 5% average	Previous 3% average	Updated 3% average	Previous 2.5% average	Updated 2.5% average	Previous 3% 95th	Updated , 3% 95th
2010	4.7	10	21.4	31	35.1	50	64.9	86
2015	5.7	11	23.8	36	38.4	56	72.8	105
2016	**6.0**	**11**	**24.3**	**38**	**39.1**	**57**	**74.4**	**108**
2020	6.8	12	26.3	42	41.7	62	80.7	123
2025	8.2	14	29.6	46	45.9	68	90.4	138
2030	9.7	16	32.8	50	50.0	73	100.0	152
2035	11.2	18	36.0	55	54.2	78	109.7	168
2040	12.7	21	39.2	60	58.4	84	119.3	183
2045	14.2	23	42.1	64	61.7	89	127.8	197
2050	15.7	26	44.9	69	65.0	95	136.2	212

Source: United States Government[50]

In order to use the SCC in cost-benefit analysis, it is first necessary to assess the difference in GHG emissions between the policy and baseline scenarios. For each year where there is a difference, each tonne of CO_2 equivalent emission reductions (or increases) needs to be multiplied by the SCC for that year. The resulting value then needs to be discounted back to present value, along with the other costs and benefits of the proposed policy. It is then possible to compare all costs and benefits on the same basis, supporting consistent analysis.

Table 5: Average Annual Real Growth Rates of Updated U.S. SCC Estimates Between 2010 and 2050

Discount rate	5%	3%	2.5%	3%
Average annual real growth rate	**Average**	**Average**	**Average**	**95th percentile**
2010–2020	1.2%	3.3%	2.4%	4.4%
2020–2030	3.4%	2.1%	1.7%	2.4%
2030–2040	3.0%	1.9%	1.5%	2.1%
2040–2050	2.6%	1.6%	1.3%	1.5%

Source: United States Government[51]

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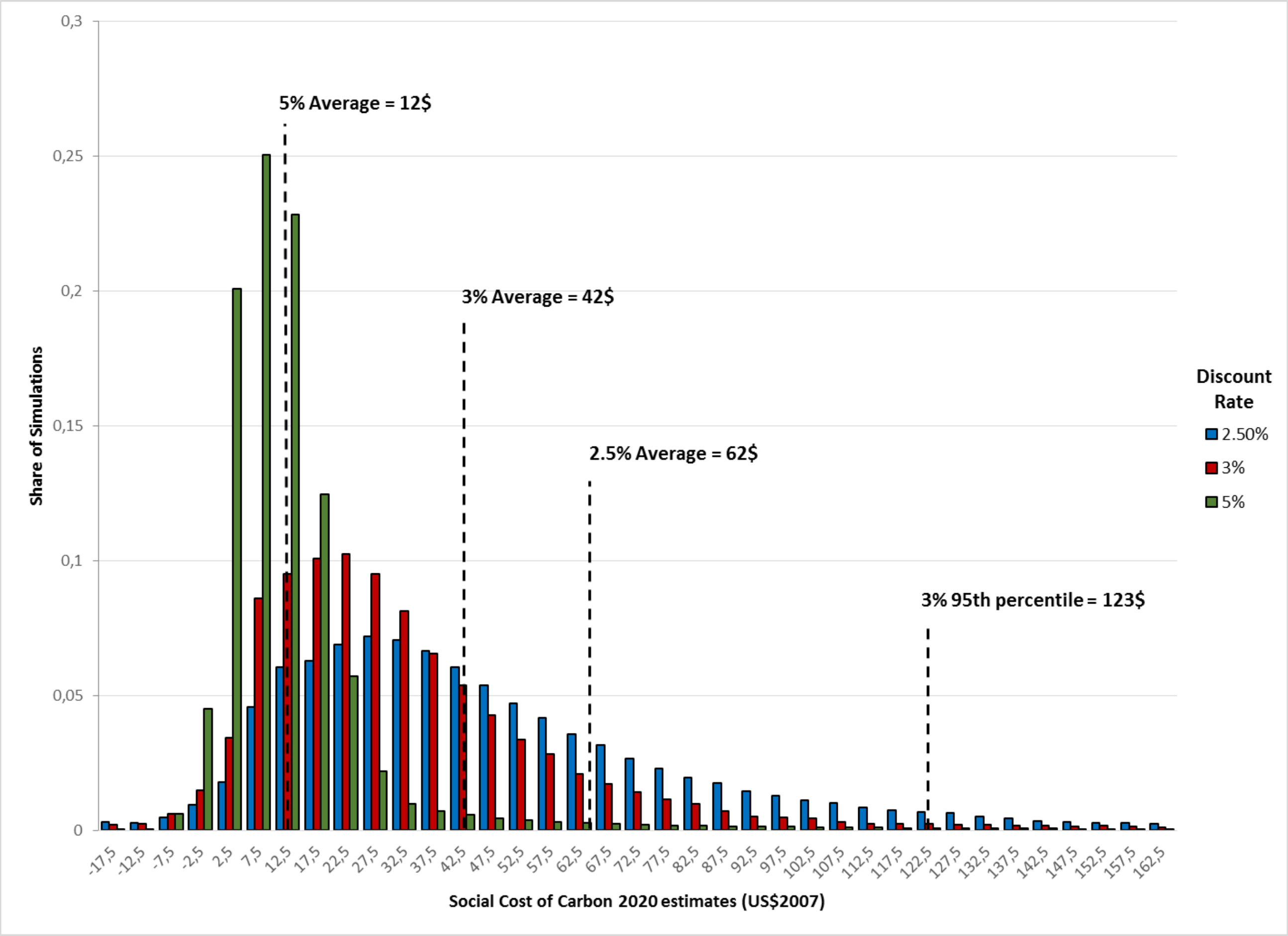
[49] Annex 1 provides these values in C$ 2012, in order to facilitate comparison of U.S. and Canadian estimates listed in this document.

[50] United States Government, *Technical Update Document: Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866*, 2013 (revised July 2015). Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866.

[51] *Ibid.*

Figure 2: Distribution of Updated U.S. SCC Estimates for 2020 (in US$ 2007/tonnes of CO_2)



Data Source: United States Government[52]

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[52] *Ibid.*

8. Updated Canadian SCC Values

Following the publication of the updated U.S. estimates in May 2013 and the technical corrections of November 2013 and July 2015, Environment and Climate Change Canada reconvened the Canadian Group to review and assess the changes. The Canadian Group concluded that the changes made to the models were peer-reviewed technical improvements, and recommended updating Environment and Climate Change Canada's recommended values accordingly.

The update of Environment and Climate Change Canada's recommended SCC values to reflect the changes to the models used in the U.S. results in a central SCC value in 2016 of $41/tonne CO_2—an increase of 30%—and an upper bound (95th percentile) value of $167/tonne CO_2 for sensitivity analysis— an increase of 34% over the previous estimate. Table 8 lists the updated SCC estimates for the years 2010 through 2050. It includes the central tendency as well as 95th percentile values (for sensitivity analysis). As Environment and Climate Change Canada's estimates are based on the U.S. dollar outputs of the three IAMs, they have been converted to Canadian dollars and are updated regularly to reflect inflation.

The SCC remains an imperfect but important tool for estimating the benefits associated with reductions in GHG emissions. In particular, in the Canadian context, the SCC is essential for cost-benefit analysis of regulations that reduce or increase GHGs.

The SCC estimates presented in this paper should be treated as provisional, with the expectation that they will be revised with further advancements in scientific and economic research. While the significant uncertainty associated with SCC estimates is openly acknowledged, expert reviews in both the U.S. and Canadian governments have concluded that it is the most credible approach available at this time. Environment and Climate Change Canada will continue to monitor research and analysis related to the SCC and to consider updating the values as new information becomes available.

The review process of the U.S. Group's estimation of the SCC being undertaken by the National Academies of Science will provide important insight on future changes to the modeling of economic impacts of climate change. Following the completion of this process, Environment and Climate Change Canada is considering the idea of initiating a peer-review of the subset of the approach which relates to the adaptation of U.S. estimates for use in Canada. This peer-review would most notably address issues such as the recent changes in the Canadian Dollar's exchange rate, the discount rates used to produce the estimates, and the removal of the FUND model from the 95th percentile estimates.

Table 6: Previous vs. Updated Canadian SCC Estimates for Period 2010–2050 (in C$ 2012, discounted at 3%)[53]

Year	Previous central	Updated central	Previous 95th percentile	Updated 95th percentile
2010	27.6	34.1	108.6	131.5
2013	29.4	37.4	116.5	149.3
2015	30.7	39.6	121.8	161.1
2016	**31.3**	**40.7**	**124.5**	**167.0**
2020	33.9	45.1	135.1	190.7
2025	38.1	49.8	151.2	213.3
2030	42.2	54.5	167.4	235.8
2035	46.4	59.6	183.6	258.9
2040	50.5	64.7	199.6	281.9
2045	54.2	69.7	213.9	300.9
2050	57.8	74.8	228.0	319.8

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[53] Estimates were modeled for years 2010, 2020, 2030, 2040, and 2050. To obtain estimates for years in between, one needs to linearly interpolate based on the estimates which are above and below the year desired.

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Annex 1: U.S. SCC Estimates Expressed in C$

Table A1-1: Previous and Updated U.S. SCC Estimates for Period 2010–2050 (C$ 2012)

Year	Previous 5% average	Updated 5% average	Previous 3% average	Updated 3% average	Previous 2.5% average	Updated 2.5% average	Previous, 3% 95th	Updated, 3% 95th
2010	5.1	11.4	23.2	34.1	38.1	54.4	70.5	93.2
2015	6.2	12.1	25.9	39.6	41.7	60.9	79.1	113.6
2016	**6.5**	**12.2**	**26.4**	**40.7**	**42.4**	**62.3**	**80.8**	**117.6**
2020	7.4	12.8	28.6	45.1	45.3	67.5	87.7	133.9
2025	8.9	14.9	32.2	49.8	49.9	73.3	98.2	149.4
2030	10.5	17.1	35.6	54.5	54.3	79.0	108.6	164.9
2035	12.2	19.7	39.1	59.6	58.9	85.0	119.2	181.8
2040	13.8	22.3	42.6	64.7	63.4	91.1	129.6	198.7
2045	15.4	25.1	45.7	69.7	67.0	97.0	138.8	214.1
2050	17.1	28.0	48.8	74.8	70.6	102.9	147.9	229.6

Annex 2: Technical Corrections to the SCC

In November 2013, the U.S. Interagency Working Group made two minor technical corrections to elements of its modeling runs based on the FUND model. The first correction relates to the potential dry land loss in the algorithm that estimates regional coastal protections, which was not specified correctly in the model's computer code. This correction is discussed in an erratum (article announcing an error in a previous publication) in the Climatic Change journal in October 2013 (Anthoff and Tol). The second correction was needed because the equilibrium climate sensitivity (ECS) distribution was inadvertently specified as another type of distribution than is intended to be used for the purpose of developing SCC estimates. This means that the values ECS took in the simulations were distributed differently than was intended. The impact of these changes to the original estimates is very minor, resulting in a change of less than a dollar for each estimate.

In July 2015, the U.S. Interagency Working Group revised its estimates to make two more necessary minor technical corrections. First, the PAGE model had been indexed incorrectly, producing estimates in 2008US$, although they were labelled as 2007US$ like the other estimates. Second, the DICE model had been run through the year 2299, which was contrary to the runs undertaken for the other IAMs that run through the year 2300. Although the correction to the DICE runs were very minor, the changes to the PAGE model were more significant. On average, the change represents about a dollar reduction to central estimates, while the impact on 95th percentile estimates is slightly larger, as the estimates are more heavily influenced by the PAGE model. For Canadian estimates specifically, this correction has a more prominent effect, as PAGE accounts for half of the estimates considered for the 95th percentile of the distribution (FUND being left out of this metric). This results in a reduction of $6 to the 2015 estimates, and to $14 in 2050, as the estimates grow significantly bigger through time.

Annex 3: Developments Around the Valuation of Non-CO_2 GHGs

In considering impacts in regulatory proposals from non-CO_2 GHGs that are emitted at a large scale globally such as methane and nitrous oxide, the most appropriate approach is to use directly-modeled estimates for the GHG that is being valued. In the literature, a number of directly-modeled Social Cost of Methane estimates have been produced. However, up until recently, none of these modeling efforts were consistent with the SCC as developed by the U.S. Group. In the absence of direct modeling of estimates, an alternative method to valuing non-CO_2 GHG emissions consists of using the Global Warming Potential (GWP) as an approximation approach. The GWP measures the cumulative radiative forcing (warming effect) from a non-CO_2 GHG as compared to CO_2 over a fixed time horizon, with 100 years being the most commonly used. For example, the IPCC Fourth Assessment Report[54] estimates that methane and nitrous oxide have significantly different radiative forcing through time as opposed to CO_2 possessing 100 year GWPs of 25 and 298, respectively. While the GWP approach is considered simple and transparent for estimating impacts from non-CO_2 GHGs, there are issues with incorporating this methodology, as explained by the U.S. EPA in its recent Regulatory Impact Analysis for the *Proposed Emission Standards for New and Modified Sources in the Oil and Natural Gas Sector*[55]:

> The GWP is not ideally suited for use in benefit-cost analyses to approximate the social cost of non-CO_2 GHGs because it ignores important nonlinear relationships beyond radiative forcing in the chain between emissions and damages. These can become relevant because gases have different lifetimes and the SC-CO_2 [Social Cost of Carbon] takes into account the fact that marginal damages from an increase in temperature are a function of existing temperature levels. Another limitation of gas comparison metrics for this purpose is that some environmental and socioeconomic impacts are not linked to all of the gases under consideration, or radiative forcing for that matter, and will therefore be incorrectly allocated. For example, the economic impacts associated with increased agricultural productivity due to higher atmospheric CO_2 concentrations included in the SC-CO_2 would be incorrectly allocated to methane emissions with the GWP-based valuation approach.

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[54] Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, J. Haywood, J. Lean, D.C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz and R. Van Dorland, *2007: Changes in Atmospheric Constituents and in Radiative Forcing. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p. 212.

[55] Full document available at Proposed Emission Standards for New and Modified Sources in the Oil and Natural Gas Sector

> Also of concern is the fact that the assumptions made in estimating the GWP are not consistent with the assumptions underlying SC-CO_2 estimates in general, and the SC-CO_2 estimates developed by the IWG [U.S. Interagency Working Group] more specifically. For example, the 100-year time horizon usually used in estimating the GWP is less than the approximately 300-year horizon the IWG used in developing the SC-CO_2 estimates. The GWP approach also treats all impacts within the time horizon equally, independent of the time at which they occur. This is inconsistent with the role of discounting in economic analysis, which accounts for a basic preference for earlier over later gains in utility and expectations regarding future levels of economic growth. In the case of methane, which has a relatively short lifetime compared to CO_2, the temporal independence of the GWP could lead the GWP approach to underestimate the SC-CH_4 with a larger downward bias under higher discount rates (Marten and Newbold, 2012).

In 2011, the USEPA published a request for comments on the approach that should be considered for including non-CO_2 GHGs in Regulatory Impact Analyses. In general, while commenters agreed that the GWP approach to valuing non-CO_2 GHGs provides an approximation of the damages, they also supported the U.S. EPA's assessment that the development of direct estimations of non-CO_2 GHG impacts was preferable to overcome the challenges associated with this approach. In the months following the 2011 period for comments, the U.S. EPA began to include consideration of non-CO_2 GHGs in cost-benefit analyses, by multiplying the non-CO_2 GHGs by their GWP.[56] However, this estimation was only used as part of the sensitivity analysis, as it was deemed to be an interim method of analysis until directly modeled estimates for non-CO_2 GHGs were developed for use in the central analysis.

In 2014, researchers working for the U.S. EPA published a paper (Marten et al. 2014) which, for the first time, contained valuations of damages expected from methane and nitrous oxide (i.e., SCCH_4 and SCN_2O estimates) that are consistent with the methodology that the U.S. Group used to develop the SCC.[57] The paper also found that modeling costs directly for non-CO_2 GHGs provides a more accurate estimation than the GWP approach, which is particularly true for shorter-lived GHGs such as methane, for which the heating effect is condensed in time and the

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[56] An example of this inclusion is the Light-Duty Vehicles Regulations Phase 1, for which the Regulatory Impact Analysis is available at the following location: Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards; Final Rule

[57] Marten et al., *Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates*, Climate Policy, 15(2), 2014.

discounting of future impacts has less of an effect on the present value of the damages. This leads to slightly higher estimates overall, an effect that is even more profound if a higher discount rate is used.

In July 2015, the U.S. EPA published a proposed rule-making (Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles-Phase 2) which incorporated the Marten et al. (2014) estimates of the $SCCH_4$ and the SCN_2O for the first time in a cost-benefit analysis (within the sensitivity analysis) in order to monetize methane and nitrous oxide reductions. In August 2015, following a peer review process of the estimates developed by Marten et al. (2014), the U.S. EPA published two additional Regulatory Impact Analyses for proposed rule-makings[58], with cost-benefit analysis that included the $SCCH_4$ as part of its central analysis.

Although the U.S. Group has not, at the time of finalizing this document, published a technical support document with estimates of the social costs of non-CO_2 GHGs, Environment and Climate Change Canada considers that the U.S. EPA's approach for $SCCH_4$ and SCN_2O, which has met the U.S. analytical requirements and guidance for regulatory analysis, is a technical improvement over the GWP approach. It is ultimately based on the same modeling framework and assumptions initially made when the SCC was developed while reflecting the different time horizons for the effects of CH_4 and N_2O. More specifically, the methodology maintains the use of the same set of three IAMs, five socioeconomic and emissions scenarios, equilibrium climate sensitivity distribution, and aggregation approach used by the Interagency Working Group to develop the estimates. By applying the same methodology that is used to adapt U.S. SCC estimates into Canadian estimates, Environment and Climate Change Canada has produced estimates for $SCCH_4$ and SCN_2O based on the estimates from Marten et al. (2014). Tables A3-1 and A3-2 display these estimates and, for comparison purposes, the values that would result from the GWP approximation approach. Environment and Climate Change Canada has presented to the Interdepartmental Working Group on the SCC, which has agreed that the $SCCH_4$ and SCN_2O represented a more robust approach than the use of the GWP of these GHGs. Environment and Climate Change Canada will continue to monitor and assess the evolution in the literature around the valuation of non-CO_2 GHGs, and update its estimates as needed.

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[58] *Proposed Emission Standards for New and Modified Sources in the Oil and Natural Gas Sector*, and *Proposed Revisions to the Emission Guidelines for Existing Sources and Supplemental Proposed New Source Performance Standards in the Municipal Solid Waste Landfills Sector*

Table A3-1: $SCCH_4$ Estimates vs. GWP approach for Period 2010–2050 (in C$ 2012 per tonne CH_4, discounted at 3%)

Year	$SCCH_4$[59]	GWP approach	$SCCH_4$ 95th percentile	GWP 95th percentile
2010	946	851	2,857	3,288
2015	1,129	990	3,394	4,028
2016	**1,165**	**1,017**	**3,501**	**4,176**
2020	1,312	1,128	3,931	4,768
2025	1,519	1,246	4,735	5,332
2030	1,726	1,364	5,539	5,895
2035	1,971	1,490	6,480	6,472
2040	2,215	1,616	7,421	7,049
2045	2,462	1,743	8,233	7,521
2050	2,709	1,869	9,046	7,994

Table A3-2: SCN_2O Estimates vs. GWP approach for Period 2010–2050 (in C$ 2012 per tonne N_20, discounted at 3%)

Year	$SCCH_4$	GWP approach	$SCCH_4$ 95th percentile	GWP 95th percentile
2010	12,847	10,148	42,476	39,196
2015	14,551	11,796	48,483	48,017
2016	**14,892**	**12,126**	**49,684**	**49,781**
2020	16,255	13,444	54,490	56,837
2025	18,185	14,850	61,839	63,553
2030	20,115	16,256	69,188	70,268
2035	22,287	17,761	77,356	77,143
2040	24,460	19,267	85,525	84,018
2045	26,798	20,775	94,118	89,656
2050	29,135	22,282	102,711	95,294

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[59] As developed by Marten et al. (2014)

Additional information can be obtained at:

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