



Estimating the Value of Carbon: Two Approaches

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Resources for the Future (RFF)*

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Record of Revision

Revision Date	Description of Changes	Revision on Page(s)
April 2021	Replacement of text instances of "CLCPA" with "Climate Act"	multiple
April 2021	Text additions and modifications to reflect the Value of Carbon Guidance released by the NYS Department of Environmental Conservation in December 2020	p. 1, p. 5
April 2021	For consistency with IWG interim estimates released in February 2021, estimates of SC-CO ₂ are revised to reflect usage of the annual GDP Implicit Price Deflator values in the U.S. Bureau of Economic Analysis' (BEA) NIPA Table 1.1.9	p. 4 (Table 1), p. 29 (Table C1) and text on multiple pages
April 2021	Text additions and modifications to reflect Executive Order 13990 and the associated release of IWG interim estimates.	p. 4
April 2021	Updates to the reference list to include Executive Order 13783, Executive Order 13990, IWG interim estimates, the BEA implicit price deflator, and NYS Department of Environmental Conservation Value of Carbon Guidance.	p. 23, 24
April 2021	For consistency with the IWG approach, estimates of SC-CH ₄ and SC-N ₂ O are revised to reflect usage of BEA implicit price deflator, rounding to two significant figures, and recalculation of estimates using the PAGE model to exclude a small number of model runs in which a climate discontinuity is triggered in the marginal run but not the baseline run, leading to spuriously high values.	p. 27, p. 29, Tables C2, C3
April 2021	Correction of text to reflect that each model was run 50,000 times rather than 10,000 times as originally written.	p. 29
April 2021	Inclusion of Appendix I, 2020-2050 annual values of SC-CO ₂ , SC-CH ₄ , and SC-N ₂ O for discount rates of 3%, 2%, and 1%	p. 36

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1. Introduction

The value of carbon is a monetary estimate of the value associated with small changes in emissions of carbon dioxide (CO₂) and other greenhouse gases (GHGs). Pursuant to the Climate Leadership and Community Protection Act (Climate Act), the New York State (NYS) Department of Environmental Conservation (the Department), in consultation with the New York State Energy Research and Development Authority (NYSERDA), is directed to establish a value of carbon for use by NYS agencies,¹ expressed in terms of dollars per ton of carbon dioxide equivalent (CO₂e).²

In establishing a value of carbon for NYS, the Climate Act requires the Department to consider the two main analytic approaches for quantifying the dollar value of avoided CO₂ emissions. These are:

- The *social cost of carbon* (SCC) approach, or *marginal damages approach*, provides monetary estimates of the future environmental and social impacts caused by a small (1 metric ton) increase in greenhouse gas emissions in a given year. Equivalently, the SCC approach values the economic benefit that results from reducing greenhouse emissions by the same amount in that year.
- The *marginal abatement cost* (MAC) approach, or *target-consistent approach*, provides monetary estimates for greenhouse gas emissions based on the marginal abatement cost for achieving a given emissions reduction target—that is, the cost of abating the last metric ton of carbon dioxide needed to meet a particular emissions target at least cost to society.

The value of carbon is an important analytic input in policy deliberations and appraisal, including for benefit-cost analysis and regulatory impact assessment of policies that affect emissions and for estimating the economic benefits of existing climate policy. In applying the value of carbon, NYS policymakers can also be expected to evaluate policy options based on criteria such as their ability to deliver the specific emissions reductions required by the Climate Act and whether they will deliver such reductions at lowest cost.

In support of the Department's issuance of guidance on the value of carbon, this memo reviews both the SCC approach and the MAC approach to carbon valuation, with attention to specific considerations for the application of each approach to inform policy analysis and decision-making in NYS. This memo also presents associated estimates for the value of carbon, and certain other GHGs, issued and adopted by the US federal government, US states, and several European countries, including estimates that are calculated at a range of discount rates. Though the SCC and MAC approaches provide distinctly different information, they may play complementary roles in the NYS policy process to drive emissions reductions.

¹ Governor Andrew Cuomo signed the *Climate Leadership and Community Protection Act (Climate Act)* into NYS law on June 18, 2019. Section 75-0113 of the *Climate Act* addresses the value of carbon. Since the initial preparation of this memo, the Department issued value of carbon guidance on December 30, 2020 (New York State Department of Environmental Conservation. n.d.).

² The emissions from various greenhouse gases are converted to carbon dioxide equivalent (CO₂e) by multiplying by their global warming potential (GWP) over a specific timescale. As discussed in this memo, the social cost of carbon dioxide (SC-CO₂) is the \$ damage per ton of CO₂. Any other greenhouse gas, such as methane (CH₄), would be multiplied by its respective GWP value to determine its CO₂ damage equivalent (e.g., tons CH₄/ton CO₂) and derive its \$ per ton CO₂e. This memo suggests using direct estimates for the social cost of methane and the social cost of nitrous oxide, and developing direct estimates for the social cost of other common greenhouse gases, while using \$ per ton CO₂e when a gas-specific estimate of social cost has not been established.

2. Social Cost of Carbon: Valuing Damages from Climate Change

In evaluating energy- and climate-related policy options, multiple NYS agencies currently use a *social cost of carbon* estimate³ developed from a methodology that has been subject to broad stakeholder and peer review and issued by a US federal interagency working group. This section describes the mechanics of the SCC approach as well as ongoing research to refine this methodology. It identifies key decisions in its use, with specific focus on considerations for discounting and for non-CO₂ gases. The term SCC is used in this memo in a general sense to refer to the estimation of the marginal damages resulting from GHGs. The specific application of the SCC approach to evaluate the social costs of carbon dioxide, methane (CH₄), and nitrous oxide (N₂O) is referred to as SC-CO₂, SC-CH₄, and SC-N₂O, respectively.

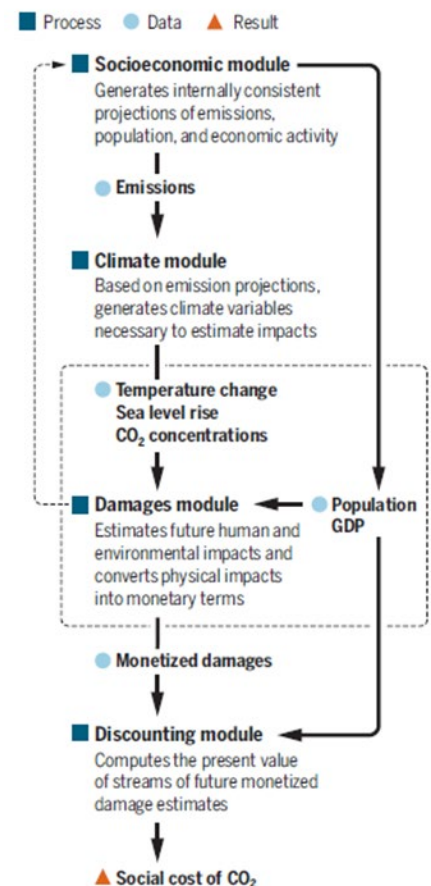
The SCC for a given year is “an estimate, in dollars, of the present discounted value of the future damage caused by a 1 metric ton increase in carbon dioxide (CO₂) emissions into the atmosphere in that same year or, equivalently, the benefits of reducing CO₂ emissions by the same amount in that year” (NAS 2017). It is intended to be a comprehensive measure of net damages due to climate change from one additional ton of CO₂, including changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services (IWG 2010). SCC calculations take into account future costs because CO₂ emitted today will have consequences for centuries into the future.

SCC estimates are calculated using integrated assessment models (IAMs), such as the Dynamic Integrated Climate-Economy model (DICE); the Climate Framework for Uncertainty, Negotiation, and Distribution model (FUND); the Policy Analysis of the Greenhouse Effect model (PAGE); and the Regional Integrated model of Climate and Economy (RICE). The vast majority of SCC estimates in the academic literature use one or more of these models (Isacs et al. 2016). These IAMs link together a global economic model and a global climate model (Figure 1). IAMs simulate the cost of the expected incremental damage along an emissions pathway due to a small increase in CO₂ emissions released at a certain point in time. The IAMs account for future economic growth, population growth, and technological change, from which emissions trajectories are defined. These trajectories are translated to climate

Figure 1. Schematic of the Modeling Approach Taken by Integrated Assessment Models to Estimate the SCC

Computing the benefits of reduced climate change

Four modeling components are necessary to estimate the benefits from reduced climate change, summarized by the social cost of CO₂. This figure illustrates those components and their linkages.



Source: Reproduced from Pizer (2017).

³ The NYS Public Service Commission, Department of Public Service, and NYSERDA use the SC-CO₂ average estimate at the 3 percent discount rate that was issued by the federal Interagency Working Group in 2016, as discussed in this memo. These NYS agencies have used this value of carbon in setting zero-emission credit (ZEC) payments to at-risk nuclear generation power plants; to guide avoided CO₂ cost compensation to clean distributed generators; in benefit-cost analyses of utility energy efficiency programs and other utility expenditures that may impact CO₂ emissions; and in a range of analytic studies, such as to assess the statewide potential for increased adoption of energy efficiency and renewable energy technologies and to inform NYS policy on offshore wind energy and the Clean Energy Standard.

impacts and then to monetized damages, with future damages converted into their present-day value by using a discount rate. The SCC is estimated as the net difference in total damage cost between the baseline case and the case with a small additional amount of CO₂ emissions. The model is typically run hundreds of thousands of times to evaluate the uncertainty of the estimates.

2.1. SCC at the Federal Level

Established by the US federal government in 2009, the Interagency Working Group (IWG) on the Social Cost of Greenhouse Gases developed estimates of the social cost associated with CO₂ emissions for use by federal agencies in regulatory impact analysis. The IWG last developed SCC estimates in 2016; it was disbanded in 2017 and subsequently re-established in January 2021.⁴

The IWG used three integrated assessment models—DICE, FUND, and PAGE—to estimate the global damages caused by GHG emissions. The IWG ran the three models through the year 2300 using five emissions scenarios: four business-as-usual trajectories featuring different technology assumptions, plus one policy trajectory in which atmospheric CO₂ concentrations stabilized at 550 parts per million. The IWG then averaged the results across the models and trajectories to produce four SCC values, three of which are based on the average SCC from the three IAMs at discount rates of 2.5, 3, and 5 percent. The fourth value represents the 95th-percentile SCC estimate across all three models at a 3 percent discount rate. The final value was included to capture the damages associated with lower-probability but higher-impact outcomes from climate change, which would be particularly harmful to society.

SCC estimates are subject to both structural uncertainty (related to the functional form of the underlying models) and parametric uncertainty (related to the values employed for the primary parameters). The IWG approach was intended to mitigate or characterize such uncertainty to the extent possible (NAS 2017).⁵ Examples of uncertain elements in the SCC estimates include very long-run projections of socioeconomic variables, such as economic growth, population, and emissions; aspects of the climate system, including how sensitive it is to emissions; and the inadequate representation of catastrophic “tipping elements” in the climate system (Lenton et al. 2008). The IAMs only partially account for, or omit, many significant impacts of climate change that are difficult to quantify or monetize, including ecosystems, increased fire risk, the spread of pests and pathogens, mass extinctions, large-scale migration, increased conflict, slower economic growth, and potential catastrophic impacts (Howard 2014; Institute for Policy Integrity 2019; IWG 2010; NAS 2017). Further uncertainty comes from the extrapolation of damage functions to temperature increases above 2.5⁰ to 3⁰C (Isacs et al. 2016). To the extent that the IAMs are used to estimate an SCC that is based on optimal climate policy, additional uncertainties lie in the abatement costs as well.

Table 1 shows the SC-CO₂ estimates developed by the IWG in 2016 (since adjusted for inflation and issued in 2021), at five-year intervals through 2050, expressed in 2020\$ per metric ton of CO₂. Although the average estimate at the 3 percent discount rate is presented as the “central estimate,” the IWG emphasizes the

⁴ The IWG originally published SCC estimates in 2010, and subsequently issued four updates, all of which followed the 2010 methodology. The IWG estimates have been used for applications ranging from vehicle emission and fuel economy standards, to emission standards for industrial manufacturing and power plants, to energy efficiency standards. These estimates are also often applied at the state or local level and have been used internationally.

⁵ The National Academies (NAS 2017) further assessed sources of uncertainty in the SCC estimates and offered extensive recommendations for both reducing them and improving their characterization. These specific recommendations are currently in the process of being implemented by RFF’s Social Cost of Carbon Initiative.

importance of considering all four values for capturing uncertainty in the SCC estimates in regulatory impact analysis. The IWG also developed estimates for the social cost of methane and the social cost of nitrous oxide (Appendix A).

The range of IWG values shows the sensitivity of the SCC estimate to the discount rate assumption. The IWG's 2016 update expanded the discussion of other sources of uncertainty about the SCC estimates, including presentation of quantified sources of uncertainty in the form of frequency distributions for the SCC estimates in 2020 (Appendix B) as well as discussion of model limitations and research gaps (IWG 2016).

Table 1. Social Cost of CO₂, IWG Estimates (2020\$/metric ton CO₂)

Year of emissions	Average estimate at 5% discount rate	IWG central estimate: Average estimate at 3% discount rate	Average estimate at 2.5% discount rate	High-impact estimate: 95th percentile estimate at 3% discount rate
2020	14	51	76	152
2025	17	56	83	169
2030	19	62	89	187
2035	22	67	96	206
2040	25	73	103	225
2045	28	79	110	242
2050	32	85	116	260

Source: Federal interim social cost of CO₂ estimates provided by the IWG under Executive Order 13990 (IWG 2021).

Presidential Executive Order 13783 disbanded the IWG in 2017 and removed the requirement for federal agencies to employ a harmonized set of SCC estimates in their regulatory analyses. Federal agencies subsequently relied on a set of estimates based on the IWG methodology but with two modifications that significantly alter SCC values: attempting to calculate only damages occurring within the United States rather than global damages, and employing discount rates of 3 and 7 percent in their central analyses. At the 7 percent discount rate, the estimate for domestic SCC is just \$1 per metric ton of CO₂. This estimate is inconsistent with the Climate Act's direction to consider the global impacts of GHG emissions; moreover, it is methodologically flawed in that the existing IAMs do not model relevant interactions among regions (e.g., global migration, economic and political destabilization, impacts on trade, potential for reciprocity in climate mitigation) in the manner that would be necessary for more thoroughly estimating a domestic impact.

In January 2021, Presidential Executive Order 13990 reestablished the IWG and set a schedule requiring the publication of an interim set of SC-CO₂, SC-CH₄, and SC-N₂O estimates within thirty days and a final set of estimates in January 2022. The interim estimates, published in February 2021, are identical to the estimates previously provided by the IWG in its 2013 and 2016 Technical Support Documents, adjusted for inflation. The interim estimates therefore reflect global damages and discount rates of 5%, 3%, and 2.5%, as well as a high-impact estimate derived from the 95th percentile estimate at a 3% discount rate (IWG 2021).

2.2. SCC at the State Level

Multiple states continue to use the IWG global SCC estimates in conducting cost-benefit analysis of energy-related regulations and other actions, including California, Colorado, Illinois, Maine, Maryland, Minnesota, Nevada, New Jersey, New York, and Washington. The majority of these states use the IWG central estimate at the 3 percent discount rate, yielding an SC-CO₂ value of \$51 per metric ton for emissions occurring in 2020.

The state of Washington in April 2019 passed a law requiring utilities to use the IWG SCC estimate at the 2.5 percent discount rate (i.e., an SC-CO₂ value of \$76 per metric ton for 2020 emissions) when developing “lowest-cost analyses” for its integrated resource planning and clean energy action plans. The use of the 2.5 percent discount rate reflects the view that the IWG estimate does not capture the total future cost of CO₂ emissions because of omitted damages and uncertainty (Paul et al. 2017).

California’s Air Resources Board and Public Utilities Commission both use the IWG SCC. The former cites the SC-CO₂ and SC-CH₄ in its scoping plan for its updated climate change policy, adopting estimates at a range of discount rates from 2.5 to 5 percent. The latter requires use of the IWG SCC for evaluating distributed energy resources; utilities must conduct a societal cost test using the 3 percent SCC estimate and the high-impact estimate.

In December 2020, the New York State Department of Environmental Conservation (n.d.) adopted value of carbon guidance that recommends that New York State agencies use central values for SC-CO₂, SC-CH₄, and SC-N₂O that are estimated at the 2 percent discount rate as the primary value to inform decision-making (in appropriate contexts), while also reporting the impacts at 1 and 3 percent to provide a comprehensive analysis.⁶

Additional information on use of the SCC in state policymaking is compiled by the Institute for Policy Integrity at NYU School of Law (see <http://www.costofcarbon.org/states>) (Paul et al. 2017; Grab et al. 2019) and is provided in a report issued by the US Government Accountability Office (GAO 2020).

2.3. Updating the SCC

In January 2017, the National Academies of Sciences, Engineering, and Medicine (NAS) published recommendations on updating SCC methodologies, prepared at the request of the IWG. The report provides extensive guidance to improve the scientific basis, provide more transparency, and better address uncertainties (NAS 2017). It also recommends instituting a process for updating SCC estimates approximately every five years, an update cycle that would balance the benefit of incorporating the latest research with the need for a thorough process.

The NAS report proposes four modules, each corresponding to a step in SCC estimation, and an overall framework that integrates the modules and considers their various interdependencies. The NAS panel

⁶ Expressed in 2020 dollars per metric ton of emissions, this range translates into a 2020 value of carbon dioxide of \$51-406 per ton, with a central value of \$121 per ton; a 2020 value of methane of \$1,500-6,400 per ton, with a central value of \$2,700 per ton; and a value of nitrous oxide of \$18,000-130,000 per ton, with a central value of \$42,000 per ton. Resources for the Future provided New York State with estimates that were calculated using the same peer-reviewed models that were used by the federal IWG, at constant discount rates of 0, 1, 2, and 3 percent, revised here for consistency with IWG interim estimates released in February 2021. See Appendix C for a description of how these estimates were modeled.

suggests that using a common module for key steps in the SCC estimation framework, rather than averaging the results for different IAMs (as the current IWG methodology does), can improve transparency, consistency, and control over uncertainties. Each of the modules would allow for uncertainties, resulting in a distribution of estimates rather than a single value. As summarized below, for each module the NAS panel recommended changes that could be implemented in two to three years.

Socioeconomic module and emissions projections. These should use statistical methods and expert judgment for projecting distributions of future population growth and gross domestic product, which contribute to generation of GHG emissions projections. Potential modules should be evaluated according to time horizon, future policies, disaggregation, and feedbacks.⁷

Climate modeling. This module should use a simple Earth system model to properly capture the relationships among CO₂ emissions, atmospheric CO₂ concentrations, and global mean surface temperature change and sea-level rise; it should also incorporate their uncertainty.

Climate impacts and damages estimation. This module translates a time series of socioeconomic variables and physical climatic variables into estimates of physical effects and the associated yearly monetary value of net climate damages. It should be based on current models but include updated individual sectoral damage functions, transparent and quantitatively characterized damage function calibrations, recognition of any correlations between damage formulations, and a summary of disaggregated damage projections.

Discounting. To explicitly recognize the uncertainty surrounding discount rates over long time horizons, the discounting module should incorporate the relationship between economic growth and discounting using a Ramsey-like formula.

The NAS report further proposes longer-term research to improve each module and incorporate various feedback mechanisms that could have a significant effect on the resulting estimates.

Resources for the Future (RFF) and the Climate Impact Lab (the Lab) have begun to implement NAS recommendations in their research on the SCC.

RFF created the Social Cost of Carbon Initiative to advance the NAS framework proposals. This effort, focused on improving the scientific quality and transparency surrounding SCC estimates, involves a network of partners—RFF, UC Berkeley, Harvard, Princeton, University of Washington, PennState, and others (<https://www.rff.org/scc>). In partnership with David Anthoff and a research team at UC Berkeley, RFF hosts an open-source software platform and tools to run and adapt climate IAMs (www.mimiframework.org/Mimi.jl/stable/). RFF's research efforts to implement the NAS recommendations include building a new set of long-run projections of economic growth, population, and emissions; updating the climate model used in SCC calculations; building new climate damage functions from the best available literature; and implementing a Ramsey-like discounting framework. RFF plans to release updated SCC estimates that are responsive to the full set of near-term recommendations of the NAS by the end of 2020.

⁷ Projections should extend far enough in the future to provide inputs for estimation of the vast majority of discounted climate damages; account for the likelihood of future emissions mitigation policies and technological development; and provide the sectoral and regional detail in population and economic conditions necessary for damage calculations. The module should incorporate feedbacks from the climate and damages modules.

The Climate Impact Lab is working to leverage recent advances in sciences and economics to develop empirically derived climate damages and ultimately an SCC estimate. The Lab's approach includes gathering global climate and socioeconomic data to understand the relationship between climate and society, developing damage functions using outcome data, and using those observations to project the relationship where outcome data are not available. The Lab has created a web-based platform that presents the results of local assessments of climate impacts and is updated on an ongoing basis (<http://www.impactlab.org/map/>). It also plans to generate the first empirically derived estimate of the SCC based on a series of reports providing partial SCC estimates for a number of impact sectors, including mortality (Carleton et al. 2018), agriculture, conflict, labor, electricity demand. A broad timeline of 2021–2022 has been set to complete this work.

2.4. Choosing a Discount Rate

Economic discounting is the process of converting a value received in a future time period (e.g., 1, 10, or even 100 years from now) to an equivalent value received immediately. For example, a dollar received 50 years from now may be valued less than a dollar received today—discounting measures this relative value. The choice of the discount rate used to calculate the SCC has a large influence on the estimate, with a higher discount rate resulting in a lower SCC value.

The Climate Act directs consideration of a range of appropriate discount rates, including a rate of zero. At NYSEDA's request, RFF has employed the IWG methodology to calculate the SC-CO₂ for a range of constant discount rates (2, 1, and 0 percent) for comparison with values generated using the IWG's selected discount rates (5, 3, and 2.5 percent). Results from these sensitivity analyses are presented in Appendix C. Additional sensitivity analyses could apply a Ramsey-like approach to discounting (discussed below and in Appendix D).

The discount rate is a particularly important parameter for the social cost of carbon dioxide because the warming effects of emissions released today linger for hundreds of years into the future. Over such long time horizons, even modest changes in the discount rate can lead to large changes in the present value of long-term effects (Appendix C). It is not simply the sensitivity of the results that suggests careful consideration of the discount rate. Discounting over long time horizons also gives rise to other conceptual issues that affect the appropriate choice of the discount rate, such as intergenerational equity and uncertainties about the appropriate discount rate for the distant future.

2.4.1. Consumption Discount Rate

The social cost of carbon is used primarily for societal decision making, particularly as an input to benefit-cost analysis. The correct discount rate to use in a societal benefit-cost analysis is the social discount rate, which reflects the rate at which society as a whole is willing to trade off a value received at one point in time (e.g., today) with a value received at another point in time (e.g., the future). The IAMs used to generate the estimates of climate damages for SCC calculations report their output in terms of consumption-equivalent impacts, which are intended to reflect the effect on people's consumption (as opposed to investment). Therefore, and as explained in the NAS (2017) report, the correct discount rate to apply to these impacts is the consumption rate of discount.

Although the consumption discount rate is the appropriate one to use for the social discount rate in calculating the SCC, the analyst must still determine the right value to use for this rate. Broadly speaking, there are two approaches to choosing the social discount rate: descriptive and prescriptive. This memo focuses principally on the descriptive approach because it forms the basis of most US federal government

guidance on discounting. The prescriptive approach primarily involves ethical judgments applied in the so-called Ramsey framework and is discussed below in the context of RFF's implementation of the NAS recommendations.

2.4.2. Market Data and Expert Surveys

Descriptive approach using observed market data. The descriptive approach is based on looking at people's observed behavior, as measured through market rates of return, and is the primary basis for US federal guidance on rulemaking procedures. For example, if households are willing to accept a 3 percent rate of return, this indicates that they are willing to trade off \$1 today for \$1.03 next year. Long-standing guidance in the Office of Management and Budget's (OMB) Circular A-4 directs federal agencies to use rates of 3 percent (reflecting the consumption rate of interest) and 7 percent (reflecting the pretax return to capital), based on observed historical market rates. Conceptually, the lower consumption rate of discount is appropriate for evaluating effects (costs or benefits) on consumption.⁸ OMB guidance also allows the use of additional lower discount rates as a sensitivity analysis if benefits or costs accrue to future generations over long time horizons.

When estimating the social cost of carbon for federal rulemaking, the IWG used a 3 percent central rate, a 2.5 percent "low" rate, and a 5 percent "high" rate. The 3 percent discount rate corresponds with OMB's Circular A-4 consumption rate of interest. The 2.5 percent rate approximately accounts for uncertainty in future interest rates (and hence discount rates), which suggests using a lower interest rate for long time horizons (Weitzman 1998; Newell and Pizer 2003). The 5 percent rate was included to account for the possibility that climate damages are positively correlated with interest rates. These low and high rates were considered appropriate adjustments to approximate the implications of more complex discounting rules while retaining the constant discount rate approach.

The empirical basis for OMB's rates of 3 and 7 percent is dated, and a 2017 US government report issued by the Council of Economic Advisers (CEA) examined recent trends in interest rates, finding support for using discount rates of "at most 2 percent" for the consumption rate of discount used in US federal policymaking (CEA 2017). This is based on the persistent decline in interest rates over the past two decades; prices in futures markets that suggest rates will remain below 4 percent over the next ten years or more.

Although the 2017 CEA report on interest rates primarily pertains to short-run forecasts (over the coming 10 years), interest rates in the far future (decades and centuries hence) are actually more relevant to discounting long-term climate change impacts. Although long-run interest rates are typically difficult to measure, a novel approach based on 100-year real estate leases suggests how investors discount values in the very long run (Giglio et al. 2015a),⁹ with estimates implying discount rates "below 2.6 percent for 100 year claims." Because real estate investments are not risk free, the risk-free rate may actually be overstated (Giglio et al. 2015b).

⁸ In contrast, the return to capital is often proposed as the rate to use when private investment may be affected. This is a simplification of the more conceptually sound "shadow price of capital" approach, whereby effects on investment are converted to "consumption equivalents" and then all effects are discounted at the consumption rate of interest. In addition, Li and Pizer (2018) show that simply using the investment return is also problematic over long time horizons, and that under the shadow price of capital approach, the appropriate effective rate converges to the consumption rate over time.

⁹ Specifically, they compare the market prices of 100-year real estate leases to the prices of owning equivalent properties in perpetuity. The difference in those prices reflects the discounted value of investment returns beyond 100 years, from which the authors infer the long-run discount rate that investors use.

This again suggests support for using long-run discount rates below 3 percent and probably closer to 2 percent, in line with the conclusion in the 2017 CEA report.

Expert surveys. An alternative way of determining discount rates is through surveying professional economists with relevant expertise and asking them to recommend values for the social discount rate. This approach relies on expert judgment, where the experts may implicitly or explicitly use a combination of descriptive and prescriptive approaches.

Weitzman famously conducted a survey of 2,160 professional economists, asking, “What real interest rate do you think should be used to discount over time the (expected) benefits and (expected) costs of projects being proposed to mitigate the possible effects of global climate change?” (Weitzman 2001). At that time, the responses showed a skewed distribution with a mean of about 4 percent, a median of 3 percent, and a mode of 2 percent.

Views in the economics profession have, however, shifted toward lower discount rates over the past two decades. Drupp et al. (2018) conducted a similar survey of more than 200 economists with expertise in discounting, finding median and mean recommended social discount rates of 2.0 and 2.3 percent, respectively. These results are in line with the range of 2 to 3 percent suggested by CEA (2017) and Giglio et al. (2015a). In addition to asking respondents to recommend a specific discount rate, the authors also inquired about the maximum and minimum rates they would feel comfortable recommending. The median (mean) upper bound recommended was 3.5 percent (4.1 percent) and the median (mean) lower bound was 1.0 percent (1.1 percent).¹⁰

In summary, existing relevant guidance and recent empirical and survey evidence suggest support for using a central discount rate for the SCC of 3 percent, 2 percent, or some value within this range.

2.4.3. Ramsey Approach

One NAS recommendation for improving the SCC estimation process was to bring the descriptive and prescriptive approaches to the discount rate together by choosing “parameters for the Ramsey formula that are consistent with theory and evidence and that produce certainty equivalent discount rates consistent, over the next several decades, with consumption rates of interest” and using “three sets of Ramsey parameters, generating a low, central, and high certainty-equivalent near-term discount rate” (NAS 2017).

As part of its Social Cost of Carbon Initiative, RFF is implementing these NAS recommendations by determining the level of near-term discount rates using the descriptive approach and implementing them as part of a Ramsey-like framework (Appendix D).

For the near-term rates based on descriptive market information, RFF is focusing on central, low, and high discount rates of 3, 2, and 5 percent, respectively. The central 3 percent rate is consistent with current OMB guidance. RFF’s lower 2 percent rate is on the lower end of the range supported by the evidence and lower than the lowest value previously deployed by the IWG (2.5 percent). RFF’s high rate of 5 percent is based on OMB’s rate of return to capital of 7 percent, with an adjustment for taxes. This is because OMB’s 7 percent represents the pretax return to investment, but as explained above, the correct rate is the rate of return that

¹⁰ However, it should be noted that these are averages of the responses; some individual respondents recommended discount rates ranging from 0 to 10 percent, and an upper bound as high as 20 percent.

consumers actually face. Since consumers must pay taxes on this 7 percent return, the corresponding rate of return actually available to consumers is about 5 percent.¹¹

Under the Ramsey approach, the discount rate is given by two components, which are added together. The first component is called the rate of pure time preference, which is how much society discounts the welfare of people in the future. The second component represents an adjustment for how much the value of an incremental dollar declines as society grows wealthier.

If the intention behind the Climate Act's required consideration of a "discount rate of zero" relates only to the rate of pure time preference between future and current generation's welfare, and not to the adjustment for values accruing to wealthier individuals, then the effective discount rate under a Ramsey-like approach would simply equal the latter component. Using RFF's preliminary estimates of the size of this component, the effective near-term discount rate would equal about 1.7 percent (Appendix D). Germany has adopted a Ramsey-like approach to develop social cost of carbon estimates, including a high-impact estimate for use in sensitivity analysis that sets the rate of pure time preference at zero. In Germany's high-impact estimates, the effective discount rate starts near 2 percent and declines to 1 percent by 2250 (GAO 2020).

2.5. Social Costs of Other GHGs

In addition to carbon dioxide, the Climate Act covers methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF₆), as well as "any other substance emitted into the air that may be reasonably anticipated to cause or contribute to anthropogenic climate change." In valuing carbon, the analytic tools employed by NYS should account for the contributions of these additional non-CO₂ gases to future economic damages as part of a consistent analytical framework.

The different physical characteristics of other greenhouse gases compared with CO₂, as well as their distinct interactions within the atmosphere and biosphere, are important for the estimation of resulting damages. For example, the gases differ in their *radiative efficiency*—how much energy can be absorbed at a time on a per molecule basis. The physical and chemical processes that remove each gas, once emitted, from the atmosphere also differ, causing substantially different residence times in the atmosphere. Further, the physical and chemical interactions of these gases are also distinct, both in the atmosphere and with the biosphere. This section discusses two general approaches to account for these differences and generate values for the social costs of non-CO₂ greenhouse gases.

2.5.1. Global Warming Potentials

To facilitate comparison of characteristics across disparate greenhouse gases, climate scientists and economists often use the *global warming potential* (GWP). The GWP for a gas is calculated as the ratio of the cumulative energy absorbed by that gas over a particular time period, compared with a reference gas (CO₂). The GWP metric expresses combined information about the radiative efficiency and the atmospheric lifetime of the gas relative to that of CO₂. By construction, GWP values greater than 1 indicate greater warming than

¹¹ See IWG (2010, 20). Although the IWG also used a 5 percent "high" rate, this was to approximately account for the potential positive correlation of the discount rate and climate damages, which the IWG did not model explicitly. RFF's ongoing work explicitly models this correlation, implying the IWG's rationale for using 5 percent is no longer applicable. It is simply a coincidence that the after-tax return to capital also happens to be about 5 percent.

from CO₂. For any two gases, the one with the higher GWP causes more warming over the specified time horizon.

GWPs for greenhouse gases for both 20- and 100-year time horizons are calculated and reported by the Intergovernmental Panel on Climate Change (IPCC) in its assessment reports (Table 2).¹² The potential for strong dependence of GWP on the selection of time horizon, particularly for relatively short-lived gases such as methane, is evident.

Table 2. Global Warming Potentials and Lifetimes of Select Non-CO₂ Greenhouse Gases

Gas	Lifetime (years)	20-year GWP	100-year GWP
CH ₄ (methane)	12.4	84–86	28–34
N ₂ O (nitrous oxide)	121	264–268	265–298
SF ₆ (sulfur hexafluoride)	3,200	17,500	23,500
HFC-134a (hydrofluorocarbon)	13.4	3,710–3,790	1,300–1,550
PFC-14 (perfluorocarbon)	50,000	4,880	6,630

Source: IPCC (2013, chapter 8). Where ranges are given, the upper (lower) values represent the GWP with (without) climate-carbon feedbacks. Climate-carbon feedbacks are not included for the values presented for SF₆ and PFC-14 (Myhre et al. 2013). HFC-134a and PFC-14 are examples of HFCs and PFCs that are in common use, but HFCs and PFCs as categories comprise many more compounds that vary widely in GWP and atmospheric lifetime.

It would seem straightforward to estimate the social costs of non-CO₂ greenhouse gases by multiplying their GWP for a given time horizon by the SC-CO₂. Using GWP in this manner, however, mischaracterizes the relationship between the residence time of a gas in the atmosphere and the time profile of discounted future damages.

When the models used to estimate the SC-CO₂ calculate the undiscounted damages for a future year in response to an initial pulse of emissions, such damages depend on how much of the original pulse still resides in the atmosphere in that year. After estimating undiscounted future damages, they calculate the net present value of all future damages by discounting and summing them. The much shorter atmospheric residence time of methane, for example, means that a pulse of methane in a given year will have largely been removed from the atmosphere in a decade. Undiscounted damages associated with that initial pulse of emissions should therefore diminish more rapidly than damages from CO₂.¹³ Converting the value of the SC-CO₂ to a value for SC-CH₄ by multiplying by the GWP of CH₄ implicitly (and incorrectly) imposes the longer atmospheric lifetime of CO₂ on the calculation of the SC-CH₄, mischaracterizing the relationship between its atmospheric lifetime and the net present value of damages from the initial emissions pulse.

Further complications from applying GWP in this context arise from the fact that other physical interactions considered in some of the models are not shared across the gases. One example is CO₂ fertilization: the

¹² GWPs are published as part of the IPCC's Working Group I assessments and were most recently updated in 2013 as part of the IPCC's Fifth Assessment Report. The Working Group I contribution to the IPCC's Sixth Assessment Report is scheduled to be finalized in 2021.

¹³ Among other effects, properly accounting for this relationship implies a relatively narrower difference between the higher and lower discount rates for CH₄ when compared with CO₂.

presence of elevated levels of CO₂ in the atmosphere enhances the growth of certain plants. Elevated levels of CH₄ and N₂O do not share this effect with CO₂, but using GWP imputes such benefits to those gases, thereby underestimating their net damages.

Another inconsistency arises when using GWP to estimate the social cost of gases for future years. GWPs of various gases are calculated by the IPCC based on the energy absorption capacity of an additional ton of emissions relative to their *current* concentrations. In later years, the strength of the energy absorption of a given gas relative to CO₂ may change based on future emissions pathways. Using today's GWP therefore may not properly reflect the relative radiative forcing of these gases in the future.

2.5.2. Gas-Specific Marginal Damages

In 2016, the IWG followed the approach put forward by Marten et al. (2015) and published direct estimates for the SC-CH₄ and SC-N₂O.¹⁴ This approach modified the IAMs employed in the calculation of the SC-CO₂ to directly model pulses of the other gases in a manner reflecting their disparate physical properties and behaviors in the atmosphere and also incorporating the inputs and other assumptions employed as part of the IWG methodology.¹⁵ Appendix C provides values for the SC-CH₄ and SC-N₂O based on the IWG methodology and rates of discount, along with additional estimates for 2, 1, and 0 percent constant rates of discount generated by RFF for NYSERDA.

The differing results from the IWG and GWP approaches can be measured by evaluating the “damage-ratio” for the former and comparing it with the relevant GWP for a particular time horizon. The damage ratio is the ratio of the value for the SC-CH₄ or SC-N₂O to the value for the SC-CO₂ for a given discount rate. Table 3 shows representative damage ratios for CH₄ and N₂O, calculated using the IWG framework, for a set of discount rates, which may be compared with the GWPs for CH₄ and N₂O presented in Table 2. Damage ratios that are higher (lower) than a given GWP indicate that the IWG methodology would yield a higher (lower) value for the SC-CH₄ or SC-N₂O than the GWP approach. Notably, direct estimates of the SC-CH₄ have a damage ratio of 29 for the 3 percent discount rate used for the IWG's central estimate, which falls within the range of GWPs reported by the IPCC for the 100-year time horizon. Estimating the SC-CH₄ using a GWP calculated over a 20-year time horizon, however, would lead to an estimate nearly a factor of 3 greater than the IWG direct estimates.

¹⁴ The IWG's initial 2010 issuance of the federal government's guidance for the SC-CO₂ did not publish estimates of non-CO₂ gases, citing the limitations of the GWP approach as well as the paucity of estimates of social costs of non-CO₂ gases in the academic literature at that time.

¹⁵ An idealized implementation of this approach would involve perturbing the emissions pathways for each of the two gases in the same way that the SC-CO₂ is calculated. However, in the versions of the models used by the IWG, only the FUND model features an explicit representation of emissions of other greenhouse gases other than CO₂. In the versions of DICE and PAGE used by the IWG, the effects of other greenhouse gases are represented by exogenous radiative forcing pathways. Rather than explicitly modeling a pulse of CH₄ or N₂O emissions in DICE and PAGE, the pulse of emissions was instead represented by the equivalent increase in radiative forcing that would result from a one-ton pulse of such emissions. To calculate the amount of increased radiative forcing in these models and account for the time evolution of CH₄ and N₂O, a separate simple gas cycle model was used in which the emissions of CH₄ and N₂O could be perturbed directly. For a full discussion of the methodology and review of other estimates of SC-CH₄ and SC-N₂O see Marten et al. (2015).

Table 3. Damage Ratios for SC-CH₄ and SC-N₂O in 2020

Discount rate	SC-CH ₄ / SC-CO ₂	SC-N ₂ O / SC-CO ₂
5%	46	408
3%	29	367
2%	22	358

Damage ratios of the social cost estimates for a given gas using the IWG methodology to the value for the SC-CO₂ for a given discount rate. A comparison of damage ratios and GWPs for a given gas allows for a comparison of the relative effects of the two approaches for estimating the social costs of that gas.

The academic literature on direct estimates of non-CO₂ gases beyond CH₄ and N₂O is sparse overall and particularly limited for the NYS context.¹⁶ At present, no direct estimates that are fully consistent with the IWG methodology have been put forward by the IWG or reported in the academic literature for greenhouse gases beyond CO₂, CH₄, and N₂O.

Direct estimates of additional non-CO₂ gases consistent with the Marten et al. (2015) approach could be generated and made consistent with the IWG framework through additional research. Implementing the Marten et al. approach for additional gases would require estimates of the temporal profile of additional radiative forcing that would result from a 1 ton pulse of the specified gases in a given year, potentially generated by expanding the simple gas cycle model employed to represent additional gases.¹⁷ A potentially more expedient research approach would be to use estimates of marginal radiative forcing generated by the IPCC for its calculations of GWP for an extensive range of gases.¹⁸

2.6. Considerations for Using the Marginal Damages Approach in NYS

In its consideration of the establishment and usage of value of GHG estimates based on a marginal damages approach, the Department will need to address the following decision and guidance points.

Use of a peer-reviewed methodology. If the Department follows a marginal damages approach to value carbon and GHG emissions, NYSDA views the SCC methodology developed by the IWG as the most

¹⁶ Shindell (2015) estimated the “Social Cost of Atmospheric Release” for HFC-134a along with other short-lived greenhouse gases by calculating the temperature effects of pulses of these gases using a simplified climate model and estimating the resulting damages from such temperature perturbations based on the DICE model. Shindell’s method also accounts for non-climate effects on human health via degraded air quality, which is not natively accounted for in the Marten et al. approach. Waldhoff et al. (2014) used the FUND model to directly model estimates of the SC-SF₆. These papers are limited in that they each utilize only one of the three models employed by the IWG and use different discounting assumptions and different underlying socioeconomic, climatic, and damage functions than the IWG used.

¹⁷ For full consistency with the IWG methodology, the marginal effects of the gases would be modeled along emissions pathways for each gas that are consistent with the socioeconomic scenarios used by the IWG.

¹⁸ A limitation of this approach is that the IPCC assumes that future atmospheric concentrations and climate remain fixed at their current levels in its GWP calculations, so the marginal radiative forcing estimates are not fully consistent with the emissions scenarios employed by the IWG.

credible marginal damage cost approach for NYS agencies to use in the near term, since it has been subject to broad stakeholder and peer review.

Consideration of global impacts. The Climate Act instructs the Department to account for the global impacts from GHG emissions in establishing a value of carbon, rather than accounting only for the harm experienced within US or NYS borders. The IWG methodology accounts for global impacts.¹⁹

Application of the IWG SCC “central” estimate. As discussed in this memo, uncertainty is pervasive in SCC estimates and the estimates omit or do not fully account for many important damage categories. In partial recognition of this uncertainty, the IWG issued a range of four values to be used in regulatory impact analysis, ranging from \$14 to more than \$150 per metric ton of CO₂ emitted in 2020. NYSERDA suggests that the Department treat the current IWG “central” SCC estimate (at \$51 per metric ton of CO₂ in 2020) as a lower bound for damages, consider adopting a higher central SCC value for use by NYS agencies, and develop guidance on when to use a range of SCC values in analysis.

Time horizon. NYSERDA suggests adopting or modeling marginal damages estimates that account for impacts through the year 2300, consistent with the IWG method and the NAS (2017) findings.

Discount rate. The choice of the discount rate used to calculate the value of carbon has a large influence on the estimate, with a higher discount rate resulting in a lower value. The Climate Act directs consideration of a range of appropriate discount rates, including a rate of zero. Though no consensus exists on what approach or rate to use for discounting uncertain climate impacts over long time horizons, multiple lines of research as well as large-scale surveys of economists suggest support for using long-run discount rates below 3 percent, likely closer to 2 percent. In NYSERDA’s view, it is appropriate that the discount rate used in estimating value of GHG reductions using the marginal damages approach ultimately incorporate both empirical data and public interest value judgments.

Non-CO₂ GHGs. The approach taken by the IWG in estimating the SC-CH₄ and SC-N₂O addresses many of the limitations of the GWP approach. If the Department follows the IWG’s marginal damage approach to value CO₂, NYSERDA suggests that it should also follow the IWG approach to directly estimate the value of CH₄ and N₂O, modified as appropriate to meet the requirements of the Climate Act. For other GHGs of relevance for which fully consistent estimates using the IWG approach are not currently available (PFCs, HFCs, SF₆), NYSERDA suggests that NYS facilitate near-term research to generate IWG-consistent estimates for these gases following one of the research approaches identified while establishing interim estimates based on multiplying the SC-CO₂ by the 100-year GWP for each gas. NYSERDA notes that the Climate Act requires the usage of a 20-year time horizon for GHG accounting purposes; however, experience with the SC-CH₄ and SC-N₂O, including the damage ratio comparisons discussed in this memo, suggests that damage estimates based upon a 100-year GWP are likely to be most comparable to those that would be derived from direct estimates for these gases.²⁰

¹⁹ The IWG approach implicitly places the same weight on a dollar loss in the US as a dollar loss in the poorest regions in the world. An alternative approach discussed in the literature, and applied in Germany (GAO 2020; Bünger and Matthey, n.d.), produces an “equity weighed SCC” value that weights a dollar loss in poor regions more than a dollar loss in richer regions. Simply put, such an approach explicitly acknowledges that an incremental or decremental dollar has a larger welfare impact to a poor person than it does to a wealthy person.

²⁰ The discrepancy between using the GWP approach and direct estimates is expected to be considerably less than the expected error introduced by leaving such gases out of analyses, thereby implicitly assigning a value of zero for damages from those gases. Leaving known greenhouse gases out of analyses would also run directly counter to the directives and intent of the Climate Act.

Updating of SCC estimates. This memo discusses two major research efforts that are under way to improve on the IWG methodology and merit consideration for future updates. NYS, along with other governments and entities, can benefit from researchers' ongoing efforts to refine SCC estimates.

NYSERDA suggests that the NYS agencies also develop companion materials that provide tips, examples, and FAQs to assist analysts who need instructions for applying the SCC estimates. For example, companion materials specific to energy sector analysts could be developed by NYSERDA and the NYS Department of Public Service, in consultation with the Department, to address points such as how to account for inflation, how to combine an SCC estimate derived using a given discount rate with different discount rates for other cost and benefit streams, and how to aggregate SCC estimates with energy costs that incorporate some portion of the cost of CO₂ emissions. As such materials are developed or revised, NYSERDA encourages NYS agencies to work with the Department to facilitate their sharing among relevant agencies.

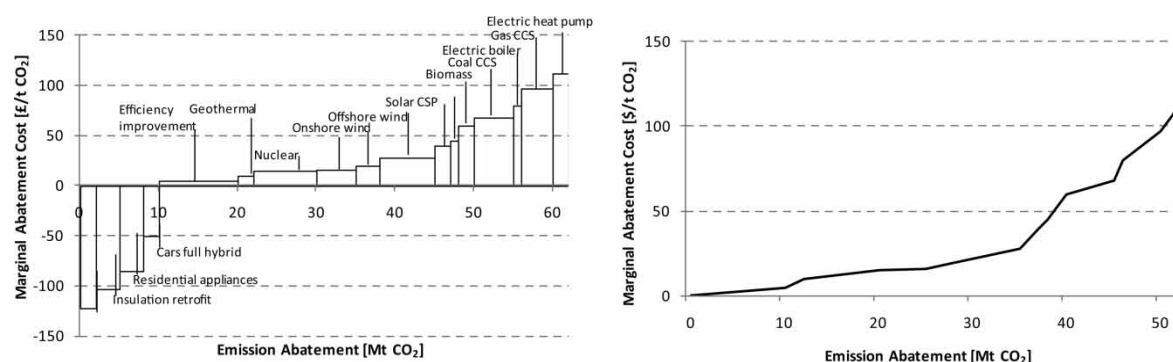
3. Marginal Abatement Cost: Evaluating Costs to Meet a Target

To achieve specified emissions goals at lowest overall cost, it is instructive to consider the marginal costs of reaching a specified emissions reduction target. The *marginal abatement cost* (MAC) approach has been incorporated by a number of governments in support of achieving their emissions targets. This *target-consistent approach* provides monetary estimates for greenhouse gas emissions based on the marginal abatement cost for achieving a given emissions reduction target—that is, the cost of abating the last metric ton of carbon dioxide needed to meet a particular emissions target at least cost to society (GAO 2020).. This section discusses the mechanics of the MAC approach, compares it with the marginal damage approach, and highlights relevant methodologies and estimates from three countries that have implemented a MAC approach. The section concludes by identifying relevant considerations if NYS incorporates the MAC approach to carbon valuation in policies or programs to achieve the emissions reductions required under the Climate Act.

The MAC approach relies on marginal abatement cost curves that represent the amount of GHG abatement that is available at a given “cost.” A MAC curve is a graph that indicates the marginal cost (the cost of the last unit) of emissions abatement for varying amounts of emissions reduction. A MAC estimate is typically derived from the marginal cost associated with the last reduced unit of emissions in the target year, which also equals the carbon price needed to meet the target (Isacs et al. 2016).

One approach to generating such MAC cost curves is to conduct a bottom-up assessment, in which experts evaluate individual abatement opportunities and costs across a set of relevant sectors and technologies. Abatement measures are arranged in order of cost per ton of emissions abated, from least to most expensive, to generate a marginal abatement cost curve. A stylized example of a MAC curve developed through such a bottom-up assessment is provided in the left panel of Figure 2.

Figure 2. Stylized Depictions of MAC Curves Drawn from Expert-Based Approach (left) and Models (right)



Source: Reproduced from Kesicki and Elkins (2012).

Alternatively, top-down MAC curves can be generated by using economic or energy models to evaluate the level of emissions reductions across an economy or a sector resulting from the imposition of a carbon price. A MAC curve can be generated in this way by varying the level and trajectory of the carbon price across multiple runs of the model and assessing the level of reductions driven at each price. MAC curves produced

through modeling studies, as depicted in the right panel of Figure 2, generally lack the level of detail about specific abatement opportunities available that are provided by expert-based studies (Kesicki and Ekins 2012). Modeling studies, however, offer the potential to account for interactions between sectors that are not accounted for with expert-based studies. Despite the significant differences between the two approaches, a review of the MAC literature found no consistent directional effect on estimated MAC curves based on the underlying modeling approach (Kesicki 2013).

Marginal abatement costs also have been determined based on historical and projected behavior in carbon markets such as the European Union’s Emissions Trading System (ETS) (see “MAC in Other Countries,” below).

3.1. MAC and SCC, Compared

The relative values of the MAC approach and the marginal damage approach for analysis of climate mitigation have been discussed and debated in the academic literature (Isacs et al. 2016) as well as in official government policy documents (Department of Energy and Climate Change 2009). The selection of approach has additionally fallen along geographic lines. The governments of the United States, Canada, and Mexico rely primarily on the marginal damage approach in the form of the SCC to support benefit-cost analysis in regulatory analysis (US Climate Alliance n.d.). Several European countries, each with clearly defined emissions targets, have adopted the MAC approach.

The MAC approach and its supporting analysis can be tailored to align closely with country, state, or regional requirements for greenhouse gas reductions. This attribute has been commonly cited as imperative by countries that have adopted the MAC approach, as well as the related ability to support a consistent policy framework across a suite of government actions (DECC 2009; Ministère de la Transition écologique et solidaire 2018).

When considered in isolation, the MAC approach avoids certain uncertainties that affect SCC estimates (DECC 2009). For example, the MAC cost curve does not depend on a representation of the climate system; it is dictated solely by cost estimates to reach a specified target or atmospheric concentration.²¹ Similarly, the MAC curve is not subject to uncertainty from translation of climate change to economic damages. Both of these sources of uncertainty have been shifted and subsumed into the policy decision of what the appropriate emissions targets and trajectories should be (Isacs et al. 2016).

Estimates of MAC curves are subject to a number of sources of uncertainty distinct from those present in the estimation of the SCC. These include uncertainty related to rates of technological improvements over time, the costs of available abatement, and the overall available potential for abatement, among others. MAC curves additionally share sensitivity to some of the same parameters as the SCC—namely, the selection of the reference case against which abatement costs are measured and the discount rate employed. MAC curves offer potential for more targeted and frequent updates as new information on technology costs and other costs of abatement is revealed in the marketplace, however, which could be expected to reduce uncertainty.

MAC curves also have limitations that should inform their development and use (Kesicki and Ekins 2012; Isacs et al. 2016). Cost curves in many cases lack a full accounting of costs, often excluding system costs and the costs of policy implementation, leading to an underestimate of the costs of abatement. MAC curves typically represent a snapshot in time, so they do not account for intertemporal uncertainty. Notably, MAC curves

²¹ Note that the translation of emissions to atmospheric concentration does involve associated uncertainty.

derived from the individual assessment of abatement measures do not typically account for economic interactions between sectors.

The following section discusses three countries' experience in choosing the MAC approach as their preferred strategy for carbon valuation: the United Kingdom, France, and Ireland. As summarized in Table 4, the countries' monetary estimates increase significantly over time, reflecting that abatement costs will rise over time as emissions targets become more stringent and as more expensive abatement measures will need to be employed, according to officials interviewed by the GAO (2020).

Table 4. Monetary Estimates for Greenhouse Gases based on the MAC Approach Developed by France, Ireland, and the UK (2020\$/metric ton CO₂e)

	France	Ireland	UK (non-traded sectors, central value)	UK (ETS sectors, central value)
2020	107	55	106	20
2030	309	172	124	124
2050	775	455	355	355

Source: Appendices F-H provide country-specific sources. Estimates converted into 2020\$ per metric ton of CO₂e. See Appendix E for exchange rates and inflation adjustment rate used.

The NYS policy context is analogous to the countries discussed, in several ways. NYS is required under the Climate Act to achieve specific levels of emissions reductions, with differentiated requirements for the power sector. The NYS economy is set within a broader context of US states and other countries whose actions to mitigate climate change are dissimilar and largely disconnected. The decision points and actions taken by these countries to develop country-specific MAC curves are illustrative of the types of decisions that would need to be addressed by NYS in incorporating information based on the MAC approach.

3.2. MAC in Other Countries²²

3.2.1. United Kingdom

The UK government began considering the use of MAC values in 2009, when the Department of Energy and Climate Change (DECC) conducted a major review of its use of the SCC for carbon valuation and laid the foundation for a transition to the MAC approach (DECC 2009). The primary reasons cited for the transition were to eliminate the uncertainty about damage cost estimates and to align UK policies with emissions reductions targets at the national level, as well as targets stipulated by the European Union (EU), and the United Nations. This review was followed by a subsequent policy document in 2012 that built on that foundation to establish the methodology and technical basis for the calculations that are in use today (DECC 2012).

²² All carbon values present in the following examples have been converted from their original currencies and inflated into 2020 USD. See Appendix E for the rates used, and Appendices F, G, and H for their original values.

For purposes of carbon price valuation, emissions from UK source categories are divided into those that fall under the European Union's ETS and those that derive from non-ETS sectors. This distinction was made because the two emissions categories are subject to different emissions reduction targets, and emissions reductions between ETS and non-ETS sectors are not fungible. The United Kingdom established separate methods for valuing the costs of abatement between the two, resulting in the evaluation and application of both a short-term "traded price of carbon" for emissions from covered ETS sectors and a short-term "non-traded price of carbon" for non-ETS sectors.

For ETS sectors, DECC in 2009 outlined an approach to generate short-term traded carbon values that would incorporate market information, suggesting that the carbon trading markets offered the best source of information about abatement costs. The proposed approach, implemented in 2012, based a central scenario for abatement costs on futures prices for EU allowances. In addition to the central estimate based on market futures prices, models are used to generate one low-cost and one high-cost trajectory to characterize potential uncertainty about the central estimate.²³ Values for the traded price of carbon based on each of the three scenarios are updated on an annual basis. The most recent low, central, and high values for the year 2020 are \$0, \$20, and \$39 per metric ton of CO₂e (Department for Business, Energy and Industrial Strategy 2019). The full schedule of short-term values is available in Appendix F.

The nontraded cost of carbon estimated for assessing policy actions in non-ETS sectors is based on an assessment of the "feasible technical" abatement options available carried out by the UK's Committee on Climate Change (CCC). In its assessment, the CCC generated six MAC curves based on varied assumptions about the feasibility of abatement opportunities across various sectors. Given the information in these MAC curves, DECC established a lower, central, and upper schedule for the nontraded carbon price. For 2020, the low, medium, and high values were \$53, \$106, and \$160 per metric ton of CO₂e (DBEIS 2019). The relatively higher projected costs of abatement for non-ETS sectors compared with those covered by the ETS reflect the higher cost of abatement in non-ETS sectors, such as transportation, relative to the less expensive abatement options available in ETS sectors, such as power generation.

Beyond 2030, when a comprehensive global trading system is expected to be in place, the values for the traded and nontraded prices of carbon are assumed to converge to a single international carbon price modeled to meet the EU's target of keeping global warming below 2°C. The low, central, and high unified carbon values for 2030 are \$62, \$124, and \$186 per metric ton of CO₂e; and for 2050, the corresponding values are \$177, \$355, and \$532 (DECC 2009).²⁴

3.2.2. France

As part of its 2018 update to its national low-carbon strategy (Ministère de la Transition écologique et solidaire 2018), the French government formed a commission to update the shadow price of carbon values employed in the assessment of public investments and climate mitigation opportunities (Quinet 2019). In its report, the commission considered employing the social cost of carbon approach but instead recommended

²³ Market fundamentals are altered in the models to generate either a low-cost (e.g., chronic oversupply of allowances) or high-cost (e.g., high economic growth) scenario. The MAC curves used in the model-based approach are taken from the Enerdata POLES model, a top-down global sectoral model for the world energy system.

²⁴ Prices are linearly interpolated, as necessary, between 2020 and 2030 and between 2030 and 2050.

taking a marginal abatement cost approach consistent with delivering France’s economy-wide target of net-zero emissions by 2050.

Rather than put forward separate prices for various emissions sectors or categories (e.g. ETS and non-ETS), the commission instead recommended establishing a uniform shadow price across the economy to maximize economic efficiency. It further focused on establishing abatement cost curves for the year 2030 as a relevant “anchor point”. 2030 was selected on the basis of its relevance for setting near-term expectations and initiating public and private investments in low-carbon programs as well as the robustness and reliability of economic and technical modeling over that time frame (Quinet 2019).

To assess the abatement cost potential, the commission employed a pair of techno-economic models (TIMES and POLES) and three sectoral macroeconomic models (IMACLIM, ThreeME, and NEMESIS). These models were deemed sufficiently robust to quantify shadow prices supporting up to a 75 percent reduction in emissions from 1990 levels but were considered insufficient to evaluate the deep decarbonization required in the later years of the period. Based on this set of analyses, the commission proposed setting a 2030 shadow price of carbon of \$309 per metric ton of CO₂e, a substantial upward revision from the previous value for the year 2030, \$136 per metric ton of CO₂e, which had been established in 2008. Carbon values for the years between 2018 and 2030 were proposed to rise linearly from the 2018 value of \$67 per metric ton of CO₂e to meet the shadow price established for 2030. See Appendix E for conversion and inflation rates used to translate 2018 EUR to 2020 USD.

Concerns about the ability of the models employed to explore deep decarbonization scenarios led the commission to integrate several approaches to establish values for the shadow price of carbon beyond 2030. The integrated approach included output from the techno- and macroeconomic models through roughly 2040, foresight on the portfolio of enabling technologies required for full decarbonization, and calibration of the shadow price on a Hotelling rule²⁵ from 2040 for a 4.5 percent rate of discount. The resulting trajectory yielded a \$617 per metric ton of CO₂e carbon value in 2040 and \$957 per metric ton of CO₂e in 2050.

In addition to its exploration of structural uncertainty in the estimates through the use of models of differing types, the commission studied and reported on uncertainty in the estimates related to the level of international cooperation. It evaluated scenarios representing delayed domestic or international action, which would have the effect of increasing the estimates, as well as the potential for increased international cooperation leading to the development of disruptive technologies. The commission did not explicitly publish a range of estimates based on these sensitivities.

3.2.3. Ireland

Ireland has implemented an abatement cost model for use in evaluating potential public investment projects across all sectors of the economy (Kevany 2019). The Irish government opted against the SCC approach, citing concerns over its level of uncertainty. The MAC approach was considered to entail lower overall

²⁵ The Hotelling rule indicates that, in order to maximize the present value of a non-renewable resource extracted over a given period, the percentage change per unit time in the net price of the resource should equal the discount rate (Hotelling 1931).

uncertainty, limited to the selection of the appropriate climate target to use and the actual abatement cost of reaching the target (Kevany and Cleary 2018).

Ireland's carbon valuation is based on the estimated societal marginal cost to reach Ireland's 2030 emissions target of 30 percent below 2005 levels by 2030. Estimates made for abatement costs for energy sector measures, as compiled in Ireland's National Mitigation Plan, are a proxy for economy-wide abatement costs. Specifically, the TIMES energy system model was used to create estimated MAC curves, and the price trajectory provided by the model was smoothed over time, starting at \$34 per metric ton of CO₂e in 2019, rising to \$55 in 2020, and reaching an estimated \$172 by 2030. These values apply only to non-EU regulated carbon emissions (Kevany and Cleary 2018).

Ireland's approach does not use MAC curves to estimate values past 2030 in light of increasing uncertainty over technology costs and the potential for their rapid change over longer time horizons. Instead, the value employed is proposed to rise by 5 percent a year beyond 2030, yielding values per metric ton of CO₂e of \$220 in 2035, \$280 in 2040, \$357 in 2045, and \$455 in 2050 (Kevany and Cleary 2018).

3.3. Considerations for Using the Marginal Abatement Cost Approach in NYS

As NYS State Agencies evaluate the potential for incorporating MAC information in policy analysis supporting implementation of the Climate Act, the Department will need to work with NYS Agencies to address the following decision and guidance points to ensure a consistent application of the MAC approach, where warranted.

MAC curve development. There is a firm foundation of MAC information on which the NYS power sector can base a MAC curve, but information for other sectors of the State's economy varies in availability and level of detail. In NYS, as in many other jurisdictions, the power sector has led other sectors in emissions abatement. Analysis consistently concludes that the power sector is structurally able to reduce emissions at lower cost than other sectors (Barron et al. 2018). By virtue of its long-standing renewable energy credit (REC) market, NYS has significant experience with assessing real-world cost signals required to deploy targeted levels of renewable electricity. Continued experience with the REC market could be used to update MAC information on an ongoing basis. In addition, the NYS power sector has recently been the subject of a detailed analysis to assess technology costs and renewable resource availability, among other relevant variables, directly in support of policy design to meet its targets for clean and renewable energy, as required by the Climate Act (New York State Department of Public Service and NYSERDA 2020).

NYSERDA also has engaged Energy and Environmental Economics to develop a strategic analysis of the State's decarbonization opportunities. This ongoing analytic work models portfolios of GHG reduction measures that will be needed to achieve the State's economy-wide 2030 and 2050 emissions reduction targets, with focus to date on the electricity, transportation, buildings, and industrial sectors (Energy and Environmental Economics 2020). Inputs to the models used in this work include cost and performance characteristics of both supply-side infrastructure and demand-side technologies. As this analysis is refined to inform the Climate Act policy process, it would allow NYS to accelerate the development of MAC curves for the initial focal sectors. Additional analytic work is needed to improve characterization of noncombustion GHG sources (such as landfills) and associated mitigation opportunities, as well to assess the potential quantity and cost of sustainable bioenergy resources, suggesting that the development of MAC curves for these sectors may take longer.

Multiple curves versus a single curve. A MAC approach could be applied to evaluate policies across the NYS economy, either by applying separate MAC values for policy actions related to specific sectors (e.g., a power sector MAC curve applied to assess power sector policies, and a transportation MAC curve applied to assess transportation sector policies) or by uniformly applying a MAC curve based on abatement cost estimates across the NYS economy to reach the economy-wide targets. In selecting between these two approaches, NYSERDA notes that it is economically rational for policymakers to seek to advance progress in the power sector in a manner that recognizes the relatively low cost at which emissions reductions may be achieved, compared with other sectors.

Holistic view of abatement costs. MAC information should ideally be incorporated in a manner that considers interactions between sectors as well as economy-wide goals. As discussed above, MAC curves are often developed for a particular sector using an approach that does not take into account potentially important interactions with other sectors. For example, meeting renewables targets in the power sector will affect electricity prices, thereby affecting the economics of consumer decisions related to vehicle electrification. Bottom-up MAC curves developed in isolation for the power and transportation sectors, however, typically would not account for this interaction. This underscores the importance of considering how a MAC approach would be applied across multiple sectors and fit coherently with the various policy approaches being taken by NYS.

Updating of MAC curves. MAC curves, once developed, would need to be maintained and periodically revisited to stay current with both the state of technology and evolution of the policy context. The limited applicability of the curves beyond NYS suggests that continual maintenance will likely require an ongoing commitment of resources by NYS and would ideally be planned for in advance.

4. Conclusion

This memo has assessed specific considerations related to analytic approach, discount rates, and prior estimates for valuing carbon in support of the Department's issuance of guidance on the value of carbon for use by NYS agencies.

NYSERDA notes in closing that there is an inherent policy interest in preserving the freedom for NYS policymakers to pursue the most economically rational abatement opportunities to their fullest potential. Although the statutory language in the Climate Act is suggestive of the identification of a uniform value for carbon, NYSERDA suggests that the Department in its guidance could take into account the value of information from both the SCC and the MAC analytic approaches, potentially providing some flexibility in applying the identified value of carbon in policymaking. It may be sensible for NYS agencies to use distinct approaches for different sectors, for example developing a MAC value for the power sector and using an SCC estimate for other sectors, or (in time) developing separate MAC values for policy actions related to specific sectors. It is important that such flexibility be coupled with Department guidance for those different sectors and implementing agencies, with attention to cross-sectoral dynamics and the role for each sector as part of New York State's holistic strategy to drive the economy-wide GHG emissions reductions required under the Climate Act. Relatedly, an outcome to avoid is allowing individual agencies or analysts to select their approaches on a discretionary or case-by-case basis, because of the absence of clear guidance that is rooted in a holistic Climate Act strategy.

Achieving the ambitious requirements of the Climate Act will require deep emissions reductions across the entire NYS economy and will necessitate detailed planning and policy evaluation across a disparate set of economic sectors. Both the SCC approach, with its focus on global societal benefits realized from the reduction of greenhouse gas emissions, as well as the MAC framework, with its focus on costs to achieve the required targets, can provide relevant, and in many ways complementary, information to NYS policymakers in this context.

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6. Appendices

Appendix A. Social Costs of Methane and Nitrous Oxide, IWG Estimates

Table A1. Social Cost of Methane Estimates (2020\$/metric ton CH₄)

Year of emission	Average estimate at 5% discount rate	IWG central estimate: Average estimate at 3% discount rate	Average estimate at 2.5% discount rate	High-impact estimate: 95th percentile estimate at 3% discount rate
2020	670	1,500	2,000	3,900
2025	800	1,700	2,200	4,500
2030	940	2,000	2,500	5,200
2035	1,100	2,200	2,800	6,000
2040	1,300	2,500	3,100	6,700
2045	1,500	2,800	3,500	7,500
2050	1,700	3,100	3,800	8,200

Source: Federal interim estimates of the SC-CH₄ (IWG 2021).

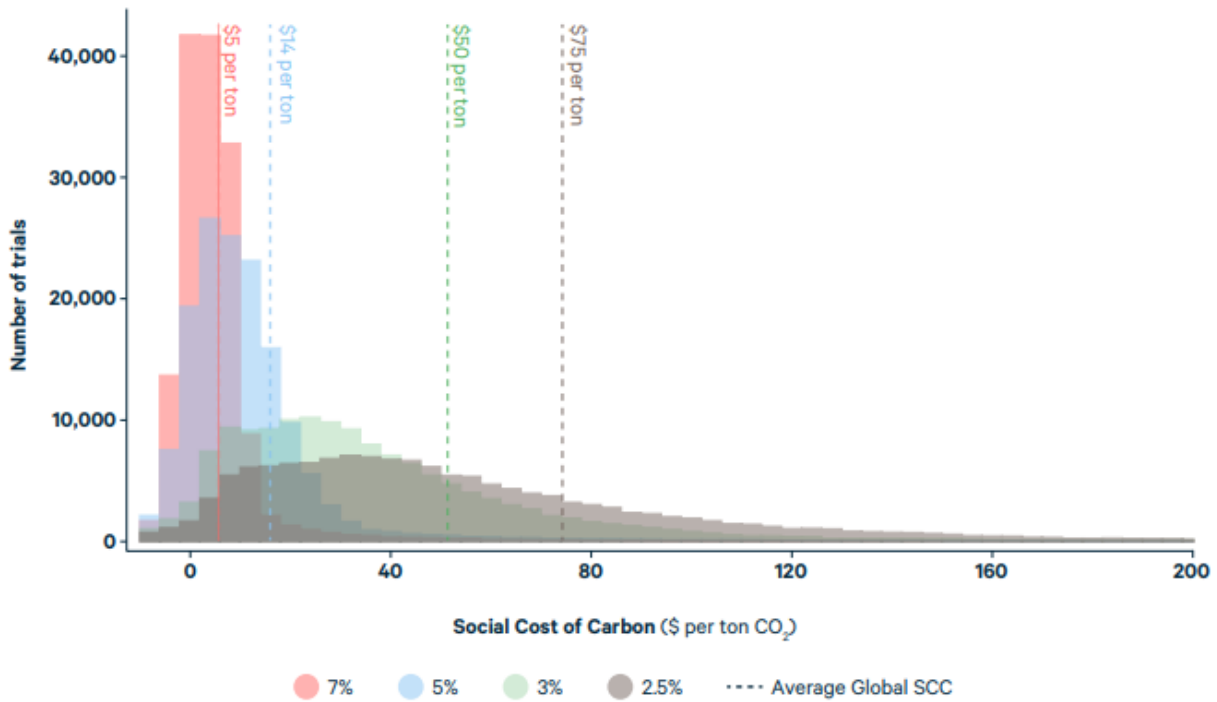
Table A2. Social Cost of Nitrous Oxide Estimates (2020\$/metric ton N₂O)

Year of emission	Average estimate at 5% discount rate	IWG central estimate: Average estimate at 3% discount rate	Average estimate at 2.5% discount rate	High-impact estimate: 95th percentile estimate at 3% discount rate
2020	5,800	18,000	27,000	48,000
2025	6,800	21,000	30,000	54,000
2030	7,800	23,000	33,000	60,000
2035	9,000	25,000	36,000	67,000
2040	10,000	28,000	39,000	74,000
2045	12,000	30,000	42,000	81,000
2050	13,000	33,000	45,000	88,000

Source: Federal interim estimates of the SC-N₂O (IWG 2021).

Appendix B. Range of IWG SC-CO₂ Values

Figure B1. Range of Values for SCC in 2020 (2019\$/metric ton CO₂)



Source: Reproduced from Rennert and Kingdon (2019)

Appendix C. Estimated SCC of Selected GHGs

The following tables show the social cost of carbon dioxide, methane, and nitrous oxide estimates for the year 2020 at different constant discount rates. Each of the three integrated assessment models and each of the discount rates were run using the same assumptions and scenarios used by the IWG. Each model is run 50,000 times across the random variable space, and the means of the resulting distributions are displayed along with the 95th percentile value as a sensitivity. Consistent with IWG estimates, SC-CO₂ values are rounded to the nearest dollar. SC-CH₄ and SC-N₂O estimates are rounded to two significant figures. Appendix I shows the annual average estimates of SC-CO₂, SC-CH₄, and SC-N₂O for the years 2020 through 2050, at constant discount rates of 3%, 2%, and 1%.

Table C1. 2020 SC-CO₂ with Constant Rate Discounting (2020\$/metric ton CO₂)

Model	5%	3%	2.5%	2%	1%	0%
DICE	15	46	70	112	392	2,154
FUND	3	23	41	68	264	1,460
PAGE	25	83	119	183	563	2,776
Average of models	14	51	76	121	406	2,130
95th percentile	43	152	220	338	1,101	5,787

Table C2. 2020 SC-CH₄ with Constant Rate Discounting (2020\$/metric ton CH₄)

Model	5%	3%	2.5%	2%	1%	0%
DICE	540	1,200	1,500	2,100	5,600	25,000
FUND	650	1,500	2,100	2,900	7,400	28,000
PAGE	810	1,800	2,300	3,000	6,000	17,000
Average of models	670	1,500	2,000	2,700	6,400	23,000
95th percentile	1,600	3,900	5,200	7,300	18,000	70,000

Table C3. 2020 SC-N₂O with Constant Rate Discounting (2020\$/metric ton N₂O)

Model	5%	3%	2.5%	2%	1%	0%
DICE	4,800	16,000	24,000	39,000	140,000	730,000
FUND	4,600	16,000	24,000	39,000	130,000	680,000
PAGE	8,300	25,000	35,000	52,000	140,000	570,000
Average of models	5,800	18,000	27,000	42,000	130,000	660,000
95th percentile	15,000	48,000	70,000	110,000	360,000	1,800,000

Appendix D. Ramsey-Like Discounting Approach

A key recommendation of the NAS report to improve SCC estimates is to introduce a “Ramsey-like” approach to discounting (NAS 2017). Ramsey discounting is a generalization of the “constant” discount rate approach (discussed above) and is based on a seminal paper by Frank Ramsey (1928). Rather than choosing a single discount rate, a Ramsey-like approach would use a discount rate (r) determined by the following formula:

$$r = \delta + \eta \cdot g,$$

where δ is the rate of pure time preference (how much society discounts the utility, or human welfare, of people in the future), η is the elasticity of the marginal utility of consumption (how much the value of an incremental dollar of consumption declines as society grows wealthier), and g is the growth rate of consumption per capita (roughly speaking, the economic growth rate). Both δ and η are typically nonnegative, meaning that the discount rate is not simply a constant number but rather depends on the values of those parameters and the rate of economic growth.

Various methods could be used to choose those parameters. The η parameter determines how we discount effects on future generations because they are expected to be wealthier (assuming economic growth is positive). As a result, this value links the discount rate to the economic growth rate. Typical values for η used in the literature are in the range of 1 to 2. The median and mean values of η from the Drupp et al. (2018) survey are 1.00 and 1.35, respectively. RFF economists Richard Newell, Brian Prest, and William Pizer are currently working to estimate values of δ and η that reconcile the empirically observed behavior of interest rates, and they plan to use the results from that estimation in future updates to the social cost of carbon dioxide. Their preliminary preferred estimates point to a value of $\eta = 1.3$, which is coincidentally very close to the mean of 1.35 reported by Drupp et al. (2018).

The δ term, also called the rate of pure time preference, determines how much the utility of people—who may be alive at different points in time—is discounted. Some economists and philosophers believe this rate should be zero, or at least very small. The original Ramsey (1928) paper argued that this kind of discounting is “ethically indefensible,” suggesting a rationale for setting $\delta = 0$, although agreement on this is not universal (Arrow 1999). The Stern (2007) review argued for using a very small δ value of 0.1 percent, simply to account for the possibility that a future generation might not exist (because, say, an asteroid has struck Earth). The survey results from Drupp et al. (2018) imply a median (mean) value of δ of 0.5 percent (1.1 percent) and a modal value of 0 percent. However, they do not find a broad consensus for a near-zero value of δ . In RFF’s ongoing work implementing the Ramsey-like framework, δ takes on values of 0.4, 1.4, and 3.4 percent (alongside an η value of 1.3) to target near-term target discount rates of 2, 3, and 5 percent respectively.

Given the common argument for considering the possibility of using a zero rate of pure time preference, $\delta = 0$ could be interpreted as corresponding the Climate Act requirement of considering “a range of appropriate discount rates, including a rate of zero.” The rate of pure time preference is the rate at which society discounts utility, so it may be closer to the underlying ethical intent of the Climate Act in assessing a rate of zero than an overall discount rate that also takes into account the lower value of an additional dollar to wealthier people.

If NYS decided to use a value of $\delta = 0$ to represent a “rate of zero” for the rate of pure time preference, then the discount rate would simply equal $r = 0 + \eta \cdot g = \eta \cdot g$. As previously mentioned, RFF’s preliminary estimate of η is 1.3, alongside an estimated near-term per capita growth rate (g) of about 1.3 percent. Using these estimates would imply a near-term discount rate of $r = \delta + \eta \cdot g = 0\% + 1.3 \cdot 1.3\% = 1.7\%$, which is close to the 2 percent “low” rate being used by RFF in implementing the NAS recommendations.

Appendix E. Exchange Rates and Inflation Adjustments

To make comparisons of values more straightforward, estimates are given in 2020 USD (2020\$) amounts. USD inflation was derived using the annual GDP Implicit Price Deflator values in the U.S. Bureau of Economic Analysis' (BEA) NIPA Table 1.1.9.

Exchange rates for GBP and EUR to USD were found on the Federal Reserve Board's Foreign Exchange Rate History data, using January 2 data in each year, found here:

<https://www.federalreserve.gov/releases/h10/hist/default.htm>

The following inflators were used:

- 2007USD to 2020USD: 1.228575 (for IWG estimates published in 2016)
- 2018GBP to 2020USD: 1.4143 (for UK traded values)
- 2009GBP to 2020USD: 1.7732 (for UK nontraded values)
- 2018EUR to 2020USD: 1.2349 (for France)
- 2010EUR to 2020USD: 1.7159 (for Ireland)

Appendix F. UK Schedules for Short-Term Carbon Valuation for Traded and Nontraded Sectors

Table F1. Traded Price of Carbon for Sectors in EU ETS (2018GBP/metric ton CO₂e)

2018GBP per ton CO ₂ e			
Year	Low	Central	High
2020	0	13.84	27.69
2021	4.04	20.54	37.04
2022	8.08	27.24	46.4
2023	12.12	33.94	55.75
2024	16.17	40.64	65.11
2025	20.21	47.33	74.46
2026	24.25	54.03	83.82
2027	28.29	60.73	93.17
2028	32.33	67.43	102.53
2029	36.37	74.13	111.88
2030	<i>converges with modeled estimates for non-traded sectors beginning in 2030</i>		

Source: DBEIS (2019).

Table F2. Traded Price of Carbon for Sectors in EU ETS (2020\$/metric ton CO₂e)

2020USD per ton CO ₂ e			
Year	Low	Central	High
2020	0.00	19.57	39.16
2021	5.71	29.05	52.38
2022	11.43	38.52	65.62
2023	17.14	48.00	78.85
2024	22.87	57.48	92.08
2025	28.58	66.94	105.31
2026	34.30	76.41	118.54
2027	40.01	85.89	131.77
2028	45.72	95.36	145.00
2029	51.44	104.84	158.23
2030	<i>converges with modeled estimates for non-traded sectors beginning in 2030</i>		

Source: RFF conversion of values in Table F1 to 2020USD as described in Appendix E.

Table F3. Nontraded Price of Carbon for Non-ETS Sectors (2009GBP/metric ton CO₂e; DECC 2009)

2009GBP per ton CO ₂ e			
Year	Lower	Central	Upper
2020	30	60	90
2030	35	70	105
2050	100	200	300

Source: Department of Energy and Climate Change (2009).

Table F4. Nontraded Price of Carbon for Non-ETS Sectors (2020\$/metric ton CO₂e)

2020USD per ton CO ₂ e			
Year	Lower	Central	Upper
2020	53	106	160
2030	62	124	186
2050	177	355	532

Source: RFF conversion of values in Table F3 to 2020USD as described in Appendix E.

Appendix G. France's MAC Estimates

Table G1. France's Shadow Price of Carbon, Proposed to Increase Linearly between 2018 and 2030

Year	2018EUR/ metric ton CO ₂ e	2020\$/metric ton CO ₂ e
2018	54	67
2020	87	107
2030	250	309
2040	500	617
2050	775	957

Source: Ministère de la Transition écologique et solidaire 2018. Conversions to 2020USD shown in right column carried out by RFF as described in Appendix E.

Appendix H. Ireland's MAC Estimates

Table H1. Ireland's MAC Estimates

Year	2010EUR/metric ton CO ₂ e	2020\$/metric ton CO ₂ e
2020	32	55
2030	100	172
2035	128	220
2040	163	280
2045	208	357
2050	265	455

Source: Kevany 2019. Conversions to 2020USD shown in right column carried out by RFF as described in Appendix E.

Appendix I. Annual estimates of SC-CO₂, SC-CH₄, and SC-N₂O

The following tables show annual average estimates of SC-CO₂, SC-CH₄, and SC-N₂O for the years 2020 through 2050, at constant discount rates of 3%, 2%, and 1%. See Appendix C for a description of how these estimates were modeled, using the same assumptions and scenarios used by the IWG.

Table I1. Social Cost of CO₂ estimates (2020\$/metric ton CO₂)

Year of emission	Average estimate at 3% discount rate	Average estimate at 2% discount rate	Average estimate at 1% discount rate
2020	51	121	406
2021	52	123	409
2022	53	124	411
2023	54	126	414
2024	55	128	416
2025	56	129	418
2026	57	131	421
2027	59	132	423
2028	60	134	426
2029	61	136	428
2030	62	137	430
2031	63	139	433
2032	64	141	435
2033	65	142	437
2034	66	144	440
2035	67	146	442
2036	69	147	444
2037	70	149	446
2038	71	151	449
2039	72	152	451
2040	73	154	453
2041	74	156	456
2042	75	158	459
2043	77	160	461
2044	78	162	464
2045	79	164	467
2046	80	166	469
2047	81	167	471
2048	82	169	472
2049	84	170	474
2050	85	172	476

Table I2. Social Cost of CH₄ estimates (2020\$/metric ton CH₄)

Year of emission	Average estimate at 3% discount rate	Average estimate at 2% discount rate	Average estimate at 1% discount rate
2020	1500	2700	6400
2021	1500	2800	6400
2022	1600	2800	6500
2023	1600	2900	6600
2024	1700	2900	6700
2025	1700	3000	6800
2026	1800	3100	6900
2027	1800	3100	7000
2028	1900	3200	7100
2029	1900	3300	7200
2030	2000	3400	7300
2031	2000	3400	7400
2032	2100	3500	7500
2033	2100	3600	7700
2034	2200	3600	7800
2035	2200	3700	7900
2036	2300	3800	8000
2037	2300	3900	8100
2038	2400	3900	8200
2039	2500	4000	8300
2040	2500	4100	8400
2041	2600	4200	8500
2042	2600	4200	8600
2043	2700	4300	8700
2044	2700	4400	8800
2045	2800	4500	8900
2046	2800	4500	9000
2047	2900	4600	9100
2048	3000	4700	9200
2049	3000	4800	9300
2050	3100	4800	9400

Table I3. Social Cost of N₂O estimates (2020\$/metric ton N₂O)

Year of emission	Average estimate at 3% discount rate	Average estimate at 2% discount rate	Average estimate at 1% discount rate
2020	18000	42000	130000
2021	19000	43000	140000
2022	19000	44000	140000
2023	20000	45000	140000
2024	20000	45000	140000
2025	21000	46000	140000
2026	21000	47000	140000
2027	21000	47000	140000
2028	22000	48000	140000
2029	22000	49000	150000
2030	23000	50000	150000
2031	23000	50000	150000
2032	24000	51000	150000
2033	24000	52000	150000
2034	25000	53000	150000
2035	25000	54000	150000
2036	26000	54000	160000
2037	26000	55000	160000
2038	27000	56000	160000
2039	27000	57000	160000
2040	28000	58000	160000
2041	28000	58000	160000
2042	29000	59000	160000
2043	29000	60000	170000
2044	30000	61000	170000
2045	30000	61000	170000
2046	31000	62000	170000
2047	31000	63000	170000
2048	32000	64000	170000
2049	32000	65000	170000
2050	33000	66000	170000