RESOURCES *for the* FUTURE

June 21, 2021

Office of Management and Budget
725 17th St., NW
Washington, DC 20503
Attn: OMB-2021-0006
Submitted via: **www.regulations.gov**

Dear Deputy Administrator Mancini,

On behalf of Resources for the Future (RFF), I am pleased to share the accompanying comments to the Office of Management and Budget on the *Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide Interim Estimates under Executive Order 13990*.

RFF is an independent, nonprofit research institution in Washington, DC. Its mission is to improve environmental, energy, and natural resource decisions through impartial economic research and policy engagement. RFF is committed to being the most widely trusted source of research insights and policy solutions leading to a healthy environment and a thriving economy.

While RFF researchers are encouraged to offer their expertise to inform policy decisions, the views expressed here are those of the individual authors and may differ from those of other RFF experts, its officers, or its directors. RFF does not take positions on specific policy proposals.

Several RFF researchers have provided comments on the issues listed below. All authors' comments are their own and submitted as independent authors.

- RFF's Implementation of Near-Term Recommendations of the National Academies of Sciences, Engineering, and Medicine to Improve the Estimation of Social Costs of Greenhouse Gases (Rennert, Prest, Newell, Pizer, Anthoff)
- A Shadow-Price-of-Capital Approach to Harmonize Discounting for Greenhouse Gases in Broader Benefit-Cost Analyses (Pizer)

If you have any questions or would like additional information, please contact Kevin Rennert at rennert@rff.org.

Sincerely,

Richard G. Newell

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RFF's Implementation of Near-Term Recommendations of the National Academies of Sciences, Engineering, and Medicine to Improve the Estimation of Social Costs of Greenhouse Gases

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On February 26, 2021, the US government's Interagency Working Group on the Social Cost of Greenhouse Gases (IWG) issued the *Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide Interim Estimates under Executive Order 13990* (EO 13990). This support document provides interim estimates of the social cost of carbon (SC-CO_2), social cost of methane (SC-CH_4), and social cost of nitrous oxide (SC-N_2O), collectively called the social cost of greenhouse gases (SC-GHG). The provision of the interim estimates is one step in the federal government's process that will culminate in the issuance of final SC-GHG estimates in early 2022 as required by EO 13990.

EO 13990 directs that the federal government's update of the SC-GHG adhere to the recommendations laid out in a landmark report issued in 2017 by the National Academies of Sciences, Engineering, and Medicine (hereafter NASEM), *Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide*, conducted in response to a study request in 2015 from the IWG. The NASEM panel conducted a comprehensive evaluation of potential updates to the SC-CO_2 estimation methodology and put forward a number of conclusions and recommendations on how to improve the conceptual underpinnings, empirical methods, and data used to calculate the SC-CO_2, as well as the transparency and flexibility of the process by which future estimates are generated (NASEM 2017). The conclusions and recommendations of the NASEM report focus primarily on the calculation of the social costs resulting from the emissions of carbon dioxide, but they are also broadly applicable to the social costs of other greenhouse gases such as methane, nitrous oxide, and hydrofluorocarbons. The report provided both near-term recommendations that were designed to be implementable within two to three years and recommendations for longer-term improvements to the methodology.

The Social Cost of Carbon initiative was established in 2017 as a multi-institutional, collaborative effort between Resources for the Future (RFF) and the University of California–Berkeley, with additional contributors from Duke University, Harvard University, Princeton University, and the University of Washington, among others. The initiative has the following key objectives:

- improve the scientific basis for SC-CO_2 estimates by implementing the full set of near-term recommendations from the 2017 NASEM study and provide a transparently updated SC-CO_2 with uncertainty bounds
- develop open-source software tools for SC-GHG estimation to implement updated methods, promote transparency, and serve as a common platform for SC-GHG development by the scientific community
- facilitate the US government process to update values for SC-GHGs

In this comment, we discuss RFF's implementation of the NASEM report's near-term recommendations. We follow the report's organizational structure and include the committee's full set of recommendations for completeness. However, some of the recommendations fall outside the scope of the federal government's activities underway to establish a near-term update of the SC-GHG estimates as well as our current research activities. Though we focus on RFF and its direct collaborators' research efforts in this comment, we note the numerous additional and significant research contributions of relevance to the IWG's near-term update of the SCC estimates that have been put forward in recent years that will be the subject of separate comments by their respective authors.

Summary of Recommendations from the NASEM Report's Executive Summary

The committee specifies criteria for future updates to the SC-CO_2. It also recommends an integrated modular approach for SC-CO_2 estimation to better satisfy the specified criteria and to draw more readily on expertise from the wide range of scientific disciplines relevant to SC-CO_2 estimation. Under this approach, each step in SC-CO_2 estimation is developed as a module—socioeconomic, climate, damages, and discounting—that reflects the state of scientific knowledge in the current, peer-reviewed literature.

Because it is important to update estimates as the science and economic understanding of climate change and its impacts improve over time, the committee recommends that estimates of the SC-CO_2 be updated in a three-step process at regular intervals of approximately 5 years. This timing would balance the benefit of incorporating evolving research against the need for a thorough and predictable process.

For each module, the committee recommends near-term changes given the current state of the science. The recommended changes would be feasible to implement in the next 2-3 years and would improve the performance of each part of the analysis with respect to the primary criteria.

- **The socioeconomic module should use statistical methods and expert judgment for projecting distributions of economic activity, population growth, and emissions into the future.**
- **The climate module should use a simple Earth system model that satisfies well-defined diagnostic tests to confirm that it properly captures the relationships between CO_2 emissions, atmospheric CO_2 concentrations, and global mean surface temperature change and sea level rise.**
- **The damages module should improve and update existing formulations of climate change damages, make calibrations transparent, present disaggregated results, and address correlation between different formulations. This update should draw on recent scientific literature relating to both empirical estimation and process-based modeling of damages.**
- **The discounting module should incorporate the relationship between economic growth and discounting. The committee also recommends that the IWG provide guidance on how the SC-CO_2 estimates should be combined in regulatory impact analyses with other calculations. (NASEM 2017, 2–3)**

In this comment, we make the following general points:

- Nearly all of the NASEM report's near-term recommendations either have been implemented in a manner that meets NASEM criteria for scientific basis, uncertainty quantification, and transparency or will be implemented and peer-reviewed on a near-term time frame relevant for inclusion by the IWG in revised estimates.

- Key research activities that are responsive to the NASEM recommendations include the following:
  - *Modularization of SC-GHG estimation methodology*. We have accomplished the modularization of the SC-GHG estimation process and corresponding improvement of transparency of the estimates through the provision of a new open-source software framework (Mimi.jl) for building integrated assessment models (IAM).
  - *Long-run socioeconomic projections*. We have used a combination of statistical information and expert judgment to generate long-run socioeconomic projections, with associated uncertainty bounds, of global emissions and regional GDP and population that account for future policies and dependencies between the variables.
  - *Improved climate model*. We have implemented a pair of updated climate modules that meet the NASEM criteria and pass the recommended diagnostic tests.
  - *Damages literature review and implementation*. We have completed an extensive review of the literature and are in the process of implementing candidate damage functions on the Mimi platform.
  - *Economic discounting*. We have developed a methodology for empirically calibrating the key discounting parameters required for implementing NASEM recommendations to move to a Ramsey-like framework for economic discounting, while also reflecting the empirical

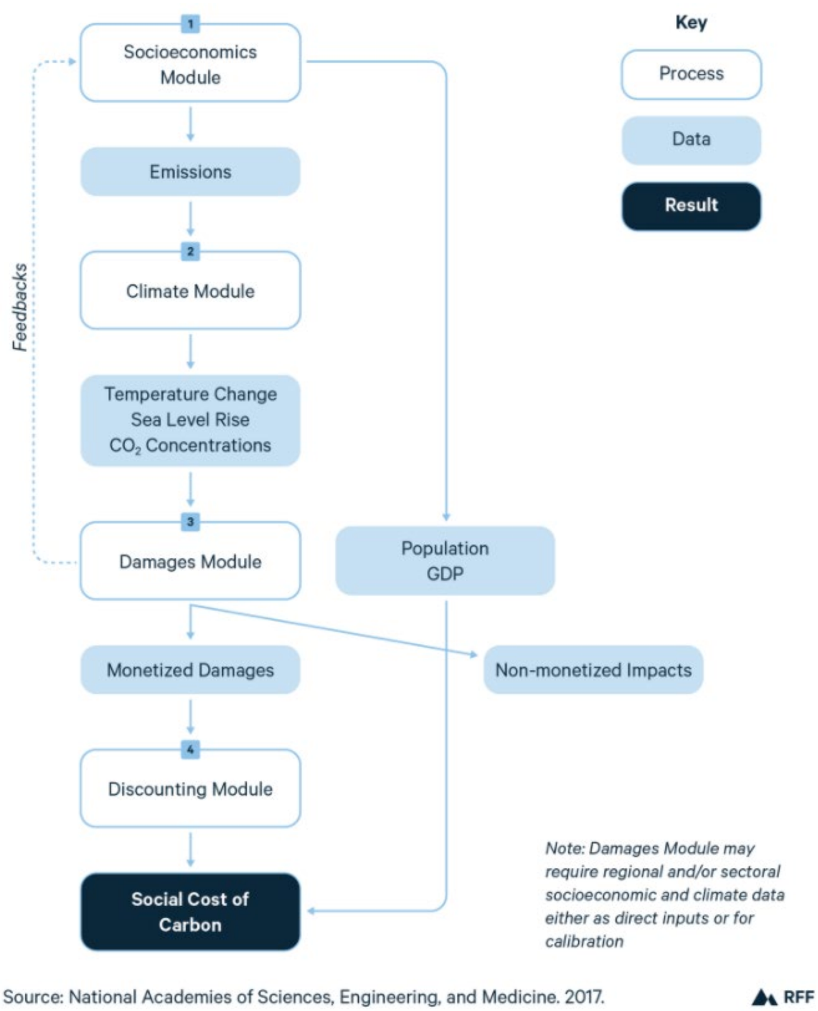
literature on the term structure of interest rates and being consistent with near-term rates associated with related federal discounting guidance.

- We also support the process by which the IWG is revising the SC-GHGs, which is consistent with the NASEM recommendations for a process that allows for scientific advance and peer review, the incorporation of scientific advances into the SC-GHG estimation methods, and public review of revised estimates in a transparent manner.

Framework for Estimating the Social Cost of Greenhouse Gases

NASEM RECOMMENDATION 2-1. The Interagency Working Group should support the creation of an integrated modular SC-CO_2 framework that provides a transparent articulation of the inputs, outputs, uncertainties, and linkages among the different steps of SC-CO_2 estimation. For some modules within this framework, the best course of action may be for the government to develop a new module, while for other modules the best course of action may be to adapt one or more existing models developed by the scientific community. (NASEM 2017, 7)

Figure 1. A Modularized Approach to Estimating the SC-CO_2



Source: National Academies of Sciences, Engineering, and Medicine. 2017.

"Unbundling" the process of SC-GHG estimation into four modular steps integrated with one another (Figure 1) provides important benefits highlighted by the NASEM report. Each module may be developed based on expertise within the relevant disciplines and reflects the state of scientific knowledge relevant to that part of the analysis. Modularization provides a transparent articulation of the inputs, outputs, uncertainties, and linkages among the different steps. Further, it can improve control over characterization of uncertainty within the steps and through an integrated framework for propagating uncertainty through the estimation process.

RFF, working with a team of researchers at UC Berkeley led by David Anthoff, has developed and released the open-source computing platform Mimi.jl (hereafter Mimi), which is fully responsive to Recommendation 2-1 and serves to improve the transparency of the estimates and foster collaboration among members of the climate impacts modeling community. Freely available on GitHub, Mimi provides an easy-to-use interface for defining components and building integrated assessment models, such as those used for SC-GHG estimation, in a modularized, transparent way. It is implemented in the open-source Julia programming language, which is computationally fast while maintaining accessible syntax and conventions for novice programmers.

Mimi fully modularizes the steps of SC-GHG estimation, and its design enhances the readability of code developed on the platform. The platform additionally provides support for more advanced features such as uncertainty (e.g., Monte Carlo) simulations and sensitivity (e.g., Sobol) analysis. Mimi is full-featured, with many of the past integrated assessment models (IAMs) used for SC-CO_2 estimation already available, including the following:

- FUND
- DICE (2010, 2013, and 2016 versions)
- RICE, RICE+AIR
- PAGE2009, PAGE-ICE
- MimiIWG (software package containing DICE, FUND, PAGE versions and specific configurations used by the IWG for calculating SC-GHGs in 2013 and 2016 releases)

Modern climate models are also available on the Mimi platform, including the FAIR climate model (Smith et al. 2018) highlighted in the NASEM report, the SNEASY climate model (Urban and Keller 2010), and the BRICK sea level rise model (Wong et al. 2017).

Mimi is in widespread use by academic research groups around the world, including the London School of Economics, Princeton University, and the University of California–Berkeley, and has been used in numerous peer-reviewed publications (e.g., Adler et al. 2017; Anthoff and Emmerling 2019; Errickson et al. 2021a,b; Moore et al. 2018; Rising 2020; Rising and Devineni 2020; Scovronick et al. 2019, 2021). The MimiIWG software package has been used for analysis conducted by RFF supporting the New York State Department of Environmental Conservation's evaluation of options for establishing a cost of carbon, as required by the Climate Leadership and Community Protection Act (RFF and NYSERDA 2020), and employed by the US Environmental Protection Agency to conduct its regulatory impact analysis for a proposed rule to reduce emissions of hydrofluorocarbons (EPA 2021).

NASEM RECOMMENDATION 2-2. The Interagency Working Group should use three criteria to evaluate the overall integrated SC-CO_2 framework and the modules to be used in that framework: scientific basis, uncertainty characterization, and transparency.

- **Scientific basis: Modules, their components, their interactions, and their implementation should be consistent with the state of scientific knowledge as reflected in the body of current, peer-reviewed literature.**

- **Uncertainty characterization: Key uncertainties and sensitivities, including functional form, parameter assumptions, and data inputs, should be adequately identified and represented in each module. Uncertainties that cannot be or have not been quantified should be identified.**
- **Transparency: Documentation and presentation of results should be adequate for the scientific community to understand and assess the modules. Documentation should explain and justify design choices, including such features as model structure, functional form, parameter assumptions, and data inputs, as well as how multiple lines of evidence are combined. The extent to which features are evidence-based or judgment-based should be explicit. Model code should be available for review, use, and modification by researchers. (NASEM 2017, 7)**

RFF has structured its research approach under the initiative to meet the three criteria in Recommendation 2-2. In our scoping and research implementation strategy, we first conducted a landscape analysis to identify existing research and tools to address each of the NASEM near-term recommendations. Following this landscape analysis, we have worked to address identified gaps through research organized by the initiative directly and in partnership with top field experts for each module. We have ensured scientific quality and transparency in multiple ways. The initiative is advised by a formal Scientific Advisory Board that includes five members of the NASEM committee on the social cost of carbon. We have convened expert workshops on economic growth, discounting, and long-run population projections to inform our research approach and review draft products. All the software tools developed under the initiative are fully open source, and data will be made publicly available upon scientific review. All research products are subject to scientific peer-review through multiple means, including the journal publication process.

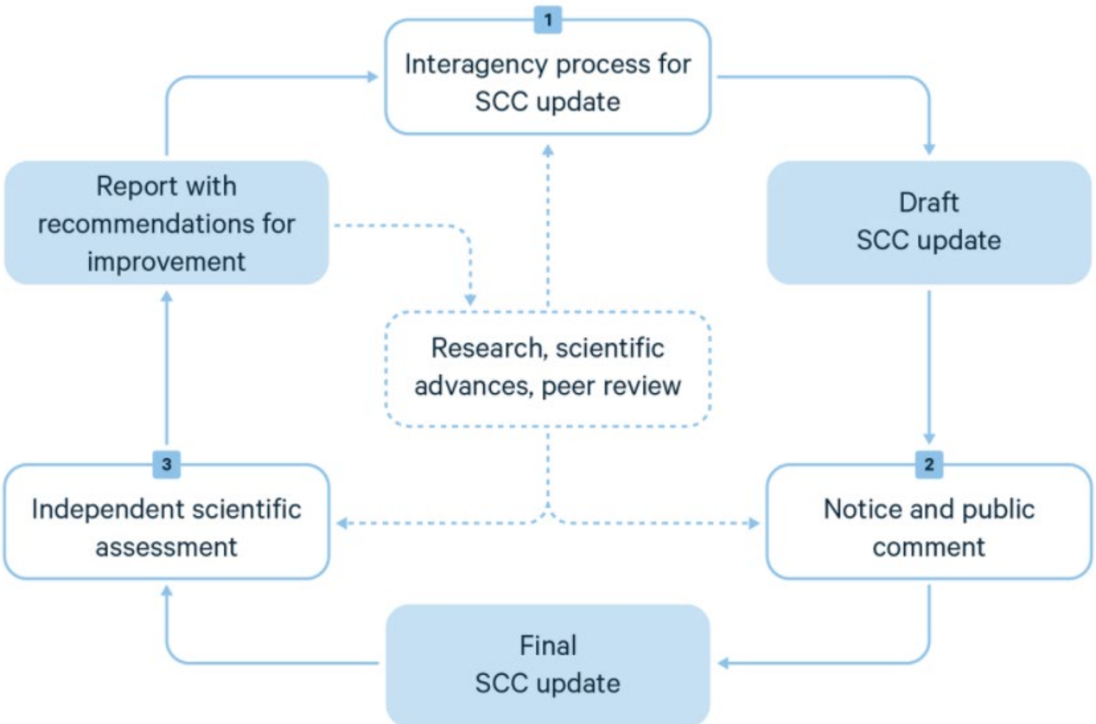
NASEM RECOMMENDATION 2-3. The Interagency Working Group should continue to monitor research that identifies and explores the magnitude of various interactions and feedbacks in the human-climate system including those not represented in implementation of the proposed modular SC-CO_2 estimation framework. The IWG should include interactions and feedbacks among the modules of the SC-CO_2 framework if they are found to significantly affect SC-CO_2 estimates. (NASEM 2017, 7)

NASEM RECOMMENDATION 2-4. The Interagency Working Group should establish a regularized three-step process for updating the SC-CO_2 estimates. An update cycle of roughly 5 years would balance the benefit of responding to evolving research with the need for a thorough and predictable process. In the first step, the interagency process and associated technical efforts should draw on internal and external technical expertise and incorporate scientific peer review. In the second step, draft revisions to the SC-CO_2 methods and estimates should be subject to public notice and comment, allowing input and review from a broader set of stakeholders, the scientific community, and the public. In the third step, the government's approach to estimating the SC-CO_2 should be regularly reviewed by an independent scientific assessment panel to identify improvements for potential future updates and research needs. (NASEM 2017, 9–10)

Within the process outlined in Recommendation 2-4, the IWG first prepares a draft of revised estimates, incorporating independent scientific assessment and research advances (Figure 2). These revised estimates are made available for notice and public comment and then finalized. Ultimately, the estimates again are subjected to independent scientific assessment.

The 2017 NASEM report represents the culmination of the final phase of the process outlined in Recommendation 2-4, and the beginning of a new cycle has now commenced under EO 13990. Per that executive order, the IWG will complete the first two steps of the process in 2021 and 2022, and we applaud the inclusion of scientific advances and a period for solicitation of public comment, as envisioned in the NASEM report.

Figure 2. Regularized Process for $SC\text{-}CO_2$ Updates



Source: National Academies of Sciences, Engineering, and Medicine. 2017. RFF

Socioeconomic Module

NASEM RECOMMENDATION 3-1. In addition to applying the committee's overall criteria for scientific basis, uncertainty characterization, and transparency (see Recommendation 2-2 in Chapter 2), the Interagency Working Group should evaluate potential socioeconomic modules according to four criteria: time horizon, future policies, disaggregation, and feedbacks.

- **Time horizon: The socioeconomic projections should extend far enough in the future to provide inputs for estimation of the vast majority of discounted climate damages.**
- **Future policies: Projections of emissions of CO_2 and other important forcing agents should take account of the likelihood of future emissions mitigation policies and technological developments.**
- **Disaggregation: The projections should provide the sectoral and regional detail in population and GDP necessary for damage calculations.**
- **Feedbacks: To the extent possible, the socioeconomic module should incorporate feedbacks from the climate and damages modules that have a significant impact on population, GDP, or emissions. (NASEM 2017, 10–11)**

NASEM RECOMMENDATION 3-2. In the near term, to develop a socioeconomic module and projections over the relevant time horizon, the Interagency Working Group should:

- **Use an appropriate statistical technique to estimate a probability density of average annual growth rates of global per capita GDP. Choose a small number of values of the average annual growth rate to represent the estimated density. Elicit expert opinion on the desirability of possible modifications to the implied projections of per capita GDP, particularly after 2100.**
- **Work with demographers who have produced probabilistic projections through 2100 to create a small number of population projections beyond 2100 to represent a probability density function. Development of such projections should include both the extension of existing statistical models and the elicitation of expert opinion for validation and adjustment, particularly after 2100. Should either the economic or demographic experts suggest that correlation between economic and population projections is important, this could be included.**
- **Use expert elicitation, guided by information on historical trends and emissions consistent with different climate outcomes, to produce a small number of emissions trajectories for each forcing agent of interest conditional on population and income scenarios.**
- **Develop projections of sectoral and regional GDP and regional population using scenario libraries, published regional or national population projections, detailed-structure economic models, SC-IAMs, or other sources. (NASEM 2017, 11)**

NASEM RECOMMENDATION 3-3. In the longer term, the Interagency Working Group should engage in the development of a new socioeconomic module, based on a detailed-structure model, that meets the criteria of scientific basis, uncertainty characterization, and transparency, is consistent with the best available judgment regarding the probability distributions of uncertain parameters and that has the following characteristics:

- **provides internally consistent probabilistic projections, consistent with elicited expert opinion, as far beyond 2100 as required to capture the vast majority of discounted damages, taking into account the increased uncertainty regarding technology, policies, and social and economic structures in the distant future;**
- **provides probabilistic regional and sectoral projections consistent with requirements of the damage module, taking into account historical experience, expert judgment, and increasing uncertainty over time regarding the regional and sectoral structure of the global economy;**
- **captures important feedbacks from the climate and damage modules that affect capital stocks, productivity, and other determinants of socioeconomic and emissions projections. It should enable interactions among the modules to ensure consistency among economic growth, emissions, and their consequences; and**
- **is developed in conjunction with the climate and damage modules, to provide a coherent and manageable means of propagating uncertainty through the components of the SC-CO_2 estimation procedure. (NASEM 2017, 12)**

RFF has conducted original research and collaborated with leading experts in economic growth and demography to fully implement the near-term NASEM recommendations on improving socioeconomic projections. In total, the research provides a set of internally consistent, multicentury projections of global emissions and regional GDP and population, with associated uncertainty bounds and accounting for future policies and dependencies among the variables.

Our research approach centers around the IPAT identity (Commoner 1972), formulated as follows:

Emissions = Population x GDP/person x Emissions/GDP

By generating density functions of projections for each of the variables on the right-hand side of the equation for the very long run, while accounting for correlations among the variables and incorporating future expectations on the global climate policy context, we are able to provide the necessary emissions inputs for assessing the future state of the climate in the IAMs as well as the population and economic inputs needed for damage calculations.

Economic Growth

Our research approach to generating economic growth projections follows a three-step process. First, we project country-level economic growth using an econometric model based on long-term historical data. Second, we elicit expert judgment to further quantify uncertainty about future economic growth. Third, we constrain the econometric projections with the combined expert uncertainty. This process yields country-level projections of economic growth incorporating benefits of both econometric and expert approaches. In addition to the peer review provided in the publication process, the research approach to the economic growth projections and the Economic Growth Survey were informed by a 2018 workshop on economic growth convened by RFF.

Econometric projections: The foundation for the economic projections is a set of econometric projections of GDP per capita produced according to Müller, Stock, and Watson (2019), referred to hereafter as MSW. The MSW methodology employs a Bayesian latent factor model that projects long-run growth based on low-frequency variation in the historic data of country-level GDP per capita. The output from this model yields 2,000 internally consistent trajectories of country-level GDP per capita from 2015 to 2300. Each trajectory is characterized by a path for a common global factor, and 113 country-specific deviations from that pathway. The MSW method represents an enhancement of the approach originally provided by Müller and Watson (2016), which was highlighted in the NASEM report. The original 2016 methodology was suitable for global estimates of economic growth but has now been revised to support generating internally consistent projections at the country level.

Quantification of expert uncertainty: RFF's Economic Growth Survey (EGS) was implemented to quantify long-run uncertainty about economic growth projections through the formal elicitation of experts. The survey included two-hour interviews with 10 experts, selected based on their expertise in the field of macroeconomics and economic growth and the recommendations of their peers.

The EGS was designed to work in tandem with the MSW model and focused on quantifying uncertainty in economic growth for the OECD countries so that the results could be used to inform the MSW projections and provide country-specific densities of long-run projections reflecting expert uncertainty.

The methodology applied in the EGS is termed the classical model (Cooke 2013) of structured expert judgment because of its analogy to classical hypothesis testing. The essence of the classical model is that experts are treated as statistical hypotheses. The experts are scored on their ability to assess uncertainty based on their responses to calibration questions from their field whose true values are known, but which are unknown to the experts at the time of elicitation. The purpose of scoring is both to enable performance-weighted combinations of experts' judgments and to gauge and validate the combination that is adopted. The ability to performance-weight combined experts' judgments under this model provides advantages of narrower overall uncertainty distributions with greater statistical accuracy as well as improved performance both in and out of sample.

The results of each expert elicitation were combined using two methods: to combine the distributions by weighting each expert equally and to performance-weight the experts according to their performance on the calibration questions. Each yields a final combined elicited value of OECD GDP per capita for each year and quantile.

Constraining the econometric projections with the combined expert uncertainty: The output from the EGS is a set of quantiles of economic growth for the OECD for four discrete years. The MSW projections provide internally consistent country-level projections that are expressed relative to an evolving frontier, taken to be the OECD, for each year through 2300. To maintain the rich country-level information provided by the econometric model while incorporating the information provided by the experts, we reweight the probability of occurrence of each of the 2,000 OECD trajectories from MSW to increasingly satisfy the experts' combined distribution over the long run. The underlying projections and structure from MSW remain unchanged by this process, but the likelihood of drawing a given OECD trajectory and its associated country-level pathways is modified such that, in aggregate, the projections reflect the uncertainties quantified by the experts.

Population

To implement the NASEM recommendations on very-long run population projections, Raftery and Ševčíková employed the Bayesian method for producing probabilistic projections of population at the country level that informs the official population projections issued by the United Nations (Raftery et al. 2012, 2014a,b). The method was modified to accommodate the generation of projections out to the year 2300 from the standard projection period ending in 2100.

Raftery and Ševčíková presented their draft methodology for peer review to a group of 10 leading experts in demography in a daylong expert workshop convened by RFF in 2018. In their review, experts provided specific feedback on ranges of values for key modeling parameters in light of the extended time horizon for the projections. This input from experts is responsive to the NASEM recommendation for the incorporation of expert judgment for the population projections. The information provided by the experts was subsequently incorporated into a revised methodology, which, along with the resulting population projections, is currently under peer review for journal publication.

Emissions Intensity

An Emissions Intensity Survey (EIS) is currently underway as the final component of RFF's implementation of the NASEM recommendations on socioeconomic projections. The methodology applied in the EIS, like the EGS, follows the classical model of structured expert judgment, including the calibration of experts for purposes of performance weighting. Participants in the EIS are leading experts based at universities, nonprofit research institutions, and multilateral international organizations with expertise in long-run energy-economic projections and modeling under a substantial range of climate change mitigation scenarios. Under the EIS, experts are asked in individual interviews to quantify their uncertainty for the range of global emissions intensity under two scenarios, one restricted to established policies to address climate change, and the other incorporating each expert's individual expectations for future climate policy. To account for potential correlations between future economic growth and emissions, experts quantify their uncertainties for emissions intensity for three ranges of future global economic growth, representing low, medium, and high economic growth futures as drawn from the economic growth and population distributions described earlier. The EIS will conclude in July 2021.

The approach taken across each of these three components of research, and in their combination into a consistent set of projections accounting for future policy and correlation among variables, is fully responsive to the set of NASEM near-term recommendations for socioeconomic projections. By providing country-level projections of both population and economic growth, the research takes significant additional steps toward meeting the longer-term recommendations for implementing a new socioeconomic model provided in Recommendation 3-3. Final results, including the detailed methodological approach and resulting socioeconomic projections, will be provided in a peer-reviewed publication in early fall 2021.

Climate Module

NASEM RECOMMENDATION 4-1. In the near term, the Interagency Working Group should adopt or develop a climate module that captures the relationships between CO_2 emissions, atmospheric CO_2 concentrations, and global mean surface temperature change, as well as their uncertainty, and projects their profiles over time. The module should apply the overall criteria for scientific basis, uncertainty characterization, and transparency (see Recommendation 2-2 in Chapter 2). In the context of the climate module, this means:

- **Scientific basis and uncertainty characterization: The module's behavior should be consistent with the current, peer reviewed scientific understanding of the relationships over time between CO_2 emissions, atmospheric CO_2 concentrations, and CO_2-induced global mean surface temperature change, including their uncertainty. The module should be assessed on the basis of its response to long-term forcing trajectories (specifically, trajectories designed to assess equilibrium climate sensitivity, transient climate response and transient climate response to emissions, as well as historical and high- and low-emissions scenarios) and its response to a pulse of CO_2 emissions. The assessment of the module should be formally documented.**
- **Transparency and simplicity: The module should strive for transparency and simplicity so that the central tendency and range of uncertainty in its behavior are readily understood, reproducible, and amenable to improvement over time through the incorporation of evolving scientific evidence.**
- **The climate module should also meet the following additional criterion:**
  Incorporation of non-CO_2 forcing: The module should be formulated such that effects of non-CO_2 forcing agents can be incorporated, which will allow both for more accurate reflection of baseline trajectories and for the same model to be used to assess the social cost of non-CO_2 forcing agents in a manner consistent with estimates of the SC-CO_2. (NASEM 2017, 13–14)

NASEM RECOMMENDATION 4-2. To the extent possible, the Interagency Working Group should use formal assessments that draw on multiple lines of evidence and a broad body of scientific work, such as the assessment reports of the Intergovernmental Panel on Climate Change, which provide the most reliable estimates of the ranges of key metrics of climate system behavior. If such assessments are not available, the IWG should derive estimates from a review of the peer-reviewed literature, with care taken so as to not introduce inconsistencies with the formally assessed parameters. The assessments should provide ranges with associated likelihood statements and specify complete probability distributions. If multiple interpretations are possible, the selected approach should be clearly described and justified. (NASEM 2017, 14)

NASEM RECOMMENDATION 4-3. In the near term, the Interagency Working Group should adopt or develop a sea level rise component in the climate module that (1) accounts for uncertainty in the translation of global mean temperature to global mean sea level rise and (2) is consistent with sea level rise projections available in the literature for similar forcing and temperature pathways.

Existing semi-empirical sea level models provide one basis for doing this. In the longer term, research will be necessary to incorporate recent scientific discoveries regarding ice sheet stability in such models. (NASEM 2017, 14–15)

NASEM RECOMMENDATION 4-4. The Interagency Working Group should adopt or develop a surface ocean pH component within the climate module that (1) is consistent with carbon uptake in the climate module, (2) accounts for uncertainty in the translation of global mean surface temperature and carbon uptake to surface ocean pH, and (3) is consistent with observations and projections of surface ocean pH available in the current peer-reviewed literature. For example, surface ocean pH can be derived from global mean surface temperature and global cumulative carbon uptake using relationships calibrated to the results of explicit models of carbonate chemistry of the surface ocean. (NASEM 2017, 15)

NASEM RECOMMENDATION 4-5. To the extent needed by the damages module, the Interagency Working Group should use disaggregation methods that reflect relationships between global mean quantities and disaggregated variables, such as regional mean temperature, mean precipitation, and frequency of extremes, that are inferred from up-to-date observational data and more comprehensive climate models. (NASEM 2017, 15–16)

Several climate components that are responsive to the NASEM recommendations have been implemented and are available for use in SC-GHG estimation on Mimi:

- **FAIR:** The Finite Amplitude and Impulse Response (FAIR) climate model (Smith et al. 2018) was presented in the NASEM report and documented as meeting the necessary diagnostic criteria for an improved climate model.
- **SNEASY:** In our evaluation, the SNEASY climate model (Urban and Keller 2010) also passes the diagnostic tests put forward by the NASEM panel for evaluating the response of the model to increases in carbon dioxide, though the model does not represent non-CO_2 gases. SNEASY's implementation on Mimi was the basis for analysis by Errickson and colleagues (2021a).
- **BRICK:** The Building Blocks for Relevant Ice and Climate Knowledge (BRICK) model of sea level rise (Wong et al. 2017) is responsive to NASEM Recommendation 4-3.

Damages Module

NASEM RECOMMENDATION 5-1. In the near term, the Interagency Working Group should develop a damages module using elements from the current SC-IAM damage components and scientific literature. The damages module should meet the committee's overall criteria for scientific basis, transparency, and uncertainty characterization and include the following four additional improvements:

1. **Individual sectoral damage functions should be updated as feasible.**
2. **Damage function calibrations should be transparently and quantitatively characterized.**
3. **If multiple damage formulations are used, they should recognize any correlations between formulations.**
4. **A summary should be provided of disaggregated (incremental and total) damage projections underlying SC-CO_2 calculations, including how they scale with temperature, income, and population. (NASEM 2017, 16–17)**

NASEM RECOMMENDATION 5-2. In the longer term, the IWG should develop a damages module that meets the overall criteria for scientific basis, transparency, and uncertainty characterization (see Recommendation 2-2, in Chapter 2) and has the following five features:

1. **It should disaggregate market and nonmarket climate damages by region and sector, with results that are presented in both monetary and natural units and that are consistent with empirical and structural economic studies of sectoral impacts and damages.**
2. **It should include representation of important interactions and spillovers among regions and sectors, as well as feedbacks to other modules.**
3. **It should explicitly recognize and consider damages that affect welfare either directly or through changes to consumption, capital stocks (physical, human, natural), or through other channels.**
4. **It should include representation of adaptation to climate change and the costs of adaptation.**
5. **It should include representation of nongradual damages, such as those associated with critical climatic or socioeconomic thresholds. (NASEM 2017, 17)**

To identify candidate research for an updated damages module, we conducted a comprehensive evaluation of the state of the damages literature regarding criteria of relevance for mortality, agriculture, energy, sea level rise, and ecosystem damage sectors. The results of this evaluation for the mortality damage sector are available as a working paper and have been submitted for publication (Raimi 2021). Results for other damage sectors will be included as part of publications documenting the implementation of corresponding damage functions as components for SC-GHG estimation. The publications reviewed as part of this landscape analysis have been used to populate an extensive database of damages literature that will be made public. On the basis of this evaluation, RFF has identified a number of candidates to serve as the basis for improved sectoral climate damage estimates. We are in the process of implementing several of the identified candidates as damage components on the Mimi platform.

Discounting Module

NASEM RECOMMENDATION 6-1. The Interagency Working Group should develop a discounting module that explicitly recognizes the uncertainty surrounding discount rates over long time horizons, its connection to uncertainty in economic growth, and, in turn, to climate damages. This uncertainty should be modeled using a Ramsey-like formula, $r = \rho + \eta g$, where the uncertain discount rate r is defined by parameters ρ and η and uncertain per capita economic growth g. When applied to a set of projected damage estimates that vary in their assumptions about per capita economic growth, each projection should use a path of discount rates based on its particular path of per capita economic growth. These discounted damage estimates can then be used to calculate an average SC-CO_2 and an uncertainty distribution for the SC-CO_2, conditional on the assumed parameters. (NASEM 2017, 18–19)

NASEM RECOMMENDATION 6-2. The Interagency Working Group should choose 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. The IWG should use three sets of Ramsey parameters, generating a low, central, and high certainty-equivalent near-term discount rate, and three means and ranges of SC-CO_2 estimates. (NASEM 2017, 19)

NASEM RECOMMENDATION 6-3. The Interagency Working Group should be explicit about how the SC-CO_2 estimates should be combined in regulatory impact analyses with other cost and benefit estimates that may use different discount rates. (NASEM 2017, 19)

Recommendations 6-1 and 6-2 are readily implementable by the IWG based on research by RFF researchers Richard Newell, Billy Pizer, and Brian Prest (Newell, Pizer, and Prest 2021; hereafter NPP). That paper implements these recommendations by calibrating the key discounting parameters in a Ramsey-like framework (ρ and η), combining projected distributions of future economic growth rates (per Recommendation 3-2, based on MSW) with evidence on the long-run term structure of interest rates (Bauer and Rudebusch 2020). This calibration results in a pair of ρ and η parameters for use in the Ramsey equation. The calibration process ensures that the discount rates resulting from the Ramsey equation when applied to growth rates from the MSW distribution (per Recommendations 6-1 and 3-2) simultaneously match a target near-term discount rate (based on observational data on the consumption rate of interest, Recommendation 6-2) and also reflect declining term structure evidence from the empirical literature (e.g., Bauer and Rudebusch 2020). NPP have performed this calibration for a variety of near-term discount rates, including 1.5%, 2%, 3%, and 5%, as well as a series of alternative rates in 0.5% increments within this range for completeness.

As described by NPP, they considered a range of near-term discount rates, in line with the approach to sensitivity analysis historically taken by the IWG and recommended by the NASEM report. US federal rulemaking has historically employed two discount rates: 3% and 7%, as directed by the Office of Management and Budget in Circular A-4 (OMB 2003). Those rates were chosen to represent the consumption rate of interest (as estimated as the real return on government debt) and the opportunity cost of capital (estimated as the before-tax return to private capital). However, both the NASEM report and the IWG have correctly emphasized that the before-tax, opportunity cost of capital is not an appropriate discount rate in this context. They argue that the costs and benefits to be discounted are generally expressed in terms of consumption, and the IWG used a set of rates centered on OMB's 3% consumption rate: specifically, 2.5%, 3%, and 5%.[1] Moreover, others have pointed out that consumption discounting is always appropriate over long horizons, whether costs and benefits fall on investment or consumption (Li and Pizer 2021).

Since those specific values were last updated and the IWG approach was developed, the economy has changed (interest rates have fallen), and the theory behind the appropriate discount rate relevant for climate change has advanced. Reflecting this, the OMB is undertaking an effort to modernize the regulatory review process, including revisions to Circular A-4 (White House 2021). The IWG's past central rate of 3% was based on OMB guidance under Circular A-4. However, that 3% rate may no longer be deemed a reasonable central value because of observed declines in market interest rates, among other reasons. Nonetheless, 3% remains current guidance under Circular A-4 and is the rate used historically by the IWG, so NPP include this as one of the near-term rates considered in implementing the NASEM recommendations. NPP account for discount rate uncertainty directly, so the past rationale for using the IWG's low and high rates of 2.5% and 5% is no longer conceptually justified once NASEM Recommendations 3-2 (probabilistic economic growth) and 6-1 (Ramsey-like discounting) are implemented, as those recommendations model uncertainty in the discount rate explicitly.

The recent literature has begun to converge toward considering a consumption discount rate of about 2% (rather than 3%), as has been adopted by New York State, if not lower. As explained in a Council of Economic Advisers (CEA) report, risk-free interest rates have recently remained well below 2%, reflecting a lower rate at

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[1] In addition, Circular A-4 explains that is it appropriate to use lower rates when discounting across generations and that "estimates of the appropriate discount rate appropriate in this case, from the 1990s, ranged from 1 to 3 percent per annum." Therefore, Circular A-4 states, it is appropriate to consider rates below 3% as a further sensitivity analysis.

which households are willing to trade off consumption between the present and the future. In the very recent past, real 10-year Treasury yields during 2010–20 were generally close to 0%, even reaching negative territory for lengthy periods of time.[2] While such near-zero rates are unlikely to continue in the long term, most macroeconomic forecasts project real yields below 2% for the foreseeable future (CEA 2017). For this reason, CEA suggests that 2% reasonably reflects the risk-free return to savings. As Drupp et al. (2018) show, there is general convergence among experts that a rate of 2% is appropriate to consider. Indeed, New York State has formally adopted 2% as its central rate, resulting in a social cost of carbon of $125 per ton (RFF and NYSERDA), holding other aspects of the IWG (2016) estimation process constant.

In another recent study, Giglio and colleagues (2015) also suggest using a rate below 3% for long-run impacts. That study estimates discount rates used by real estate investors in the very long run by comparing the prices of 100-year leases with the prices of owning an equivalent property in perpetuity. The difference in those prices reflects the discounted value of flows beyond 100 years, from which the authors can derive the long-run discount rate used by investors. They find discount rates “below 2.6% for 100-year claims” (Giglio et al. 2015, 2). Because real estate assets are not risk free, this may overstate the appropriate risk-free rate, providing additional support for the use of a rate lower than 2.6%, closer to the conclusion of 2% from CEA (2017) and Drupp et al. (2018). Based on these multiple lines of evidence, NPP also consider a 2% rate for this analysis, alongside Circular A-4’s current rate of 3%. Following NPP, we do not take a stand on the correct central rate and present results for 2%and 3%.

In addition, NPP consider low and high rates as sensitivity cases, analogous to past considerations by the IWG and consistent with the NASEM recommendations. Historically, low and high rates are meant to bound reasonable ranges based on various relevant considerations, such as observed market rates of different kinds of assets. NPP identify a low rate of 1.5% and a high rate of 5%. While exploration of this range was not meant as an endorsement of 1.5% and 5% as the low and high discount rates to be adopted by the IWG, a low and high range should be within these bounds. NPP also present results for a series of alternative rates ranging between 1.5% and 5% in increments of 0.5%, which we reproduce here.

How did NPP arrive at these values? Because the rationale for the IWG’s previous low rate of 2.5% is no longer valid, and also because market interest rates have fallen since the relevant research and policy guidance was established, NPP looked to the recent economics literature for evidence for a new low rate. Not only has the economics profession exhibited gradually growing support for the use of a rate below 2%, as supported by the CEA and Drupp et al. (2018), but the macrofinance literature has also found evidence for such a low rate. In particular, Bauer and Rudebusch (2020) find evidence for equilibrium rates of around 1.5% using long-term data. For these reasons, NPP considers 1.5% as a low case. As NPP indicate, a near-term rate of 1.5% also happens to be the point at which a non-negativity constraint on ρ becomes binding, resulting in a corresponding ρ of zero.

The IWG’s rationale for its high rate of 5% is similarly no longer valid, since that rate was also meant to approximate the uncertainty about future discount rates and their correlation with climate impacts, which we are modeling explicitly. An alternative motivation for a rate of about 5%, however, is that it corresponds approximately to the after-tax return to the stock market and other equity investment. The adjustment for taxes is necessary to calculate the consumption rate of interest, since the after-tax rate is the rate consumers actually receive. While interest rates have fallen in recent years, there has not been a marked decline in the pre-tax return to capital, which remains about 7% (CEA 2017). Simply adjusting the historical pre-tax return to a post-tax return implies that the 7% pre-tax return corresponds to approximately 5% after-tax (see IWG 2010, note 19). Based on this rationale, NPP consider 5% as a high case, while recognizing that this does not account

[2] See https://fred.stlouisfed.org/series/DFII10.

for risk, which would entail a further downward adjustment. The NPP-calibrated parameters for each near-term rate are in Table 1. Both ρ and η decline with the near-term discount rate. The calibrated (ρ, η) pairs for the 2% and 3% rates are (0.1%, 1.25) and (0.8%, 1.53). By comparison, typical values for η used in the literature are in the range of 1 to 2. Recently, Drupp et al. (2018) conducted a survey of professional economists to gauge consensus on appropriate values of these parameters. For η, they found median and mean values of 1.00 and 1.35, respectively. For ρ, they found median and mean values of 0.5% and 1.1% and a modal value of 0%. NPP's calibrated values are squarely within those ranges.

Table 1. Calibrated ρ and η Parameters for Alternative Near-Term Discount Rates

Near-term discount rate	ρ	η
1.5%	0.0%	0.99
2.0%	**0.1%**	**1.25**
2.5%	0.4%	1.40
3.0%	**0.8%**	**1.53**
3.5%	1.1%	1.63
4.0%	1.5%	1.72
4.5%	1.9%	1.80
5.0%	2.4%	1.86

Source: Newell et al. (2021). Bolded cells are the focal central rates.

When the near-term rate gets down to 1.5%, a naive calibration would yield a negative value for ρ, which would be inappropriate if interpreted as a rate of pure time preference in the Ramsey framework. NPP address this by constraining ρ to be non-negative and finding the resulting η value that when multiplied by the near-term central growth rate (slightly above 1.5% in MSW) delivers the desired 1.5% discount rate: $r_{near-term} = 0 + \eta \cdot g_{near-term}$. The resulting η value is $\eta = 0.99$. This result of $\rho = 0\%$ and $\eta = 0.99$ happens to correspond closely to Stern (2007), who used values of $\rho = 0.1\%$ and $\eta = 1$.

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A Shadow-Price-of-Capital Approach to Harmonize Discounting for Greenhouse Gases in Broader Benefit-Cost Analyses

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On February 26, 2021, the US government's Interagency Working Group on the Social Cost of Greenhouse Gases (IWG) issued the *Technical Support Document (TSD): Social Cost of Carbon, Methane, and Nitrous Oxide Interim Estimates under Executive Order 13990* (EO 13990). This support document provides interim estimates of the social cost of carbon (SC-CO_2), social cost of methane (SC-CH_4), and social cost of nitrous oxide (SC-N_2O), collectively called the social cost of greenhouse gases (SC-GHG). The provision of the interim estimates is one step in the federal government's process that will culminate in the issuance of final SC-GHG estimates in early 2022 as required by EO 13990.

EO 13990 directs that the federal government's update of the SC-GHG reflect the recommendations laid out in a landmark report issued in 2017 by the National Academies of Sciences, Engineering, and Medicine (hereafter NASEM). The NASEM report, *Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide*, was conducted in response to a study request in 2015 from the IWG. The NASEM panel conducted a comprehensive evaluation of potential updates to the SC-CO_2 estimation methodology and put forward a number of conclusions and recommendations on how to improve the conceptual underpinnings, empirical methods, and data used to calculate the SC-CO_2, as well as the transparency and flexibility of the process by which future estimates are generated (NASEM 2017). The conclusions and recommendations of the NASEM report focused primarily on the calculation of the social costs resulting from the emissions of carbon dioxide, but they are broadly applicable as well to the social costs of other greenhouse gases such as methane, nitrous oxide, and hydrofluorocarbons. The NASEM report provided near-term recommendations that were designed to be implementable within two to three years as well as recommendations for longer-term improvements to the methodology.

The purpose of this comment is to propose that the IWG consider a shadow price of capital sensitivity analysis to supplement the discounting approach for the SC-GHG. We would, in turn, propose the US Government more broadly adopt this approach to benefit-cost analysis (BCA) through a revision to the current Office of Management and Budget Circular A-4 (OMB 2003). A process to consider such a revision is now underway (White House, 2021).

By changing both the SC-GHG and A-4 approaches, the IWG could address the last NASEM recommendation,

NASEM RECOMMENDATION 6-3. The Interagency Working Group should be explicit about how the SC-CO_2 estimates should be combined in regulatory impact analyses with other cost and benefit estimates that may use different discount rates. (NASEM p. 19)

More specifically, harmonizing A-4 guidance and the IWG approach regarding discounting would eliminate any inconsistency.

This would imply an additional step in the current IWG approach; namely, consideration of potential impacts on both capital and consumption. Meanwhile, it would imply eliminating the use of an investment discount rate in A-4 guidance; instead, only a consumption rate (or rates) would be used, with concerns about capital impacts addressed through sensitivity analysis based on the shadow price.

Framing

A key question in BCA, highlighted in both circular A-4 and the IWG report on the SC-GHG, is the correct discount rate. Circular A-4 recommends using alternative rates representing the return to capital (an "investment rate") and the return faced by consumers (a "consumption rate"). This is meant to reflect an underlying uncertainty about whether near-term costs displace investment, and have an opportunity cost related to the return on investments, or displace consumption, and have an opportunity cost related to the return that consumers experience after taxes. The IWG TSD on the SC-GHG (as well as earlier versions) argues against using the investment rate (as does the NASEM report) and instead presents three alternative consumption rates.

In the attached paper, Li and Pizer (2021, hereafter LP) show that the IWG is correct in arguing against the investment rate. Possible effects on investment versus consumption do matter, but using an investment rate is generally the wrong approach, and only correct under very restrictive conditions. The discount rate can be adjusted to address this concern, but the adjustments depend on the pattern of cash flows and are small over long time horizons. Meanwhile, the IWG adjustments to the consumption rate focus on uncertainty and risk, and do not directly address the issue of how to account for investment impacts or the shadow price of capital. This is an important issue for consideration, as the possible effects on investment do change the BCA and any approach that fails to tackle that possibility could be criticized.

LP show that the conceptually correct approach, using the shadow price of capital (SPC) coupled with a consumption discount rate, does not need to be more challenging than the identification of consumption and investment rates. In particular, a shadow price can be bounded using those rates alone (though, preferably, it is calculated based on the gross savings rate as explained below). That shadow price can then be applied, alternatively, to costs (for a lower bound on net benefits) and benefits (for an upper bound). Importantly, applying the shadow price to costs is conceptually what the higher investment rate seeks to do under current A-4 guidance—making net benefits smaller (when benefits are in the future). There is no comparable case in A-4 where benefits might accrue to investment—raising net benefits.[3]

LP focus on translating the shadow price approach into a range of discount rates for the SC-CO2 that effectively achieve the same result. However, we believe a better approach—and a practical and better alternative to A-4 guidance generally—is to simply apply the shadow price approach for BCA, full stop, based on a central value for the consumption discount rate. Sensitivity to the choice of consumption rate can be separately considered as suggested by the NASEM report.

In the remainder of these comments, we outline how the shadow price approach could be applied and present our preferred shadow price estimate based on LP. We note that the main purpose of LP was to demonstrate that computing an upper bound on the shadow price was no more difficult than ascertaining the investment and consumption rates. LP then provide a better SPC estimate (smaller than the bounding case) based on a

[3] It is useful to recognize that even if a benefit effect *seems* to accrue to consumption—say improved health or mortality reductions, such effects could *in fact* induce added savings / investment as we consider behavioral responses. Moreover, climate change impacts on infrastructure, buildings, equipment, and real estate are direct effects on capital that should be valued at the SPC.

simple savings rate model. Their preferred estimate assumes investment and consumption rates based on current A-4 guidance. Here, however, we present our preferred SPC estimates using their savings rate model but based on revised consumption and investment rate choices.

How the shadow price of capital approach could be applied

One criticism of the shadow price approach is that in order to obtain a specific net benefit estimate, it requires one to examine and to then assign each benefit and cost to affect either consumption, investment, or some combination of the two. Frequently it may be hard to know that information.

Instead, we propose conducting BCA based on a central estimate with two side cases. Specifically, we propose a central case where all costs and benefits are assumed to directly impact household consumption. This is also consistent with arbitrary effects on investment and consumption if the SPC is 1, an argument often made when capital is assumed to be highly mobile (Lind, 1990). Future costs and benefits are discounted at the consumption rate.

We then propose two sensitivity cases to bound the consequences of possible effects on investment. For each case, all impacts should be separated into costs (negative values) and benefits (positive values). A low net benefit case is constructed by multiplying all costs by the SPC, and then summing benefits minus costs discounted at the consumption rate. And a high net benefit case is constructed by multiplying all benefits by the SPC and similarly discounting and summing. By taking a sensitivity approach, we avoid the need to ascertain which costs and benefits accrue to capital and which to consumption.

How the shadow price could be calculated

LP walk through a simple closed economy model to derive a shadow price of capital, following Lind (1990). That model traces the effects of an exogenous change in capital on changes in future capital, as well as both direct consumption and government tax revenue that ultimately accrues to consumers (through spending or transfers; see Figure 3 in LP). Using the consumption discount rate, the direct and indirect consumer impacts can be discounted back to the period of the exogenous change in capital. This yields a consumption value associated with that capital change; the ratio of the discounted consumption impacts to capital change is the SPC.

The 4 key parameters in this model are

- the investment rate of return (r_i),
- the depreciation rate (μ), noting $r_i + \mu$ equals a gross return to capital,
- the gross savings rate (s) determining how much of the gross capital return is re-invested, and
- the consumption rate (r_c) determining both (a) how much of the investment return accrues to consumers (versus taxes and government) and (b) how to value future cash flows.

The SPC is then given by[4]

$$SPC = \frac{(1-s)(r_i+\mu)}{r_c+\mu-s(r_i+\mu)}$$

[4] LP Equation (19). This is the same as Moore (2004) Equation (2).

LP take the consumption and investment rates from Circular A-4. They then consider two approaches to identifying a depreciation and savings rate.

The simple, bounding approach considers how the exogenous change to capital affects future capital. It seems reasonable to assume that if a government policy affects the private sector capital stock by a discrete amount in one period, the private sector should eventually compensate, absorbing the shock, and the future capital stock will return to its original path. At most, the discrete capital stock will persist but not grow. That boundary condition, that a discrete deviation persists forever but does not grow, implies that the gross savings rate exactly equals the share of depreciation rate in the gross capital return, $s = \mu/(r_i + \mu)$. That is, savings exactly offsets depreciation. This is sufficient to exactly identify the SPC, namely $SPC = r_i/r_c$, and provides LP's estimate of the shadow price's upper bound.[5]

In this sense, the shadow price approach can be implemented with the same information as Circular A-4's current approach—an assumed consumption and investment rate—coupled with the assumption that a discrete shock to the capital stock in one period does not lead to an explosive deviation in the future capital stock path.

However, this boundary condition is an extreme case in that it assumes a shock to capital never dissipates. Moreover, the assumed savings rate is high: $\mu/(r_i + \mu)$ > 50% assuming $r_i \leq 10\%$ and $\mu \approx 10\%$.[6]

A better approach requires more detailed assumptions about depreciation and the gross savings rate. LP consider a Ramsey (1928) model with income taxes to show how the gross savings rate at a steady-state equilibrium depends on the population growth rate ($n =$ 1%), the productivity growth rate ($g =$ 2.2%), and the capital-output elasticity ($a =$ 0.3), along with the depreciation rate ($\mu =$ 10%) and investment rate (r_i) as above. Parenthetical values are those in LP, in turn taken from NASEM (2017) and Nordhaus (2017). This equilibrium savings rate is given by:

$$s = \frac{(\mu + g + n)a}{\mu + r_i}$$

LP then take the investment rate from Circular A-4 to yield $s = 0.23$. Moore et al (2004) take a different approach to identifying the savings rate. They examine the ratio of private investment to income in the national income and product accounts, finding $s = 0.17$. Updating their data, that ratio has been close to 0.18 for the past two decades outside of recessions. Note that all of these savings estimates are much lower than the $s = 50\%$ value associated with the boundary case for shocks to the capital stock to persist.

Turning these savings rates into SPC estimates, LP take r_i and r_c values from Circular A-4 (7 and 3 percent, respectively) to yield $SPC \approx 1.5$. Moore et al (2004) make their own estimates of r_c and r_i (1.5 and 4.5 percent, respectively) to yield $SPC \approx\ 1.3$; they also consider a prescriptive value of $r_c = 3.5$ yielding $SPC \approx 1.1$. However, both of these SPC estimates are problematic if the distinction between investment and consumption rates is taxes. LP's approach using Circular A-4 rates implies a tax rate of 57%; Moore et al's approach implies a tax rate of 66%. It suggests, for example, that the investment rate might reflect a higher return because of risk.

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[5] Moore et al (2013) derive a different expression for the SPC ignoring depreciation and based implicitly on a savings rate net of depreciation. By construction, this implies deviations to the capital stock persist or *explode* and r_i/r_c is a *lower bound*. As indicated in the text, we disagree with this assumption.

[6] LP and Moore (2004) both find $\mu = 0.1$.

In separate comments, we and RFF colleagues suggest a central value for the consumption rate of about 2 percent to 3 percent. A corresponding investment rate, without changing any risk assumptions, should be higher based on a factor $1/(1 - tax\ rate)$. We present below the SPC using the same SPC formula and other parameters as in LP but alternative consumption rates (2 and 3 percent), alternative tax rate assumptions (30 and 40 percent), and alternate savings rate assumptions (fixed and based on Ramsey). These yield SPCs generally in the range of 1.1 to 1.2.

Table 1. Shadow prices (SPC) for different investment and consumption discount rates (r_i and r_c)

Consumption rate (r_c)	Tax rate	Investment rate (r_i)	Savings rate (s) based on Ramsey formula	Shadow price of capital (SPC), s based on Ramsey	Shadow price of capital (SPC), $s = 0.18$
2%	30%	2.8%	0.31	1.11	1.09
2%	40%	3.3%	0.30	1.17	1.14
3%	30%	4.3%	0.27	1.14	1.12
3%	40%	5%	0.26	1.22	1.19

Source: LP Equation (2) and (D.18), and LP parameters except r_i, r_c, and s, as indicated

Table 2. Discount factors by current rates (in Circular A-4) and ratio of effect over 12 years

Discount rate	1	2	3	4	5	6	7	8	9	10	11	12	Avg.
3%	0.97	0.94	0.92	0.89	0.86	0.84	0.81	0.79	0.77	0.74	0.72	0.70	0.83
7%	0.93	0.87	0.82	0.76	0.71	0.67	0.62	0.58	0.54	0.51	0.48	0.44	0.66
Ratio	0.96	0.93	0.89	0.86	0.83	0.80	0.77	0.74	0.71	0.68	0.66	0.63	0.80

A conservative approach (in terms of being a rough upper bound on the observed values) would be to choose a shadow price of 1.2. In addition, setting SPC = 1.2 would provide some continuity with current A-4 guidelines. That is, over a twelve-year period the effect of discounting a constant value at 7 versus 3 percent is a 20 percent reduction. Switching to a shadow price of capital approach with SPC = 1.2 would yield similar effects on net benefits over a twelve-year period when the shadow price is applied to costs, as occurs with the current Circular A-4 approach.

Summary

The current IWG approach of focusing on consumption discount rates for the SC-GHG is well-justified by research showing that the investment rate is an inappropriate way to account for investment impacts, particular over long horizons.

However, the IWG approach could be improved by considering the consequences of costs and benefits accruing to capital, rather than consumption, through a shadow price approach. Costs and benefits would be discounted at the consumption discount rate. Sensitivity cases would alternately consider costs, and also benefits, valued using the SPC. A similar revision to Circular A-4 guidance would harmonize benefit-cost analysis across both short and long horizons.

In general, this approach is no more difficult than identifying investment and consumption discount rates to construct an upper bound on the SPC equal to the ratio of these two rates. A better approach, based on estimates of the gross savings rate, taxes and depreciation, as well as updated central values of the consumption discount rate, yields an SPC estimate of 1.2.

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