To: Fawcett, Allen[Fawcett.Allen@epa.gov]; Shouse, Kate[Shouse.Kate@epa.gov]; Kopits, Elizabeth[Kopits.Elizabeth@epa.gov]; Wolverton, Ann[Wolverton.Ann@epa.gov]
Cc: Griffiths, Charles[Griffiths.Charles@epa.gov]; Newbold, Steve[Newbold.Steve@epa.gov]; McGartland, Al[McGartland.Al@epa.gov]; Sarofim, Marcus[Sarofim.Marcus@epa.gov]
From: Marten, Alex
Sent: Thur 6/25/2015 1:36:10 PM
Subject: RE: Start on list of potential candidates for NAS SCC committee

Ex 5

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Alex L. Marten
phone: (202) 566-2301
email: marten.alex@epa.gov

From: Fawcett, Allen
Sent: Thursday, June 25, 2015 9:35 AM
To: Marten, Alex; Shouse, Kate; Kopits, Elizabeth; Wolverton, Ann
Cc: Griffiths, Charles; Newbold, Steve; McGartland, Al; Sarofim, Marcus
Subject: RE: Start on list of potential candidates for NAS SCC committee

A few more edits, mainly cleaning things up a bit in the formatting that went awry with all the track changes. Ex 5

Ex 5

John Weyant (2014). Integrated assessment of climate change: state of the literature. Journal of Benefit-Cost Analysis, 5, pp 377-409. doi:10.1515/jbca-2014-9002.

From: Marten, Alex
Sent: Wednesday, June 24, 2015 5:52 PM
To: Shouse, Kate; Kopits, Elizabeth; Wolverton, Ann
Cc: Griffiths, Charles; Newbold, Steve; McGartland, Al; Fawcett, Allen; Sarofim, Marcus

Subject: RE: Start on list of potential candidates for NAS SCC committee

Ex 5

--

Alex L. Marten
phone: (202) 566-2301
email: marten.alex@epa.gov

From: Shouse, Kate
Sent: Wednesday, June 24, 2015 4:12 PM
To: Kopits, Elizabeth; Wolverton, Ann
Cc: Marten, Alex; Griffiths, Charles; Newbold, Steve; McGartland, Al; Fawcett, Allen; Sarofim, Marcus
Subject: RE: Start on list of potential candidates for NAS SCC committee

Ex 5

Ex 5

From: Kopits, Elizabeth
Sent: Wednesday, June 24, 2015 2:38 PM
To: Wolverton, Ann
Cc: Marten, Alex; Griffiths, Charles; Newbold, Steve; Shouse, Kate; McGartland, Al; Fawcett, Allen
Subject: RE: Start on list of potential candidates for NAS SCC committee

Thanks, Ann. This is really helpful.

From: Wolverton, Ann
Sent: Wednesday, June 24, 2015 1:46 PM
To: Kopits, Elizabeth
Cc: Marten, Alex; Griffiths, Charles; Newbold, Steve; Shouse, Kate; McGartland, Al; Fawcett, Allen
Subject: Re: Start on list of potential candidates for NAS SCC committee

Ex 5

Ex 5

Ann

Sent from my iPhone

On Jun 23, 2015, at 12:47 PM, Kopits, Elizabeth <Kopits.Elizabeth@epa.gov> wrote:

Hi all,

I have started to pull together some names we could potentially forward to the NAS for consideration. See attached list and notes. Please let me know what you think, including views on whether any should be deleted or added. Also, please let me know if you have a preference for how we organize/transmit our suggestions, e.g.:

Ex 5

While there is no firm deadline, it would be great to have your thoughts soon (Thursday?) so we can send some suggestions along to Josh by the end of the week/early next week. If it would be helpful to have a short meeting to discuss let me know and I will send an invite.

Thanks,

Elizabeth

<potential committee suggestions.docx>

EPA-HQ-2015-011157 Interim 1
J. Benefit Cost Anal. 2014; 5(3): 377–409

John Weyant*

Integrated assessment of climate change: state of the literature

Abstract: This paper reviews applications of benefit-cost analysis (BCA) in climate policy assessment at the US national and global scales. Two different but related major application types are addressed. First there are global-scale analyses that focus on calculating optimal global carbon emissions trajectories and carbon prices that maximize global welfare. The second application is the use of the same tools to compute the social cost of carbon (SCC) for use in US regulatory processes. The SCC is defined as the climate damages attributable to an increase of one metric ton of carbon dioxide emissions above a baseline emissions trajectory that assumes no new climate policies. The paper describes the three main quantitative models that have been used in the optimal carbon policy and SCC calculations and then summarizes the range of results that have been produced using them. The results span an extremely broad range (up to an order of magnitude) across modeling platforms as well as across the plausible ranges of input assumptions to a single model. This broad range of results sets the stage for a discussion of the five key challenges that face BCA practitioners participating in the national and global climate change policy analysis arenas: (1) including the possibility of catastrophic outcomes; (2) factoring in equity and income distribution considerations; (3) addressing intertemporal discounting and intergenerational equity; (4) projecting baseline demographics, technological change, and policies inside and outside the energy sector; and (5) characterizing the full set of uncertainties to be dealt with and designing a decision-making process that updates and adapts new scientific and economic information into that process in a timely and productive manner. The paper closes by describing how the BCA models have been useful in climate policy discussions to date despite the uncertainties that pervade the results that have been produced.

Keywords: benefit-cost analysis; climate change; integrated assessment; optimal carbon emissions; social cost of carbon.

DOI 10.1515/jbca-2014-9002

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1 Introduction

This paper examines the use of benefit-cost analysis (BCA) in the assessment of climate policy. The paper initially discusses how these models are being used to answer questions such as "what is the optimal rate of carbon emissions?" or "what is the optimal (implicit or explicit) price to put on carbon?" This focus on optimality is a somewhat different application of BCA concepts than is often used in regulatory analysis, where the benefit-cost ratio of a particular policy intervention is the objective (that is, whether the total benefits resulting from the intervention exceed the total costs) and less direct emphasis is usually placed on assessing the appropriate scale of the intervention. From that perspective, the "optimal" carbon policies defined here are simply those *for which* marginal costs equal marginal benefits.

The paper then goes on to discuss the unique challenges that arise when BCA is used for decision making in formulating climate policy, and briefly describe some of the key debates on the topic, including the difficult issues of discount rates, equity (whose preferences matter), fat tails, climate sensitivity, tipping points, and uncertainty. The paper discusses how some of these assumptions are critical – or not – in determining the magnitude (and sometimes the direction) of the results obtained, and the various approaches that have been used or are being developed to address these conceptual and practical challenges. In addition to the numerical results produced by them, and despite the large uncertainties that accompany those numbers, these models have provided many valuable insights into climate policy development. They have been especially useful in identifying the key drivers of climate policy outcomes, and ascertaining better and more robust policies over wide ranges of input assumptions. The paper will also discuss the development and use of the concept of the social cost of carbon (SCC), as another policy context in which these BCA tools have been applied. The computation of the SCC is closer to the normal regulatory usage of BCA, where the benefits of a one-ton reduction in carbon emissions are computed and compared with the cost of that one-ton reduction in carbon emissions. The now extensive and rapidly growing literature on the use of BCA in supporting climate change adaptation decision making is covered in another paper in this issue (Li, Mullan, & Helgeson, 2014).

2 Background

As now is clear (IPCC, 2013), human-induced climate change is caused by: (1) oil, gas, coal, and bio-fuel combustion in utility and industrial boilers and land, sea, and air transportation systems that produce emissions of CO_2 and other radiatively active gases to the atmosphere; and (2) land use and land use change activities that

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release CO_2, methane, and/or nitrous oxide to the atmosphere. These emissions lead to net increases in the accumulations of these gases in the atmosphere above those that occur naturally. These chemical species have the property of allowing more of the heat from the sun's radiation through to the earth's surface than from the earth's surface back out to deep space. Although these gases are commonly referred to as greenhouse gases (GHGs) because of this property, their effect is much more similar to that of a blanket holding extra heat near a baby than to how a greenhouse actually works (Masters & Ela, 2007). In the aggregate, this increase in GHG concentrations in the atmosphere also leads to a concomitant increase in ocean acidity as some of this extra carbon dioxide is absorbed by the oceans. The basic physics, chemistry, and biology of these effects are not in question (IPCC, 2013), but there is uncertainty about the ultimate amount and rate of change in temperature to expect. This uncertainty stems from a lack of knowledge about the rate at which the deep ocean absorbs excess heat and the degree to which combustion products (most of which come from the same fossil fuel burning that causes the warming) impede solar radiation from reaching the surface of the earth. Lack of complete understanding about these phenomena results in uncertainty about the precise relationship between GHG concentrations in the atmosphere and observed temperature changes. These uncertainties hinder precise projections of how much temperature change to expect and the rate at which the new higher temperature equilibrium will be approached. Put differently, based on observations since the beginning of the industrial revolution, it is not yet possible to easily distinguish between a rapid adjustment to a small increase in equilibrium temperature and a very slow adjustment to a much larger ultimate equilibrium temperature level. Despite these uncertainties, however, changes in climate and impacts of those changes have already been observed over the last half century (IPCC, 2013, 2014a).

In addition to causing atmospheric changes, the extra heat in the atmosphere leads to an expansion of water in the oceans and melting of land-based ice sheets, both of which cause sea levels to rise. The warming of the earth system in the aggregate also leads to changes in the circulation of heat and air masses around the globe, which can lead to changes in regional and local temperature and precipitation patterns. These changes in local temperatures and rainfall can lead to impacts on agricultural, forest, and ecosystem productivity, as well as on human health through changes in the incidence of heat stress, infectious diseases, and illnesses caused by increased air pollution. Sea level rise coupled with more intense storms can also lead to coastal zone damage to infrastructure and property, which are often quite valuable due to their proximity to the water. Changes in other weather extremes, such as increases in droughts or floods, may also occur.

These effects on people and their property, wildlife, and ecosystems can be significant (IPCC, 2014a) and have thus led to consideration of three basic

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approaches for ameliorating the impacts of climate change: (1) mitigation of GHG emissions, (2) adaptation to any climate changes that might occur, and (3) geo-engineering to influence the amount of solar energy reaching the earth surface and/or the chemistry of the oceans. Since the relationships within and between the various bio-geo-chemical and socioeconomic components of the earth system can be quite complex, a number of quantitative models have been developed to study earth-system-wide climate changes and the effect of various types of public policies on projections of future climate change. These models have become known as "integrated assessment of climate change" or "integrated assessment" models (IAMs). The objective of these models is to project alternative future climates with and without various types of climate change policies in place, in order to give policy makers at all levels of government and industry an idea of the stakes involved in deciding whether or not to implement them.

Although as many as 20 or so integrated assessment models have been developed (see IAMC, 2014), they are of two basic types. Both include projections of GHG emissions and the costs of mitigating them in various ways (e.g., energy conservation, changes in production processes, fuel switching). Where they differ is in how climate change impacts are handled. The first type of IAM is more disaggregated and seeks to provide projections of climate change impacts at detailed regional and sectoral levels, some with economic valuation, but others terminating with projections of physical impacts such as reductions in crop growth, land inundated by sea level rise, and additional deaths from heat stress. The second type of IAM includes a more aggregated representation of climate change mitigation costs and an aggregation of impacts by sector and region into a single economic metric. It is this last type of integrated assessment model that is our focus here, as the main motivation for the construction of these models has been BCA for finding "optimal" climate policies. In discussing the challenges in building such models and interpreting their results, however, concepts and insights from the more complex IAMs are brought in both to critique the simple aggregate BCA models and point to where they might be improved. Obviously, there is only one earth system that both types of models seek to represent, so the two types of models should not be viewed as totally independent of each other.

Concepts and results from the integrated assessment models that are not fundamentally BCA models can be important to the BCA-oriented models for a number of important reasons. First, the cost of carbon emissions mitigation functions in the aggregate BCA-focused models are often calibrated to results from the non-BCA-focused integrated assessment models, which consider much more energy sector and land use detail (including things like agricultural and forestry activities, as well as changes in unmanaged ecosystems). In fact, these more detailed models have frequently been used to examine the "cost effectiveness" of

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alternative policies for meeting various climate targets, such as limits on carbon concentrations or a maximum permissible global mean temperature increase at the lowest possible societal cost.

In addition to more detailed information on the cost side of the climate BCA calculation, the non-BCA-oriented IAMs can also provide richer information on the physical and economic costs of climate change and benefits of carbon emission mitigation. This has two important implications for the BCA models in general, and this review of them in particular. First, similar to the aggregation and calibration required on the mitigation side of the BCA models, the more complex IAMs can also provide projections of the economic costs net of endogenous adaptation of climate change on key sectors by region. These estimates can be aggregated for use in the BCA models where appropriate. Since most climate impacts take place at the watershed, agricultural growing region, ecological zone, or similar level, this degree of additional geographical disaggregation is essential for improving the validity of the damage functions used in the aggregate BCA models. Second, the additional information on both the physical and economic impacts of climate change may be vitally important to decision makers in some regions and sectors, as discussed more fully elsewhere in this issue. Consideration of this additional information amounts to putting the BCA model results into a broader decision-making framework than conventional BCA, while leaving open the possibility of using the information the BCA model provides directly as a critical part of what is considered in an assessment.

The simple aggregate climate-change-focused BCA models have been used in two ways. BCA has been used for several decades to compute the optimal trajectory of global GHG emissions, and the corresponding prices to charge for those emissions. The optimal policies that are computed equate the marginal benefits (in terms of climate damages avoided) with the marginal costs (in term of mitigation effort required) of climate change policy. This is shown conceptually for the simple static one period case in Figure 1. In the single period, the marginal benefit (MB) curve for emissions reductions is flat. The figure represents alternative MB estimates in that period, with the values on the horizontal axis each representing the corresponding path of future emissions.[1] The costs of reducing carbon

1 There are many emissions trajectories that lead to the same amount of cumulative emissions over time, so these curves are not strictly speaking one-to-one functions. Since the models actually equate the marginal discounted present value of mitigation benefits (damages avoided) and costs over time, this is not a problem for them because they select a whole emissions trajectory as optimal. The purpose of this figure is simply to make the point that the optimal carbon tax is computed along the optimal benefits less costs of mitigation emissions trajectory discounted present value emissions trajectory over time, and the social cost of carbon is computed as the marginal discounted present value cost of the damages caused by an additional ton of carbon emissions at a particular point in time along a baseline scenario without assuming any future restrictions on carbon emissions.

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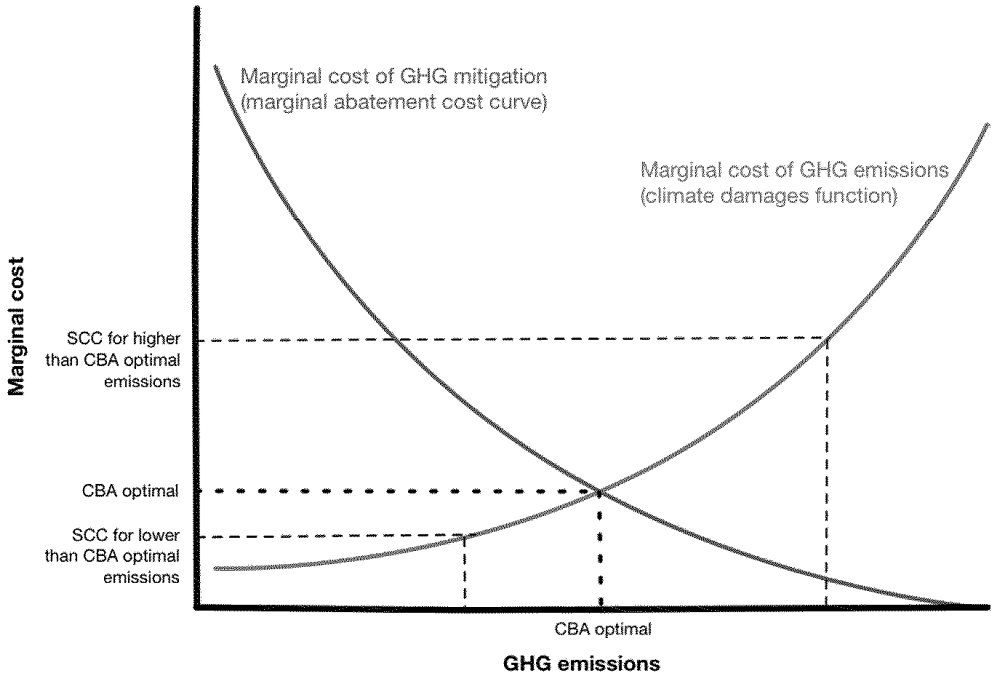

Figure 1 Conceptual overview of one period benefit-cost analysis (BCA) applied to the problem of optimal carbon emissions policy and relationship to the social cost of carbon (SCC).

emissions[2] in the single period can be similarly constructed, which allows for the optimal carbon tax and level of carbon emissions to be found at the intersection of these benefit values with the marginal abatement cost values. The point at which the marginal benefit and marginal cost curves intersect is the level of mitigation/residual climate change impacts that minimizes total societal costs.

Second, the BCA models have been used, especially in current US climate policy deliberations, to compute the SCC, which is roughly the incremental damage caused by one more ton of carbon emissions. As shown in Figure 1, the baseline emissions used in this calculation could be higher, lower, or the same as for the optimal carbon emissions case. US regulatory rules have generally required that the emissions trajectory used in computing the SCC be a "no climate policy" reference emissions path (e.g., higher than optimal emissions path).

2 From this point on this paper discusses only carbon dioxide emissions and not those of other GHGs, as the majority of the results available in the literature have focused on carbon dioxide. There are now a small number of newer analyses that add in the other GHGs on a "CO_2 equivalent" basis, and a few studies that have included these gases in a way that represents their projected impacts on radiative forcing and temperature change directly (cf., Marten & Newbold, 2012).

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Thus, the SCC estimates have generally only really required use of the climate damage elements of the aggregate BCA models and not their aggregate GHG mitigation modules. Thus, for "regulatory policy requirements," BCA models are not being used in full traditional benefit-cost mode. In this case, however, it is easy to compare marginal costs and benefits for whatever emissions trajectory is used in the SCC calculations with optimal BCA results. The desirability of doing this kind of comparison will be discussed more fully later in this paper, after the three most popular aggregate BCA models and some representative results from them are described.

3 The DICE, FUND, and PAGE models

Ranges of optimal carbon taxes have been produced by several authors. Their results depend on climate change damage projections, mitigation cost projections, how costs and benefits are "discounted" over time, and how uncertainty and risk are reflected.

Projections of carbon price and quantity trajectories that satisfy BCA optimality conditions come in different varieties. The primary sources are integrated assessment BCA models. An examination of the literature (Nordhaus, 2014) finds that three aggregate climate change BCA-oriented models mentioned are the basis of virtually all estimates. One is the DICE/RICE family of models developed over a number of years by William Nordhaus of Yale University and his colleagues. A second is the PAGE model, originating with the work of Chris Hope of Cambridge University, UK, which has several vintages. The third is the FUND model, developed by Richard Tol of Sussex University, UK, with David Anthoff of the University of California at Berkeley, a co-author of the current version.

Another set of estimates come from modifications of one of these three models. Some studies take one of the models and change parameters or do sensitivity analyses with them. For example, the *Stern Review* (Nordhaus, 2007; Stern, 2007,2008, 2013) based its quantitative modeling and estimates of optimal carbon emissions policies, including BCA results with enlightening sensitivities, on a version of the PAGE model that primarily varied the discount rate. Others are compilations or reviews of studies, which include primary models, variations of models, and reviews of models. There are a small number of independent analyses of the BCA applied to climate change and computations of the SCC. In 2013, Zhimin and Nordhaus (2013) published a systematic evaluation of estimates of SCC from 1980 to 2012. They found 27 studies that actually produced independent estimates. Of these, 19 were from different vintages of the three standard models

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listed above. Most of the eight other estimates were reduced-form models that took one of the three standard models and either simplified it or added specific features. The conclusion from this short summary is that most of the computations of the optimal carbon emissions policy and estimates of the SCC come from one of the three IAMs that have been developed and revised over a period of at least a decade.

In light of the central importance of the three most widely used climate change policy BCA models, they will be briefly described here to set the stage for a comparison of BCA and SCC estimates produced by the architects and critics of these models later in this paper. At the highest level, these three models are dynamic implementations of the conceptual diagram shown in Figure 1. Instead of working to equalize static costs and benefits of climate change, or equivalently minimizing the sum of climate damages and carbon mitigation costs at a single point in time, they work to equilibrate the discounted present values of carbon emissions mitigation and climate damage costs. Since the carbon emissions caused by an incremental ton emitted in any year persist in the atmosphere for many years (CO_2 molecules have a mean residence time in the atmosphere of about a hundred years, with a wide temporal distribution depending on where and how they are dispersed), the damages caused by that ton of emissions must be cumulated over a long period of time. This is generally done by discounting future climate damages (and mitigation costs), making the discount rate used for this purpose an extremely important parameter in these calculations as will be evident in the discussion that follows.

The DICE (Dynamic Intertemporal Carbon Emissions) model views climate change within the framework of economic growth theory. In a standard neoclassical optimal growth model known as the Ramsey model, society invests in capital goods, thereby reducing consumption today in order to increase consumption in the future (Koopmans, 1965; Ramsey, 1928). The DICE model modifies the Ramsey model to include climate investments, which are analogous to capital investments in the standard Ramsey growth model. The model contains simplified representations of all elements of the causal sequence from GHG emissions to GHG concentrations, through climate change to climate change damages. The geophysical equations are simplified versions derived from large models or model experiments. The first version of the global model was presented in Nordhaus (1992, 1994a; Nordhaus & Boyer, 2000). The first regional model was introduced in Nordhaus and Yang (1996), with the most recent updated version in Nordhaus (2010). A more complete description of these models is contained in Nordhaus (2008, 2010) and Nordhaus and Sztorc (2013).

FUND and PAGE share the same basic integrated structure of the DICE/RICE models in linking output, emissions, concentrations, temperature, and damages,

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but differ in other important respects. The FUND model (Climate Framework for Uncertainty, Negotiation and Distribution; Anthoff & Tol, 2010, 2013) was developed primarily to assess the impacts of policies in an integrated framework. It is a recursive model that takes major economic variables as exogenous. Climate change impacts are monetized and include agriculture, forestry, sea level rise, health impacts, energy, consumption, water resources, unmanaged ecosystems, and storm impacts. Each impact sector has a different functional form and is calculated separately for 16 geographic regions. The model runs from 1950 to 3000 in time steps of one year. The source code, data, and a technical description of the model are public, and the model has been used by other modeling teams (Anthoff & Tol, 2013).

The PAGE model (Policy Analysis of the Greenhouse Effect; Hope, 2006, 2011) projects future increases in global mean temperature, the economic costs of damages caused by climate change, and the economic costs of mitigation policies. It has a relatively simple economic structure, taking output and emissions as exogenous with many periods, countries, and sectors. The major innovations are detailed inventories of GHGs; reduced-form treatment of the atmospheric chemistry of gases; simplified global and regional climate models, including of aerosols; and detailed regional impacts. Moreover, the PAGE model makes uncertainty a central focus, with 31 uncertain variables (such as climate sensitivity, carbon-cycle dynamics, impacts, and discontinuous impacts). The damage structure is highly developed, with catastrophic thresholds and sharp discontinuities introduced probabilistically. The model is proprietary, but is available to others with permission and credits (Nordhaus, 2014).

In sum, the three standard aggregate BCA models used for computing optimal climate change policies and calculating SCCs are very different in their structure, assumptions, treatment of uncertainty, and economic modeling. These differences mean that there is no easy way to judge the relative reliability of the models or their results. The next section of this paper gives an overview of the optimal climate policy results, while Section 5 summarizes recent SCC projections.

4 Recent applications of BCA in informing optimal climate change policies

At the broadest level, aggregate BCA-oriented climate policy models provide guidance as to the optimal level of carbon emissions and carbon pricing at a national or international level. For example, policymakers can use estimates to determine the optimal BCA-oriented carbon taxes or the target rate of emissions reductions under a cap on carbon emissions.

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Table 1 shows recent projections of the optimal cost of carbon for an incremental ton of carbon emissions in 2015 from the three aggregate cost-benefit models: DICE, FUND, and PAGE. The mean estimates range from $10 per ton for the FUND model to $18 per ton for the DICE model to $71 per ton for the PAGE model. These differences between models result primarily from differences in the climate damages functions included in the models, with FUND including the lowest cost projections and PAGE – especially with its focus on extreme events – the highest cost damage function. In addition, FUND and PAGE embed their models in a Monte Carlo simulation that draws from probability distributions over key model inputs and parameters and then uses the model to produce probability distributions over model outputs.

As shown in Table 1, for FUND a $2 value ($10 with PAGE) on the optimal carbon price is larger or equal to 10% of the simulation outputs and a $35 ($117 with PAGE) value >90% of them.

A key driver of the differences between models is their incorporation of the potential for catastrophic outcomes. FUND does not account for that possibility, while DICE and PAGE do. Moreover, the potential for a catastrophic outcome (which, in DICE, is based on a survey) accounts for roughly 70% of global damages at 2.5°C in both DICE and PAGE (Wolverton et al., 2012). Another key driver of the lower damage projections from FUND are assumptions made about the ability of those who are significantly impacted by climate change (e.g., farmers) to adapt to those changes (e.g., farmers can change crops, adjust planting schedules, incorporate irrigation, or apply fertilizer). PAGE also reports that the standard deviation of the optimal SCC is $266 per ton if all 100,000 runs in their MC simulation are included, but only $56 per ton if the highest 1% of the optimal SCC results are eliminated – highlighting the significance of the "thick tail" in their probability

Table 1 Recent social cost of carbon projection for "Optimal" BCA calculations from big three models.

Model	Optimal social cost of carbon		
	10th Percentile value	Mean value	90th Percentile value
DICE	–	$18	–
FUND	$2	$10	$35
PAGE	$10	$71	$117

Source: Nordhaus (2014).

The social cost of carbon for the marginal ton emitted in 2015 is measured in 2005 international US dollars. Therefore, for DICE $18.6 is the cost of emissions in 2015 in terms of consumption in 2015.

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distribution over damage outcomes. See further discussion of the challenges and importance of dealing with the possibility of thick tails in probability distributions over climate damages below.

Thus, model choice can easily lead to large range in the projections of the optimal carbon tax, and plausible ranges of key input assumptions (many discussed in more detail below) can lead to a similarly large spread in the range of projections from a single model. Combining model structure and model input uncertainties can lead to an order of magnitude or two in the projected optimal carbon tax. Beyond these highly uncertain numbers, however, the application of BCA models to climate change policy has provided numerous insights into many important dimensions of climate policy. BCA models have helped identify many of the most important drivers of the results produced. This has made it possible to start characterizing the level of understanding of the drivers and uncertainty about them, which has improved the ability to quantify uncertainties about model outputs of interest. The BCA models have also improved policy makers' understanding of the importance of cost effectiveness in policy development and implementation, the value of market instruments as compared with command and control regulations, the value of information about new technologies and improved science, the importance of broad participation, the potential volatility of carbon prices in policies that cap carbon emissions, and the costs of alternative approaches to reducing emissions. Perhaps the most important contribution of these models is the ability of systematic modeling to highlight the critical issues (such as discounting, risk, and damages) that arise in making the projections and to bring new scientific findings into account in a timely and orderly fashion.

The demand for optimal carbon policy emissions and price numbers on the country, regional, and international scene is strong and growing. In making decisions about climate change mitigation at this level over time, decision makers want to know how to trade off resource commitments (whether from the federal budget or the influence of their policies on the private sector) devoted to climate change against those devoted to other pressing societal priorities. On the other hand, specific numbers are hard to defend. At the very least, these calculations need to be more transparent and a full set of plausible sensitivity analyses across modeling platforms and model input and parameter assumptions needs to be considered, as is now starting to happen.

5 Recent projections of the social cost of carbon

A second application of the aggregate climate change policy-oriented BCA models is for rulemaking where countries do not have comprehensive policies covering all

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GHGs. In this context, regulators might use the SCC in a calculation of the incremental social costs and benefits of policies involving energy or climate-affecting decisions. US executive orders issued since EO12291 (Reagan, 1981) have called for major regulations to be accompanied by a "regulatory impact analysis," or RIA.[3] While it is not generally necessary that regulations pass a benefit-cost test, regulators have paid close attention to the analyses. Prior to 2008, the valuations of carbon emissions were not included in monetary estimates of costs and benefits. As a result of a 2007 Supreme Court decision, the U.S. EPA was required to regulate CO_2 and other GHG emissions as "air pollutants" under the Clean Air Act.

A particularly influential and important set of estimates of the SCC was provided by the Interagency Working Group on Social Cost of Carbon, hereafter Interagency Working Group or IWG (Greenstone, Kopits, & Wolverton, 2011, 2013; Interagency Working Group, 2010). These estimates were updated in Interagency Working Group (2013). The original analysis was developed by technical experts from numerous agencies in the U.S. federal government who "met on a regular basis to consider public comments, explore the technical literature in relevant fields, and discuss key model inputs and assumptions. The main objective of this process was to develop a range of SCC values using a defensible set of input assumptions grounded in the existing scientific and economic literatures" (Interagency Working Group, 2010, p. 1). The 2013 estimates update the models but use the same methodology as the 2010 estimates. The analysis has been used for rulemaking by the U.S. government. See Johnson and Hope (2012), Tol (2008, 2009), and Nordhaus (2013) for more on the projections of the social cost of carbon.

Table 2 shows the IWG estimates for the SCC. All figures in Table 2 are the global SCC for 2015 in 2005 US dollars. Panels A and B show the results of the IWG calculations (from 2010 and 2013, respectively). These use the IWG estimates and discounting methodology. The 2013 estimates are revised upward substantially for the FUND and PAGE models, reflecting the incorporation of new scientific information into those models. For the preferred 3% constant discount rate, the SCC for 2015 is revised upward from \$22.4 to \$35.8 per ton of CO_2.

As well-summarized in a recent report from the Electric Power Research Institute (Rose et al., 2014), a wide range of SCC estimates characterizes the IWG SCC reports, with results varying substantially across models and input assumptions. Figure2, which is taken from that report, shows that – in a pattern of results similar

3 The source of regulatory analyses dates to the 1970s. The current relevant rule is Executive Order 12,866, which states that agencies must, to the extent allowed by statute, "assess both the costs and the benefits of the intended regulation and … propose or adopt a regulation only upon a reasoned determination that the benefits of the intended regulation justify its costs" (OMB, 2003).

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Table 2 Estimates of the social cost of carbon for 2010 from U.S. Interagency Working Group and comparison with alternative model estimates.

Model and scenario	Constant discount rate on goods			
	5%	4%	3%	2.5%
A. Estimates of 2015 SCC from US Working Group, 2010				
DICE-2007	10.2	17.4	29.6	43.5
PAGE	7.4	15.3	31.3	50.9
FUND	–1.5	2.5	6.3	14.0
Average	5.4	11.7	22.4	36.2
B. Estimates of 2015 SCC from US Working Group, 2013				
DICE-2010	11.0	18.6	31.4	48.1
PAGE	20.2	34.4	58.6	85.3
FUND	2.7	6.9	17.3	30.4
Average	11.3	20.0	35.8	54.6

Source: Nordhaus (2014).

Panel A shows estimates of the 2010 SCC from the Interagency Working Group. The three models have harmonized outputs, emissions, populations, and temperature sensitivity coefficient (TSC) distribution and use constant discount rates.

Panel B shows the revised IWG estimates from the 2013 report.

The 2015 estimates are interpolated from the given figures in the 2010 and 2013 reports.

to the optimal carbon tax projections discussed previously – PAGE produces the highest average SCC estimates and more uncertainty than the other models, while FUND produces the lowest average SCC estimates. For all models, averages and uncertainty decline with higher discount rates due to greater discounting of the models' estimates of positive annual damages over the next three centuries. SCC results also vary by socioeconomic and emissions assumptions, with variation differing across models. As can be seen in this figure, there is roughly an order of magnitude range of SCC projections from the running of the three models with similar input assumptions, and about an order of magnitude range in SCC projections across plausible ranges of input assumptions. The critiques and challenges discussed in the next section provide additional sources of uncertainty to keep in mind when interpreting and assessing these SCC projections.

6 Critiques and major open issues for optimal climate policy and SCC projections

The benefit-cost models that have been used to help formulate optimal climate change policies and compute the SCC have been widely and constructively criti-

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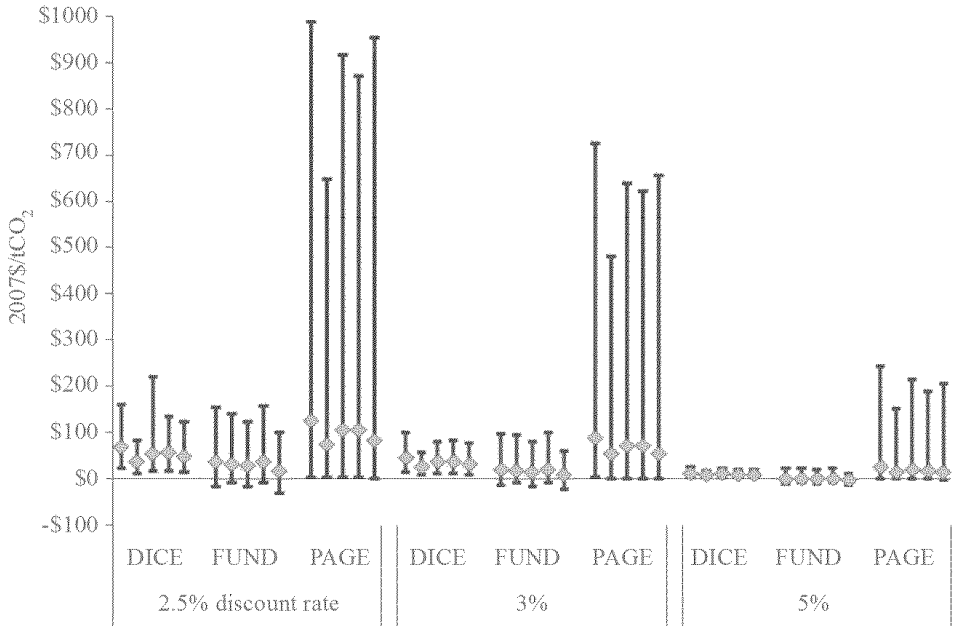

Figure 2 USG IWG 2020 SCC average and 1st–99th percentile values by discount rate, model, and reference socioeconomic/emissions assumption.
Source: Rose et al. (2014).
The figure shows SCC results from USG (2013), with averages in blue and 1st–99th percentiles in red. Each percentile range reflects USG standardized and model specific parametric uncertainties. Values adapted from USG (2013). Each point on the bottom three lines is an average SCC value for a specific year and given discount rate, averaging results across models, alternative socioeconomic scenarios, a distribution of potential climate sensitivities, and random model specific parameters; "3% (95th percentile)" is the 95th percentile from the distribution of the 150,000 SCC estimates discounted at 3%.

cized on several grounds. Most of these criticisms fall into five general categories. First are from those (perhaps appropriately referred to as extremes-oriented critics) who hold that the models exclude major dangerous or potentially catastrophic impacts of climate change. In these critiques, the optimal carbon policy solutions and SCC projections are thought to be underestimated, possibly dramatically so. Second are from those who are critical of the way in which regional costs and benefits are calculated, compared, and interpreted because they may distort or obscure fundamental equity tradeoffs across space and time (here referred to as environmental justice critics). Third are from those who believe that climate change is such a long-run phenomenon that consideration of inter-generational equity is crucially important and not well handled in the BCA models or IAMs in general (the generational justice advocates). Fourth, there are those who believe that the baseline elements of the models are very difficult to construct

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because of the challenge of projecting socioeconomic conditions and technological changes over long periods of time, such that even if the aggregate microeconomic cost and benefits of climate change policies can be projected reasonably well, the actual implementation of climate policies will include other fiscal and income distribution policies that will be more important than the climate account numbers on their own. This may be called the "devil is in the details" critique. A final category of concerns about the models (partly confounded with categories one through four) holds that the models and estimates are dependent on so many highly uncertain parameters and exogenous inputs that much more work needs to be done to characterize and communicate the implications of these uncertainties in order to be useful to decision makers. This could be termed the "incomplete uncertainty characterization" critique. Each of these concerns is addressed here in turn.

6.1 Tipping points, fat tails, and potential catastrophes

There have been several critiques of the calculations in the DICE model (as well as FUND and PAGE) arguing that the models omit significant earth system responses, especially when they may present themselves in a very non-linear and/or abrupt manner. For a particularly sharp assessment along these lines see Ackerman and Stanton (2010, 2012).

One of the most troubling concerns about climate change is the potential for abrupt, irreversible, or catastrophic climate change or climate change impacts to occur (see IPCC, 2012, 2013, 2014a; Lenton et al., 2008; National Research Council, 2002). Estimates for the economic costs of such scenarios are included in the PAGE model directly and captured conceptually in the damage estimates in the DICE-2013R model. However, the model does not deal explicitly with tipping elements, primarily because these have not been reliably determined. It must be emphasized that, other than expert opinion, there is virtually no basis for determining the size, timing, or probability of such events or the economic damages that would ensue.

Work on using expert elicitations to characterize the form and characterize the uncertainty of these crucially important phenomena is barely in its infancy at present. This is a vital avenue for future research, because the fundamental scientific uncertainties in this area seem unlikely to be resolved any time soon. Making this investment would bring with it an obligation to develop methods designed to use this type of information in formulating climate policy, which is also an enterprise that is just starting to take serious form in the analytical community – and which so far has dominantly used hypothesized probability distributions

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and utility functions applied to extreme economic outcomes with varying degrees of reasonableness. Early expert probability elicitations in the climate arena have been very useful but quite crude (Morgan & Keith, 1995; Nordhaus, 1994b), and have ignored the typical decision theory challenges of assessing whether experts are "calibrated" (roughly defined as internally consistent) and/or not "independent," which can easily occur if many of a group of experts have identical training, approaches to the analysis-modeling, and maybe even the same mentors. This latter issue can be addressed through consideration of ways of "combining expert opinions" (Browne, 1996; Clemen, 1984, 1985, 1986, 1989; Clemen & Winkler, 1985, 1986, 1987, 1992, 1993; Jouini, 1992; Jouini & Clemen, 1994; Morris, 1971, 1974, 1977, 1983, 1986), which is difficult to accomplish, but almost assuredly ultimately necessary.

Another difficulty that has not been fully addressed in the literature is the potential for highly skewed distributions of uncertain variables and potentially unbounded values of the SCC. This issue was raised in Weitzman (2009) and has been discussed extensively in the literature (cf., Weitzman, 2013). A simplified way to state Weitzman's argument is that the combination of fat tails and strong risk aversion may lead to large losses in expected welfare. As a result, the true BCA results may be unbounded or extremely large.

Table 3 (from Nordhaus, 2013) shows the SCC with and without abatement policies for different thresholds. An important feature of catastrophic damages is that the "catastrophic" SCC depends critically on whether adequate policies are taken. For the threshold of 2°C and no climate-change policies, the SCC is $1046 per ton CO_2. However, when optimal policies are taken immediately, the SCC is only $54 per ton of CO_2. This result – that fat tails or catastrophic damages generally

Table 3 Social cost of carbon with catastrophic threshold, with and without climate policy.

Threshold temperature, T*	Social cost of carbon (2015 in 2005$)	
	With optimal policy	With no policies for 100 years
1.5°C	125	1495
2°C	54	1046
3°C	24	197
4°C	19	33

Source: Nordhaus (2014).

The cases without policy assume no abatement for a century. The cases with policy assume immediate optimal abatement. The catastrophic damage function assumes that the damage-output ratio is $0.01[T(t)/T^*]^8$, where T* is the catastrophic threshold.

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have extreme results on the SCC only when good policies are not taken – should be taken into account by everyone involved in climate policy development.

An important limitation of the simple climate policy benefit-cost models is that the whole climate system is represented with a very small number of equations drawn from highly reduced-form climate models (e.g., the MAGICC model) (Meinshausen, Raper, & Wigley, 2012), which were initially designed for interpolating between steady state climate regimes projected by very complex full-scale climate models. These models generally include energy balance equations only, and not the conservation of momentum and mass balance equations included in a full-scale climate or earth system model (Washington & Parkinson, 2005). In actual tests (Schaeffer et al., 2013; van Vuuren et al., 2011) these models match the behavior of full-scale climate models for scenarios in which climate conditions change gradually, but do not match very closely for scenarios in which abrupt changes occur. In other words, the two types of models produce similar results in scenarios that move gradually from one steady state to another but are not very good in cases where the dynamics of change are important. It is not clear that full-scale climate models include these dynamics very satisfactorily, but the simplified climate models do not even match what is represented in the full-scale climate models.

6.2 Treatment of geographical equity: regional, national, international

BCAs applied to climate change policy have generally been heavily efficiency focused, with equity considerations rarely addressed directly except occasionally an ex-post reporting of economic impacts across various socioeconomic strata within and between nations. This is unfortunate, because equity and fairness issues often completely dominate the political debate on what to do about climate change. Moreover, this is not something that can easily be fixed after running a model with an efficiency-based optimizing architecture because of the many equity trade-offs and approximations that are typically made in constructing those models in the first place.

For one simple example, consider the plight of the approximately two billion people who live in areas without functioning goods and financial markets. Since they have no markets, they have no (measured) income and make no (measured) expenditures. So if climate changes, they absorb no (measured) impacts and would not benefit from any reductions in those impacts resulting from any policy designed to reduce carbon emissions. If an optimal carbon policy/SCC is computed for a market or country and the desire is to include global costs and

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benefits in those calculations, the impacts on the poorest people on earth are not included. In fact, the global environmental justice movement includes efforts to improve "energy access" as a major objective, so these initiatives may be working to improve welfare in a way that in itself makes (measured) climate damages larger. See Adler (2012) for more on this type of critique of BCA, but also a well-developed argument for a much more nuanced use of Social Welfare Functions (SWFs) as a viable and practical alternative. As he observes in the introduction to the book cited above: "While BCA is defensible as a rough proxy for overall wellbeing, it is insensitive to the distribution of wellbeing. By contrast, the SWF approach can incorporate distributive considerations into policy analysis in a systematic way." The book also includes some simple SWFs that can be used to reflect equity considerations in a simple and transparent way (Adler, 2012, Chapter 5).

This critique may be a bit extreme and unfair to some global-scale climate policy analyses, as they do try to value "non-market" impacts in some way. In such studies, however, these calculations are quite crude and even if physically and monetarily sensible still need to be aggregated with cost and benefits for other people living under completely different circumstances. This task has historically vexed economists of all stripes (e.g., Arrow, Sen, Dasgupta, & Scrinivasan) and is sometimes disregarded by climate policy analysts as not being important because all nations transition to modern market forms of organizations. But will that actually happen everywhere, and if so, when? The answer to that question has sometimes been "by the time significant climate change impacts emerge," but to many that time has already passed (IPCC, 2014a).

Another key challenge in the BCA/SCC work on climate is aggregating across countries: whose damages should be considered and how should they be weighted in computing an aggregate metric? Some daunting analytic issues arise here, as well as some deep philosophical issues. For example, should market exchange rates or purchasing power parity weights be used to value economic damages in developing countries relative to economic damages in developed ones? This by itself can lead to a factor of two or more difference in Chinese impacts valuation vis-à-vis those in the Organisation for Economic Co-operation and Development (OECD). But the difficulty does not stop with dollar equivalent issues: weighting losses in wealthy versus poor countries is not straightforward (Adler, 2012), and it is not lost on poor countries that weighing their impacts less because they produce less marketed economic output may be patently unfair to their interest in global climate policy.

Another important, but contentious, issue is whose GHG mitigation benefits to include in the optimal carbon policy or SCC estimates. In US regulatory analysis, only costs and benefits of policies imposed on US citizens are typically

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included (see Gayer & Viscusi, 2014). In international negotiations, however, not including the full global impacts in these calculations is typically viewed as unfair as it leads to damages being imposed on populations around the world by US firms and citizens with no compensation. Thus, applying this practice to GHG emissions would directly violate a fundamental international negotiating principle called the "polluter pays" principle (Morin & Orsini, 2015). Although the "polluter pays" principle has no legal standing in the US, it became law in the European Union in April of 2004 (Morin & Orsini, 2015).

A final practical difficulty with global BCA is that, even if all the site-specific physical climate change impacts can be projected and valued and aggregated with impacts on other people in other sectors and other regions at a specific point in time, all the aggregations and approximations would probably need revision over time. This could arguably be done fairly well for small fluctuations, but could be problematic for the types of large systematic variations that are the biggest concern as the climate changes.

6.3 Treatment of intertemporal discounting and intergenerational equity

In one sense, the challenge of accounting for intergenerational equity in climate policy analysis brings with it all the issues just discussed regarding dealing with equity across regions and socioeconomic strata at a specific point in time. In that sense, time is just another distinction among the earth's inhabitants that needs to be dealt with. However, making tradeoffs across this dimension is particularly tricky to address, even beyond discount rate issues. First, if investment (public or private) is to be made on climate mitigation or adaptation, one needs to account for who will receive the proceeds of that investment, and whether that allocation is equitable.

Second, a large number of individuals who will be affected by future changes in climate and climate change policies are not yet born, making a direct elicitation of their preferences infeasible. As partially addressed in the papers contained in Portney and Weyant (1999), there are ways in which these challenges can be addressed (e.g., a "global referendum" on what legacy the current generation of earth's inhabitants wants to leave future generations), but these are hard to implement and almost never done.

In addition to consistency and fairness between countries it is also necessary to weigh costs and benefits over time, ultimately requiring consideration of the preferences of as-yet unborn generations. This obviously cannot be done directly, so people making decisions today on behalf of those not yet alive today need to

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collectively make ethical choices about what kind of opportunities they want to leave future inhabitants of planet Earth. It is a gross understatement to say that this is a very hard problem.

Central in this debate is the role of discounting. Discounting involves two related and often confused concepts (Nordhaus, 2013). One is the idea of a discount rate on goods, which is a market-based concept that measures a relative price of goods at different points of time. The discount rate is also variously referred to as the real return on capital, the real interest rate, the opportunity cost of capital, and the real return. The real return measures the yield on investments corrected by the change in the overall price level. In principle, this is observable in the marketplace, although the exact numbers differ based on the risk characteristics of the return involved. For example, the real return on 10-year U.S. Treasury securities over the period 1960–2000 averaged 3.0% per year. Similarly, the real pretax return on U.S. corporate capital (a risky investment) over the same four decades has averaged about 6.6% per year. Estimated real returns on human capital range from 6% per year to more than 20% per year depending upon country and time period (Nordhaus, 2013).

The second important discount rate concept involves the relative weights of the economic welfare of different households or generations over time. This is typically called the pure rate of social time preference or generational discount rate (Nordhaus, 2013). It is calculated in percent change in value per unit of time (as with an interest rate), but refers to the discount in future welfare, not in future goods or dollars. A zero generational discount rate means that future generations into the indefinite future are treated symmetrically with present generations; a positive generational discount rate means that the welfare of future generations is reduced or "discounted" compared with that of nearer generations (For examples, see Arrow et al., 1995, 2013; Portney & Weyant, 1999).

While the concept of discounting has very broad philosophical and ethical foundations, most analyses of the discounting issue in the economic and IAM literature use the approach of the Ramsey-Koopmans-Cass model of optimal economic growth (Cass, 1965; Koopmans, 1965; Ramsey, 1928). The economic agents in the economy are generations or cohorts. Similarly, the key parameters are α (the elasticity of utility with respect to a generation's consumption, or consumption elasticity) and r (the generational discount rate). One of the major confusions about discounting is whether the variables apply to the welfare of different generations or to individual preferences (Nordhaus, 2013). The individual rate of time preference, risk preference, and utility functions do not enter directly into the formulation. An individual may have a high rate of time preference, but this has no necessary connection with how different generations should be weighted in making social decisions. Similar cautions apply to the consumption elasticity,

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which relates to the social valuation of inequality across different generations and not to individual risk preferences.

Optimizing the social welfare function with a constant population, no risk or taxes, and a constant rate of growth of consumption per capita across different generations, g^*, yields the standard equation for the relationship between the equilibrium real return on capital, r^*, and the other parameters: $r^*=\rho+\alpha g^*$. This is usually called the Ramsey equation (Nordhaus, 2013). There are two ways of using the Ramsey equation as a framework for discounting in global warming or other long-run questions. One is the *prescriptive view*, in which analysts argue for particular values of the ethical parameters, r and a, and from this derive the ethically appropriate discount rate on goods. This is the approach taken in Cline (1994) and the Stern Review (2007). The latter argues that it is indefensible to make long-term decisions with a positive generational discount rate: "[Our] argument, and that of many other economists and philosophers who have examined these long-run, ethical issues, is that [a positive generational discount rate] is relevant only to account for the exogenous possibility of extinction." The generational discount rate used in the Stern Review is 0.1% per year, which is justified by estimates of the probability of extinction. The Stern Review further assumes a consumption elasticity of α=1 and a long-run growth rate of g^*=1.3% per year, which leads to a real interest rate (discount rate on goods) of 1.4% per year. A similar approach was endorsed by Cline (1992).

A second approach is the *descriptive approach*, advocated by Lind and Ruskin (1982), Lind (1995), and Nordhaus (1994a). This approach assumes that investments to slow climate change must compete with investments in other areas. The tradeoff for this should therefore reflect the opportunity cost of investment. If the IAMs are interpreted as computing market equilibria by maximizing welfare as discussed above, then the real interest rates in the model (as with other prices and outputs) are calculated to reflect market prices. In this interpretation, there is no ethical presumption that these are the correct prices or interest rates, but they should reflect market realities. It is inefficient, in the descriptive view, to accept investments in climate mitigation with a yield of 1.4% per year if there are available investments in education or capital with yields of 6% per year. In the descriptive view, the relevant equation is still the Ramsey equation, but the primitives are the rate of return (r) and the growth rate (g), and the other two parameters must be calibrated to be consistent with observed market realities. The calibration for DICE-2010 is slightly different from these equilibrium calculations because of population growth and changing consumption growth, but the equilibrium calculations give the flavor of the results. In the baseline empirical model, a generational discount rate of 1.5% per year with a consumption elasticity of 1.5 is adopted. These yield an equilibrium real interest rate of 5% per

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year with the consumption growth that is projected over the next century by the model.

Most of the debate about discounting has concentrated on the ethical concerns with using a positive generational discount rate. However, the fundamental Ramsey equation includes two observable parameters (r and g) and two unobservable ethical parameters (ρ and α). A low real interest rate in the prescriptive view cannot be justified by a zero generational discount rate alone, but also depends upon the consumption elasticity, the growth rate of consumption, and population growth. Similarly, observations on the real interest and growth rates are insufficient to determine the generational discount rate in the descriptive view. In both approaches, there is one free parameter. This implies that they are observationally equivalent in a steady state (Nordhaus, 2013). The paradox of low discounting can be illustrated with a "wrinkle experiment." Suppose that scientists discover a wrinkle in the climate system that will cause damages equal to 0.1% of net consumption starting in 2200 and continuing at that rate forever after. How large a one-time investment would be justified today to remove the wrinkle that starts only after two centuries? Using a near-zero discount rate of the kind proposed by the Stern Review, the answer is that society should pay a substantial fraction of a year's consumption today to remove the wrinkle (see Nordhaus, 2008).

6.4 Projections of baseline drivers and policy implementation details

As mentioned above, calculations of the BCA-determined optimal level of carbon emissions are dependent on the carbon emissions baseline used. This dependence is even stronger for the SCC estimates, as the baseline used to calculate the incremental damages over time resulting from an additional ton of GHG emissions today is not constrained by the optimality condition (MC=MB) that characterize the BCA projections. The emissions scenario employed for this purpose could be the optimal scenario, an expected scenario, a muddling-through scenario, multiple scenarios, a scenario that maximizes utility for some stakeholders, a scenario that is robust for some stakeholders, or another scenario altogether. The SCC along the "optimal" path of emissions would be the same as the implicit or explicit price on carbon emissions produced by a traditional BCA of optimal climate policies.

Since most national- and global-scale BCAs aggregate costs and benefits over 50–100 years, a major challenge on both the mitigation and impacts/adaptation accounts is projecting the impacts of technological change on costs and benefits

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over such a long period of time. The challenges of including technological change into the impacts and adaptation calculations is covered in papers by Neumann and Strzepek (2014) and Li et al. (2014). That this degree of uncertainty about mitigation cost projections, especially in the technology dimension, still remains with us today is carefully and systematically documented in the IPCC's Fifth Assessment Report, *Mitigation* (2014b). In addition to the demographic and technological uncertainties, another major explanation for this large uncertainty range in mitigation cost projections is uncertainty about the specific policies that decision makers will implement to achieve their objectives: these can explain up to half of the total range of projections (c.f., Weyant, 2001).

6.5 Dealing with uncertainty and risk

The complexities of the operation of the earth system and of policies designed to cope with human-induced climate change bring with them vast uncertainties regarding key model parameters and important model outcomes. In this paper, many of these key uncertainties have already been identified as challenges to be dealt with, but there may be additional uncertain parameters and relationships that have not yet been fully observed or appreciated. There are a number of ways to deal with all this uncertainty, starting with sensitivity analysis on key parameters and inputs of the type discussed above. In addition, Monte Carlo simulations can be performed in which a large number of draws are made from probability distributions over inputs to the models and run through them, which produces probability distributions over important model outputs – such as changes in temperatures and sea levels – as well as total climate change damage and mitigation costs to be constructed. These are a good start, but two other crucial dimensions of the problem should also be included in any comprehensive attempt to inform decision making about climate policies. First, decisions made today can be revisited and modified at any point in the future as new information on climate change damages and mitigation costs becomes available. Thus, decision making about climate change is one of sequential decision making under uncertainty. One can formulate the climate change policy problem explicitly in this way using a stochastic control or stochastic dynamic programming formulation, but the data input and computational requirements of these methods can be prohibitive and the assumptions made too constraining to be practical. One technical challenge here is to distinguish between how decision makers responsible for many people should factor uncertainty into their thinking and analysis, and how the individual agents represented in the BCA models should take them into account. This difference between public and private perspectives can be very important,

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which calls into question the use of optimizing models that treat them (implicitly or explicitly) as being identical.

The second crucial additional dimension to be considered is the decision makers' attitudes toward risk, both individually and collectively. Much of the application of modern decision theory targets decisions where the stakes are important, but not important enough to necessitate higher derivatives of utility functions or higher moments of probability distributions. For example, since at least Raiffa's classic book on decision analysis (Raiffa, 1968), practitioners have appreciated the analytical tractability of using exponential utility functions with constant relative risk aversion to represent the preferences of individual decision makers. These assumptions tend to provide good approximations to preferences when the outcomes of decisions are not expected to have a major influence on the individual's overall level of wealth. This constant relative risk aversion assumption means that a decision on climate change, for example, can safely be analyzed without looking at the correlations between the outcomes that could emerge from that decision and all the other decisions one has made for which the payoffs are not yet known with certainty (Pratt, Raiffa, & Schlaifer, 1995). Put differently, if one were to add a constant amount to the utility measure for all alternatives the individual faces, this would not change the utility ranking of the alternatives. This property, called the "delta property" for obvious reasons by the people who first observed it (cf., Howard, 1984), does make the analysis of individual decisions by well-calibrated individual decision makers (which means that they make decisions in an internally consistent manner) much easier, as otherwise all the correlations with other investments would need to be considered simultaneously. In the case of climate change, where group decisions rather than individual ones usually need to be considered, the stakes under certain conditions can be extremely high and highly correlated with other big societal decisions, and our experts in some areas (if there are any) may not be well calibrated. The papers in this issue by Lempert (2014) and Toman (2014) provide guidance on what to do when the simplifying assumptions do not hold.

7 Conclusions and recommendations

This review summarizes the results of current optimal climate change policy BCAs and efforts to compute the social cost of carbon. Given the challenges involved in producing these numbers and the many uncertainties underlying them, it is probably appropriate to think of these numbers as providing a good rough guide to current policy development, but in need of much refinement as time goes on.

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Thus, in this way they can be considered a good place to start thinking about climate policy formulation but a poor place to finish in terms of specific long-term policies involving the whole planet.

To some, however, the challenges highlighted in this paper and the complexities and uncertainties inherent in the climate problem and in its possible solutions make the models described above worse than useless. In a recent article, Pindyck (2013)[4] concludes that IAMs "are of little or no value for evaluating alternative climate change policies and estimating the SCC." Although agreeing with many of Pindyck's individual criticism, Nordhaus (2014) reaches a different conclusion regarding the usefulness of the current generation of climate policy BCA models.

Pindyck's criticism of IAMs touches both empirical and conceptual issues. Beginning with the empirical questions, he highlights (1) the social preference function, particularly the discount rate, (2) the damage function, (3) the potential for catastrophic changes, and (4) the temperature sensitivity to greenhouse gas increases.

While Pindyck's observations about the empirical weaknesses of IAMs or calculations of the SCC are worthy of careful study, the conclusion that IAMs are therefore useless fundamentally misconceives the enterprise. IAMs and the SCC are conceptual frameworks for dealing with highly complex, non-linear, dynamic, and uncertain systems. The human mind is incapable of solving all the equations simultaneously, and modeling allows making "If…, then…" analyses of the impacts of different factors. The models have provided important insights into many aspects of climate-change policy.[5]

IAMs have improved our understanding of the importance of cost-effectiveness in designing climate policies, the value of market instruments as compared with command and control regulations, the value of information about new technologies and improved science, the importance of broad participation in mitigating carbon emissions, the potential volatility in carbon prices that can result from systems that cap emissions, and the costs of alternative approaches to reducing emissions. Perhaps its most important contribution is the ability of systematic modeling to highlight the critical issues (such as discounting, risk assessment,

4 Note that Pindyck refers to only the three aggregate BCA models as "integrated assessment" models, thus missing the existence and potential contributions to understanding of the many non-BCA-focused IAMs.

5 Another concern about Pindyck's condemnation of the "integrated assessment" models is his use of results from the models discussed here from the IWG report in his alternative approach to guiding decision making on climate policy.

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and damages) and to bring new scientific findings into the assessments in a timely and orderly fashion.

The demand for the numbers the models produce at the country, regional, and international levels is strong and growing over time. In making decisions about climate change mitigation over time, decision makers want to know how to trade off resource commitments (whether from the federal budget or the influence of their policies on the private sector) devoted to climate change against those devoted to other pressing societal priorities. On the other hand, specific numbers are hard to defend at the current state of the art, and the challenges preventing more precision are so formidable that this situation will not improve any time soon. It is important to realize, though, that the complexities and uncertainties discussed here are inherent in the climate change problem and not manufactured by the models. On the contrary, the models can help us understand implications of alternative assumptions within a broader and more decision-focused whole systems context than otherwise would be possible. At the very least, the model calculations need to be made more transparent and a full set of assumptions needs to be considered – as is now starting to happen.

The emergence of the SCC concept, especially in regulatory proceedings in the US, is a useful, although at times somewhat confusing, enterprise. Motivated in large part by the successful Clean Air Act (Domike & Zacoroli, 2013), it is more narrow than what would be considered in a more traditional benefit-cost analysis, but consistent with standard regulatory impact assessments, especially those produced in the US. The idea is to compute the marginal cost of an additional ton of GHG emissions assuming no future climate policies are implemented. This calculation, which is what the U.S. EPA has used for computing the benefits of regulating much shorter lived "criteria pollutants" such as emissions of sulfur and nitrogen compounds, is thus almost assuredly higher than what would be obtained if climate policies were assumed to be in place, but many would argue that the models used leave out important impacts, which would bias the estimate in the opposite direction (i.e., lead one to conclude they are too low). This leads to a pragmatic regulatory system where the numbers can be adjusted over time as additional information about climate damages is obtained. Interestingly, Nordhaus (2014) also concludes that unless the discount rate is on the very low side of the range of current opinion, the SCC along any reasonable baseline is very close to his own optimal BCA carbon price for the first decade or two. Thus, stakeholders may scream that the numbers are too high or too low, but the system moves us in the right direction while avoiding the gridlock that can emerge if perfect numbers are deemed necessary in order to act.

Another conclusion of this review is that it is hard to apply the conventional BCA approach at the national or international level because of the large number

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of important stakeholders potentially involved in climate change and climate change policy development. Thus, it is challenging to work with a formulation in which it is assumed that there is a single decision maker whose framing of the problem, probability assessments, and preferences are shared by all the relevant stakeholders. There are two immediate implications of this observation. First, moving to a setting where a more unified decision frame makes sense – such as one where a major coastal zone, growing region, or urban landscape is involved – will make the problem of whose preferences to include and how to include them much easier (although not trivial given the complexity of the climate system). As Li et al. (2014) argue that circumstance has led to some very successful applications of BCA to climate change adaptation decision making at the local to regional level.

The second implication of the limitations on larger scale use of BCA in the climate change policy arena is not only the advisability of continuing to improve the information and analysis behind these more aggregated calculations, but to include a more comprehensive set of sensitivity analyses than has typically been included so far – one that includes alternative treatments of concepts such as equity, attitudes toward risk, and degrees of technological optimism. In this way, numbers and policies that are robust [see Lempert (2014) for a working definition] across all these dimensions can be identified and used to look for stochastically dominant solutions or those that minimize the expected maximum regret of major stakeholders over time.

Especially challenging areas for future work are methods for aggregating – or at least trading off – welfare across vastly different socioeconomic populations in vastly different climatological zones around the world. Another great challenge is determining how other countries will control carbon emissions, including especially whether action in one country (such as the US) will affect the extent to which other nations will control them as well. Further complications arise if it is thought that most countries will eventually decide to control carbon emissions and those that do so first will have a comparative advantage in technology and institutional innovation.

The most important results from the BCA-oriented IAMs at present are as follows: First, the cost of carbon along a BCA-determined optimal emissions trajectory from the DICE model for the current time (2015) is about $20 per ton of CO_2 in 2005 US international prices, with a range of $5 to $50 over a plausible range of uncertainties. Thus, there is a lot of uncertainty in these projections across plausible inputs to one model. Second, in accordance with the intertemporal optimization formulation of DICE, this price is expected to increase at approximately the rate of interest over time, thus rising to about $150 per ton by 2100. Third, the DICE model results are substantially lower (by about a factor of four)

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than one of the other two major modeling estimates (the PAGE model) but substantially higher (by about a factor of four) than the other (the FUND model). There is thus a lot of uncertainty in the results produced by the different models, even with similar input assumptions. Fourth, because of the formidable challenges required to aggregate climate damage costs and GHG mitigation costs into a single aggregated value at each point in time, all of these estimates should be viewed as rough preliminary estimates and subject to change and further interpretation (e.g., disaggregated by socioeconomic class). Fifth, work on the individual challenges discussed in this paper and complementary work with the more disaggregated IAMs should be closely monitored and used to refine the numbers currently coming from application of the models.

Finally, given all these uncertainties, decision support tools other than BCA should continue to be developed and the insights from them compared with the BCA results. Society cannot afford to wait for the BCA calculations to be refined before making climate policy decisions today, but – as suggested in several places [e.g., the papers by Lempert (2014) and Toman (2014)] – the analysis of these decisions can be put in a broader context that recognizes that the world is made up of many stakeholders with differing perceptions of the severity of the climate change problem, different stakes in climate outcomes, different preferences, different attitudes toward equity, and different attitudes toward risk. Thus, what is optimal for one group may be suboptimal for another. So unless the world quickly reorganizes into one where global welfare can be optimized and then the distribution of benefits decided upon equitably with no arguments, tradeoffs about both what is efficient and what is fair will need to be made, and these calculations continually subjected to scrutiny and revised or clarified when necessary.

Acknowledgments: The author thanks David Anthoff, Chris Hope, Jia Li, William Nordhaus, Richard Richels, Steve Rose, Fran Sussman, James Sweeney, Richard Tol, Delavane Turner and two excellent anonymous reviewers for suggestions on this paper.

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To: Durham, Natalie[Durham.Natalie@epa.gov]; Wolverton, Ann[Wolverton.Ann@epa.gov]; Kopits, Elizabeth[Kopits.Elizabeth@epa.gov]; Dockins, Chris[Dockins.Chris@epa.gov]; Simon, Nathalie[Simon.Nathalie@epa.gov]; Maguire, Kelly[Maguire.Kelly@epa.gov]; Moore, Chris[Moore.Chris@epa.gov]; Marten, Alex[Marten.Alex@epa.gov]; Griffiths, Charles[Griffiths.Charles@epa.gov]; Newbold, Steve[Newbold.Steve@epa.gov]
From: McGartland, Al
Sent: Mon 7/20/2015 8:31:06 PM
Subject: Fwd: meeting with NCEE

I was thinking of two meetings one on scc and the other Non-Responsive But if we want three we can do that I'm sure.

Sent from my iPhone

Begin forwarded message:

From: "Rennert, Kevin" <Rennert.Kevin@epa.gov>
Date: July 20, 2015 at 4:27:42 PM EDT
To: "Means-Thomas, Janet" <Means-Thomas.Janet@epa.gov>
Cc: "Kime, Robin" <Kime.Robin@epa.gov>, "McGartland, Al" <McGartland.Al@epa.gov>
Subject: meeting with NCEE

Janet – could you please work with Natalie to set up a meeting with Al and his Social Cost of Carbon team (listed in his email response below) for later this week or early next week?

Non-Responsive

Best,

Kevin

From: McGartland, Al
Sent: Monday, July 20, 2015 4:19 PM
To: Rennert, Kevin

Subject: Re: follow-up

I don't think order matters too much (unless it takes a long time to meet).

Having Janet work with us would work well. I suspect your calendar will get more crowded so having her involved will make it easiest to accommodate possible changes. Janet knows my admin asst (Natalie). They can figure it out. Later this week will probably work.

Ex 5

Non-Responsive

Sent from my iPhone

On Jul 20, 2015, at 4:12 PM, Rennert, Kevin <Rennert.Kevin@epa.gov> wrote:

All sounds good to me. Do you think that's the appropriate order as well – SCC before SAB? Either is ok with me. Shall I ask Janet to coordinate a good time with you and your staff for each of those meetings for later this week / early next week?

Thanks,

Kevin

From: McGartland, Al
Sent: Monday, July 20, 2015 2:03 PM
To: Rennert, Kevin
Subject: Re: follow-up

I'm very flexible. Ex 5

Ex 5 we should spend at least an hour with you.

Non-Responsive

I'm at these Econ meetings in Boston today. So is Elizabeth. Richard Newell is here along with Michael greenstone and a number of other Economists. The meeting is by invite only but it's a good chance to learn where these folks are going on energy efficiency, scc, and even fracking.

Sent from my iPhone

On Jul 20, 2015, at 12:57 PM, Rennert, Kevin <Rennert.Kevin@epa.gov> wrote:

> Al – thanks again for the overview briefing last week. It was great to get a sense of everything that's on the horizon and the way that you're approaching all of it. I was hoping that I could do some targeted follow up with you and the relevant staff on
>
> - The NAS/SCC meeting (I can reach out directly to Elizabeth on this if you like – we've already been in touch about the contract).
>
> Non-Responsive
>
> How would you suggest we tackle these – in one meeting, or in a few shorter, more targeted meetings?
>
> Thanks!
>
> Kevin

Cc: steps-directors@ucdavis.edu[steps-directors@ucdavis.edu]; steps-students@ucdavis.edu[steps-students@ucdavis.edu]; steps-alumni@ucdavis.edu[steps-alumni@ucdavis.edu]
From: Paul W Gruber
Sent: Thur 4/30/2015 12:12:26 AM
Subject: STEPS Program Report: Jan-Mar 2015
STEPS Report Jan-March 2015.pdf

Dear consortium sponsors and affiliated experts,

On behalf of the STEPS team, I'm pleased to share with you our first quarterly report (attached) of the new STEPS 2015-2018 program. This detailed report summarizes many of our research and program accomplishments from January to March.

I'd like to call your attention to the **Publications and Reports**, pasted below. As a reminder, if you do not have subscription access to a journal article, you may request the article from us and we'll send it to you. As always, feel free to reach out to me or team members with questions or comments.

Title	**Author(s)**	**Publication Type** ***(Journal, if applicable)***
Comparison of Low-Carbon Pathways for California	Morrison, Geoffrey M., Sonia Yeh, Anthony R. Eggert, Christopher Yang, James Nelson, Ana Mileva, Josiah Johnston, Daniel M. Kammen, Jeffery Greenblatt, Max Wei, Christina Zapata, Raphael Isaac, Mark Z. Jacobson, David Roland-Holst, Ray Williams, John Weyant	Article (*Climatic Change*)
"Modal Shift of Passenger Transport in a TIMES Model: Application to Ireland and California," chapter in *Informing Energy and Climate Policies Using Energy Systems Models*	Daly, Hannah, Kalai Ramea, Alessandro Chiodi, Sonia Yeh,Maurizio Gargiulo , Brian Ó Gallachóir	Book chapter
Applications of Supercapacitors in Electric and Hybrid Vehicles	Burke, Andrew, Hengbing Zhao	Research Report

Analytic Tool to Support the Implementation of Electric Vehicle Programs	Burke, Andrew, Gustavo O. Collantes, Marshall Miller, Hengbing Zhao	Research Report
Do Biofuel Policies Seek to Cut Emissions by Cutting Food?	Searchinger, T., Robert Edwards, Declan Mulligan, R. Heimlich, Richard J. Plevin	Article *(Science)*
Exploring the Role of Natural Gas in U.S. Trucking	Jaffe, Amy Myers, Rosa Dominguez-Faus, Allen Lee, Kenneth B. Medlock III, Nathan C. Parker, Daniel Scheitrum, Andrew Burke, Hengbing Zhao, Yueyue Fan	Research Report
North American Resources and Natural Gas Supply to the State of California	Medlock III, Kenneth B.	White Paper/ report
Past and Future Land Use Impacts of Canadian Oil Sands and Greenhouse Gas Emissions	Yeh, Sonia, Anqi Zhao, Sean D. Hogan, Adam R. Brandt, Jacob G. Englander, David W. Beilman, Michael Q. Wang	Research Report
Carbon Accounting and Economic Model Uncertainty of Emissions from Biofuels-Induced Land Use Change	Plevin, Richard J., Jayson Beckman, Alla Golub, Julie Witcover	Article *(Environmental Science & Technology)*
Multi-Objective Regulations on Transportation Fuels: Comparing Renewable Fuel Mandates and Emission Standards	Rajagopal, Deepak, Richard J. Plevin, D. Zilberman, G. Hochman	Article *(Energy Economics)*
Electric Vehicle Fast Charger Planning for Metropolitan Planning Organizations: Adapting to Changing Markets and Vehicle Technology	Ji, Wei, Michael A. Nicholas, Gil Tal	Research Report *(Transportation Research Record)*
Achieving California's 80% Greenhouse Gas Reduction Target in 2050: Technology, Policy and Scenario Analysis Using CA-TIMES Energy Economic Systems Model	Yang, Christopher, Sonia Yeh, Saleh Zakerinia, Kalai Ramea, David L. McCollum	Article *(Energy Policy)*
China's Electric Car Frustration	Wan, Zheng, Daniel Sperling, Yunshi Wang	Article *(Transportation Research Part D)*

We look forward to seeing many of you on May 12 and 13 for our first symposium of the new STEPS 2015-2018 program.

Best regards,

Paul

Paul W. Gruber

Executive Director

NextSTEPS (Sustainable Transportation Energy Pathways)

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SUSTAINABLE TRANSPORTATION ENERGY PATHWAYS

An Institute of Transportation Studies Program

STEPS Program Report: January to March 2015

April 29, 2015

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Contents

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THIS QUARTER'S ACCOMPLISHMENTS

✓ Publications and Reports

STEPS team members authored and contributed to **13 publications and reports** this quarter. All STEPS publications are accessible at ITS publications.

Title	Author(s)	Publication Type *(Journal, if applicable)*
Comparison of Low-Carbon Pathways for California	Morrison, Geoffrey M., Sonia Yeh, Anthony R. Eggert, Christopher Yang, James Nelson, Ana Mileva, Josiah Johnston, Daniel M. Kammen, Jeffery Greenblatt, Max Wei, Christina Zapata, Raphael Isaac, Mark Z. Jacobson, David Roland-Holst, Ray Williams, John Weyant	Article (*Climatic Change*)
"Modal Shift of Passenger Transport in a TIMES Model: Application to Ireland and California," chapter in *Informing Energy and Climate Policies Using Energy Systems Models*	Daly, Hannah, Kalai Ramea, Alessandro Chiodi, Sonia Yeh,Maurizio Gargiulo, Brian Ó Gallachóir	Book chapter
Applications of Supercapacitors in Electric and Hybrid Vehicles	Burke, Andrew, Hengbing Zhao	Research Report
Analytic Tool to Support the Implementation of Electric Vehicle Programs	Burke, Andrew, Gustavo O. Collantes, Marshall Miller, Hengbing Zhao	Research Report
Do Biofuel Policies Seek to Cut Emissions by Cutting Food?	Searchinger, T., Robert Edwards, Declan Mulligan, R. Heimlich, Richard J. Plevin	Article *(Science)*
Exploring the Role of Natural Gas in U.S. Trucking	Jaffe, Amy Myers, Rosa Dominguez-Faus, Allen Lee, Kenneth B. Medlock III, Nathan C. Parker, Daniel Scheitrum, Andrew Burke, Hengbing Zhao, Yueyue Fan	Research Report
North American Resources and Natural Gas Supply to the State of California	Medlock III, Kenneth B.	White Paper/ report
Past and Future Land Use Impacts of Canadian Oil Sands and Greenhouse Gas Emissions	Yeh, Sonia, Anqi Zhao, Sean D. Hogan, Adam R. Brandt, Jacob G. Englander, David W. Beilman, Michael Q. Wang	Research Report
Carbon Accounting and Economic Model Uncertainty of Emissions from Biofuels-Induced Land Use Change	Plevin, Richard J., Jayson Beckman, Alla Golub, Julie Witcover	Article *(Environmental Science & Technology)*
Multi-Objective Regulations on Transportation Fuels: Comparing Renewable Fuel Mandates and Emission Standards	Rajagopal, Deepak, Richard J. Plevin, D. Zilberman, G. Hochman	Article *(Energy Economics)*
Electric Vehicle Fast Charger Planning for Metropolitan Planning	Ji, Wei, Michael A. Nicholas, Gil Tal	Research Report *(Transportation*

Organizations: Adapting to Changing Markets and Vehicle Technology		*Research Record)*
Achieving California's 80% Greenhouse Gas Reduction Target in 2050: Technology, Policy and Scenario Analysis Using CA-TIMES Energy Economic Systems Model	Yang, Christopher, Sonia Yeh, Saleh Zakerinia, Kalai Ramea, David L. McCollum	Article *(Energy Policy)*
China's Electric Car Frustration	Wan, Zheng, Daniel Sperling, Yunshi Wang	Article *(Transportation Research Part D)*

✓ Program Highlights

Research insights and event invitations were distributed, to help inform your planning and decision making:

Month	*Dissemination Activity*
January	NextSTEPS October-December 2014 Quarterly Report
January	Green Light Blog: Is a Natural Gas Trucking Corridor Feasible on California's Interstate 5?
February	Green Light Blog: Policy Drivers Creating a Perfect Storm for U.S. Energy Independence?
February	Exploring the Role of Natural Gas in U.S. Trucking White Paper released
February	North American Resources and Natural Gas Supply to the State of California White Paper released
March	Webinar: Exploring the Role of Natural Gas in U.S. Trucking
March	BP Energy Outlook 2035 –STEPS guest seminar by Mark Finley, General Manager, Global Energy Markets & U.S. Economics, BP
March	Critical Barriers to Commercialization of Emerging Alternative Fuel, Vehicle and Infrastructure Technologies (STEPS Assessment Meeting -- CA stakeholders invited)
Ongoing	Invitations to attend STEPS-relevant events in California and Washington, D.C. (e.g., TRB annual meeting, BP Energy Outlook 2035 seminar, Natural Gas webinars, STEPS 2030 Targets Workshop and Spring Symposium)

California Climate Policy Modeling Dialogue at UC Davis

On February 23, the California Climate Policy Modeling Dialogue was held at UC Davis, an event co-organized by STEPS researcher Sonia Yeh, Cliff Rechtschaffen of the governor's office, and Michael Gibbs of the California Air Resources Board. More than 100 people gathered, including representatives from state agencies involved in climate policy, legislative representatives, academics, industry, NGO leaders, climate policymakers, modelers and other stakeholders, to review the current status of greenhouse gas emissions (GHG) modeling for the California and examine pathways for achieving the state's climate goals. STEPS researcher Chris Yang presented the CA-TIMES: Energy System Model for California.

The discussion considered:

- achievable GHG emission reductions through 2030;

- scenarios for technologies and actions required economy-wide and from individual sectors that may enable deep reductions in state GHG emissions;
- costs and benefits of reducing emissions, including contributions to local air quality improvements; and
- potential aggregate and distributional impacts of GHG mitigation policy options on the State/regional economy.

Agenda and presentations from the February 2015 California Climate Policy Modeling Dialogue are here.

Exploring the Role of Natural Gas in U.S. Trucking

Our white paper, Exploring the Role of Natural Gas in U.S. Trucking, and the associated joint ITS-Davis/Rice University Baker Institute study North American Resources and Natural Gas Supply to the State of California, were released in February and the first of three webinars on natural gas was held in March. Earlier in February the paper was released for exclusive review by STEPS members with comments incorporated in the final version.

The second webinar "Environmental Assessment of Natural Gas in Transportation," was held on April 3rd and the third webinar, "North American Natural Gas Resources and Supply for CA," presented by Ken Medlock of Rice University is being scheduled.

STEPS hosted Assessment Meeting on "Critical Barriers to Commercialization of Emerging Alternative Fuel, Vehicle and Infrastructure Technologies"

On March 17th, the STEPS program hosted an all-day assessment meeting for select stakeholders in California who fund R&D and demonstrations of alternative fuel and vehicle technologies, especially related to AB118/AB8. Representatives from CEC, CARB, Caltrans, CALSTART, SCAQMD, San Joaquin Valley APCD, Governor's Office, regional business incubators and private investors shared:

- Specific emerging technology projects that are the most promising, why they are most promising, and what current barriers are preventing their successful commercialization.
- Specific emerging technology projects that have struggled to meet their objectives and why.
- What policies/regulations would aid commercialization?
- What commercialization strategies do you see for these emerging technologies?

The meeting provided an opportunity for an engaging discussion of the commercial and policy barriers facing the successful deployment of emerging alternative fuel, vehicle, and infrastructure technologies in California.

STEPS and the National Center for Sustainable Transportation have been tasked by the California Energy Commission (ARV-13-020) with planning and hosting three workshops with emerging technology stakeholders in the state to identify and address the obstacles to widespread adoption of alternative fuel, vehicle, and infrastructure emerging technologies in California. If you have interested in attending any/all of these workshops, contact Paul Gruber, pwgruber@ucdavis.edu:

Workshop #1 (July 13, 2015)	**Bio-fuels, bio-methane, bio-diesel** – production and marketing and renewable hydrogen from wind and solar PV
Workshop #2 (Sept. 18, 2015)	**Medium and heavy-duty trucks** for long-haul and ports - natural gas and H2 - alternative powertrains including fuel cells
Workshop #3 (Dec. 8, 2015)	**Light-duty ZEV technologies & infrastructure** – batteries, supercapacitors, smart charging, fuel cells, hydrogen infrastructure

✓ Media Wrap Up

Research and expertise by STEPS team members and affiliates at UC Davis are increasing being reported in the public domain by state, national, and international media. Some top stories, shared via print and online media, radio, and newsletters, include:

- Guest post: A driving force behind the Low Carbon Fuel Standard sees credit prices rising (Platts)
- Sacramento International Airport to power future operations with on-site solar farm (The California Aggie)
- Calif. Considers a plea for plug-in hybrids (Automotive News)
- California house of the future takes green to a higher level (The Washington Post)
- The Complete Business Case for Converting Street Parking Into Bike Lanes (The Atlantic – CityLab)
- California wins by collaborating with China on electric vehicle market (Sacramento Bee)
- China could pass US in electric-car market, expert says (China Daily)
- Will Tesla Ever Make Money? (Bloomberg Business)
- West Coast pact on climate action pulled into former Ore. governor's scandal (ClimateWire)
- Oil industry takes aim at California's war on carbon (Sacramento Bee)
- Study: natural gas heavy-duty trucking fleet could benefit economy, but has mixed environmental effects (Green Car Congress)
- Calif. utility sparks debate, proposing to install 25,000 charging stations to promote electric vehicles (ClimateWire)
- President Obama's budget to boost funding for California transportation projects (NPR KPCC Take Two)
- Democrats: Low-carbon still has green light despite Hayes questions (Bend Bulletin)
- Oil Geopolitics: The Changing Equation (Capital Public Radio)
- Even At $30 A Barrel, Saudis Are Still Making Money On Oil (NPR)
- Oil Prices Probably Won't Keep Gains Made After Death of Saudi King (Bloomberg Business)
- Myers Jaffe available to discuss future of fossil fuels at World Economic Forum (UC Davis News)
- Preserved Under Fiberglass Domes, a Counterculture Spirit Thrives (New York Times)
- LAURELS: Distinguished Emeritus and Dickson Professorships (UC Davis Dateline)
- Environment, logic taken for a ride by surging SUV sales (Sacramento Bee)
- Transportation Research Board has new chairman (Today's Trucking)
- Engineering for the Future (Huffington Post)
- UC Davis Professor Leading U.S. Transportation Research in 2015 (Techwire)
- The Bloomberg Advantage: Retail Show, Oil and Electric Cars (Bloomberg Radio)
- Cutting oil use by 50 percent difficult but doable, experts say (SF Chronicle)
- What California Gov. Jerry Brown's Ambitious Green Energy Plan Means for You (Takepart)
- 2015 Tech Prediction: What's Down The Road For Uber? (Silicon Beat)

Twitter: @ITS_UCDavis
Facebook: www.facebook.com/ITSUCDavis

✓ Blogs, Briefings and Articles

21st Century Energy Markets: How the Changing Dynamics of World Energy Markets Impact our Economy and Energy Security
Congressional testimony by Amy Jaffe. Read more here… / Watch here…

ITS-Davis GreenLight Blog shares and discusses some of our latest research:

- **Is a Natural Gas Trucking Corridor Feasible on California's Interstate 5?**
  By Amy Myers Jaffe | 02/18/2015

Switching from diesel fuel to natural gas may hold advantages for the U.S. heavy duty trucking fleet, and California's high volume I-5 truck corridor would be a commercially optimum location to launch first investments, according to, "Exploring the Role of Natural Gas in U.S. Trucking," the new white paper released today from the Institute of Transportation Studies at UC Davis and Rice University. Such a network could help the state enable a faster transition to renewable natural gas, biogas and waste-to-energy pathways. But it would require significant policy intervention to reap climate change advantages, our research found.

- **Policy Drivers Creating a Perfect Storm for U.S. Energy Independence?**
  By Amy Myers Jaffe | 01/07/2015

Oil prices have hit their cheapest level since the height of the 2009 recession, and U.S. oil imports are at a 16-year low. As a result, policymakers across the country will be rethinking energy strategies, including the new U.S. Congress and California Governor Jerry Brown. Governor Brown suggested in his inaugural speech on January 5 that California should try to reduce current petroleum use in cars and trucks by up to 50 percent by 2030 as part of the state's climate action plan, with the Air Resources Board outlining California's policies to meet this target. President Barack Obama is also expected early this year to announce a set of additional climate policies.

STEPS Seminar Spotlights Global Energy Future with BP Outlook 2035

The STEPS program hosted a special seminar on March 2nd with Mark Finley, General Manager, Global Energy Markets & U.S. Economics, BP, presenting BP Energy Outlook 2035.

ZE MAP Actionable Science Webinar 1 Available Online

The UC Davis Policy Institute's Zero Emission MAP Initiative presented the first of its new "ZEV Actionable Science" webinar series in February. MIT doctoral candidate Stephen Zoepf presented his webinar titled "Energy use and charging behavior in a large plug-in vehicle fleet." The webinar and slides are now available at this link.

The Future of Sustainable Transportation

Our colleagues with the National Center for Sustainable Transportation and STEPS team members held a briefing on Capitol Hill in January. Read more…

Hydraulic Fracturing In California: A Landmark New Law with Unresolved Questions

Last quarter, we missed reporting our UC Davis colleagues' report on fracking. Read more…

Alt Fuels and Vehicles in California

In February we submitted the two remaining chapters of the draft final report for the Alternative and Renewable Fuel and Vehicle Technology Program (ARFVTP) California Energy Commission contract. The nine research chapters included in this contract represent significant California case studies and have added great value to our white papers. The final report is expected to be released by summer 2015.

CEC Contract Tasks and Leaders		
Task	***Title***	***Leaders***
1	CEC Agreement Management	**Paul Gruber**
2	Transition Scenarios for Alternative Fuels & Vehicles in California	**Joan Ogden**

3	Consumer Behavior & Vehicle Choice: Longitudinal Tracking Study	**Ken Kurani**
4	Biofuel Investment Strategies	**Lew Fulton**, Nathan Parker
5	Best Policy and Incentive Strategies	**Sonia Yeh**, Anthony Eggert, Dan Sperling
6	Fuel Availability and Choice	**Ken Kurani**
7	Technology Training for Transportation Division Staff	**Joan Ogden,** Paul Gruber
8	Low Carbon Options for Non-Light Duty Vehicle Subsectors	**Lew Fulton**
9	Detailed Assessment of Natural Gas as a Transportation Fuel	**Amy Jaffe**, Rosa Dominguez
10	Biorefinery Case Studies for Biofuels Production in California	**Steve Kaffka,** Nathan Parker
11	Plug-in Hybrid & Electric Vehicle Dealership Study	**Tom Turrentine**, Eric Cahill

✓ Students' Research Progress

Below we present a sampling of preliminary research findings, meant to spur discussion on these topics. The process for most of these studies is to hone the research findings for presentations and posters at STEPS symposia and, ultimately, for publication in peer-reviewed journals.

Modeling Grid Impacts of PEV Deployment and Demand-Side Management: Case Study of Sacramento Municipal Utility District

-- Kadir Bedir, Ph.D. Candidate, TTP program; Dr. Joan Ogden

Energy-planning agencies in California consider PEV-based grid services as a potential way to integrate renewables into the grid, and to increase economic value in PEV ownership. However, stakeholders currently do not have enough experience to understand technical and economic impacts of the PEV load on the grid, which is highly dependent on the future PEV market, and regional characteristics of the grid operations. This study demonstrates a stochastic method of assessment for widespread PEV deployment on the grid, with and without considering demand-side management (DSM). The Sacramento Municipal Utility District (SMUD) is chosen as being a mid-size utility company, which provides DSM programs for the PEV consumers in their region. Monte-Carlo simulations have been performed to spread high numbers of PEVs in the region based on the tract-level vehicle ownership data from U.S. Census. Consumer adoption of various DSM scenarios is modeled by algorithmic optimization.

The preliminary results show that the deployment of PEVs in Sacramento has a significant impact on the peak demand, and overloading distribution transformers, while having a small impact on the total annual energy.In a high PEV adoption scenario, the annual peak demand of electricity in SMUD region increased by 78 MWs. Providing dynamic-pricing signals to the PEV drivers, however, can greatly decrease these impacts based on the season of the year, and dynamic-pricing signals.

COCHIN-TIMES model

-- Kalai Ramea, Ph.D. Candidate, TTP program; Dr. Sonia Yeh

Cochin-TIMES is a light-duty vehicle model that integrates optimization and consumer choice frameworks. It includes consumer choice characteristics in the linear programming framework. A disutility cost is given in addition to vehicle cost and fuel cost, demand is disaggregated, and each consumer group's perception towards the vehicle technology is recorded in terms of disutility cost. There are also different components of disutility costs to capture the various characteristics of consumers and vehicles. The following tasks were completed this past quarter:

a) Additional consumer groups were added to the model, now the model has 36 groups on the demand side
b) US and California COCHIN models were developed

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c) Sensitivity analysis of different 'clones' of consumer groups and step-by-step results of COCHIN model were generated
d) Policy analysis on vehicle subsidies and infrastructure investments were performed based on a consumer choice model in order to meet the ZEV action plan targets. It was also observed that it is quite challenging to meet the current action plan goal of reaching 1.5 ZEVs in 2025 in the business as usual scenario. Sensitivity analysis was also performed with comparisons between CA and the rest of the nation.

Conference Paper: Patents and Biofuels: Using Natural Language Processing to Assess Biofuel Innovations.

-- Jeff Kessler, TTP PhD Candidate; Prof. Dan Sperling. Transportation Research Board 94th Annual Meeting. Issue 15-0208 (link)

Summary: The Renewable Fuel Standard, seems to have had limited impact on promoting innovation and patenting activity for 2nd generation fuels, but may have played a large role in encouraging the proliferation of entrepreneurial firms into the market.

Biofuel Technology Innovation Analysis:

There is good evidence to support the idea that policy, like the Low Carbon Fuel Standard in California, is encouraging technology innovation for biofuels. Innovation System Analysis shows that this significant innovation activity happening in California is almost entirely for 1st generation biofuels, and that 2nd generation biofuels are no better supported in California than in the rest of the U.S.

Mitigation of Distributed Generation Impact Study: energy storage, demand response, smart inverter planning

-- Zhaomiao Guo, CEE PhD Candidate; Prof. Yueyue Fan

Preliminary findings:

- In order to be economically competitive, storage costs need to be cut to half;
- Smart inverters are relatively cheaper than storage to curtail solar, which means we would prefer to pay customers for unwanted solar rather than storing them;
- Study of mitigation technologies individually may overestimate the value of particular technologies; integrating multiple potential technologies is necessary.

The role of residential and commercial sectors in achieving California's 2050 emissions reduction target using CA-TIMES

-- Saleh Zakerinia, TTP MS student; Dr. Sonia Yeh

Results show that significant efficiency improvement, electrification and electricity decarbonization are the most important factors in reducing emissions from these sectors. We also show that demand reduction can play a significant role in reducing the cost of mitigation in these sectors.

We also started a new project on effects of technology forcing policies, which tries to understand how policies can increase the penetration of alternative vehicles using CA-TIMES. Moreover, in another project we investigate the cost-effectiveness of mitigation options. In this project, we calculate the marginal abatement cost curves for the entire energy sector of California using the results from CA-TIMES and study how different policies might affect the cost-effectiveness of different technologies in achieving California's 2050 emissions reduction target as well as a 2030 possible target.

"Using (Big) Data to Improve Transportation Projections: A Case Study in India

-- Anqi Zhao, TTP PhD student; Dr. Sonia Yeh

Initiatives to plan for sustainable transportation and identify infrastructure challenges require access to meaningful, dynamic, and timely data sets regarding urban development and transportation system. Yet, there are key information gaps in developing countries like India. The proposed thesis addresses these challenges by

leveraging multiple urban data sources, ranging from conventional data source such as socioeconomic data and satellite images to emerging "urban big data" sources such as geo-tagged social media data, citizen-created maps, and real-time traffic data. The big challenge is the innovative and effective integration of available urban data sources together to capture urban development and transport in fast-growing Indian cities.

This research can contribute to sustainability planning and research from three angles. First, the research is important to further understanding of how Indian cities operate and grow. Second, the findings emphasize the role that the combination of several urban data sources can play in understanding urban development and transport and the strengths of big data sources to complement the traditional data sources. Third, the findings provide useful guides and implications to policymakers charged with planning sustainable cities.

This thesis is composed of three proposed papers. Paper 1 compares urban growth and population growth trends of selected Indian urban agglomerations, from 1981-2011. I also reviewed both city plans and mobility plans to understand the impacts of transport decisions and land use decisions on these trends. In Paper 2, the proposed research focuses on spatial and temporal characteristics of urban traffic congestion in four Indian cities using Google real-time traffic information. Finally, in Paper 3, I study urban mobility pattern and sentiment by analyzing geotagged Twitter data. Remote sensing images capture changes of urban physical environment, while new social media data can help detect urban social attributes. More precisely, I aim at answering the following question in this paper: Can we aggregate individuals' or vehicles' trajectories to obtain traffic flows between places? Can social media data be a good indicator to show sentiment about traffic?

Air Quality Impacts of Alternative Fuels and Low Carbon Futures

-- Christina Zapata, CEE PhD candidate; Prof. Mike Kleeman, Prof. Joan Ogden

Several emissions estimations were developed for non-road transportation modes such as aviation, marine, and off-road. Non anthropogenic or natural emission sources were also created or determined for dust and biogenic sources. Corrections were made to other emission sources including petroleum supply, hydrogen production, reduction in dairy emissions with the use of manure digesters, on-road non-conventional emissions estimation. Several California and national emission standards and regulations were also deployed, including the Tier4 off-road diesel standards, the Sulfur content fuel reductions for marine vessels and the increase of shoreline power for hotelling ocean vessels. Improvements were also made to processing the raw emissions to be read by the airshed model. Several errors were also fixed related to averaging the wind fields before formatting it to the input format read by the airshed model. Also several errors were corrected in the air quality model to read boundary conditions correctly for the San Joaquin Valley and South Coast domains, and additional initial condition offsets corrections for other inputs such as land use files. The airshed model was also made more robust to ensure domain compatibility of all the input files read including the region file of the nested domains, the emissions files, and meteorology files.

Preliminary Results (Results *may change. Need to verify significance and robustness of methodology and calculations*): Changes in emissions provide the greatest opportunity for air pollution reduction. As certain sources that are already fairly clean with respect to criteria pollutants using aftertreatment devices and are expected to become more zero-emitting through the use of electrification and renewables, the increase growth and share of less regulated emission sources become larger contributors of pollution. Many of these sources include less historically regulated transportation modes such as marine and off-road equipment. The significance of siting of biofuel and hydrogen production facilities becomes significant if these fuels expected to be consumed in large volumes, and hence produced in large volumes, and thus potentially high emitters. Due to the complexity of mix of VOCs and NOx precursors and sources contributing to ozone, the most likely way to ensure ozone reduction is the reduction of both NOx and VOCs.

Estimating cost of liquid hydrogen as aviation fuel

-- Guozhen (Allen) Li, TTP MS student; Dr. Lew Fulton

Liquid hydrogen (LH2) has been proposed as a long-term substitute for traditional petroleum-based aviation fuel. LH2 is potentially attractive in a low carbon future because it can be made with essentially zero net carbon emissions from renewables such as wind and solar, or from fossil sources with carbon capture and sequestration (CCS). Additionally, the use of LH2 can relieve dependence on crude oil and reduce environmental impact from air traffic. Technology assessments indicate that developing hydrogen-powered aircraft is not an insurmountable hurdle given near-term aero technologies. However, the issues regarding aviation hydrogen fuel supply system and the operational cost effectiveness remain relatively unexplored. This article analyzes a range of possible scenarios for LH2 production and distribution, based on air traffic demand at San Francisco International Airport (SFO). We adapted the United States Department of Energy's Hydrogen Analysis Model (H2A Model) to estimate the cost of LH2, based on technologies available today, to meet the forecasted air traffic demand in the time frame of 2035. We estimate that with near-term technologies, large-scale mass produced LH2 would cost $3.03/kg (USD 2005) at the refueling pumps if produced from steam methane reforming (SMR), or $4.74/kg if produced from electrolysis (given $0.06/kWh electricity price). These costs are 21%-88% higher than jet fuel prices for predicted for 2035, on a per-unit-energy basis. In addition to this relatively high cost, supplying LH2 at an airport-level scale would also create difficult challenges for the electricity supply and airport land use.

PEV Dealer Study
-- Eric Cahill, TTP PhD candidate; Dr. Tom Turrentine; Prof. Dan Sperling
We recently posted an updated presentation that includes the results of this latest analysis on the Dealer Study page of the PH&EV Center website.

✓ Achievements

Cummins and Daimler Trucks join STEPS program
STEPS welcomes two new members into the program. Along with Westport, these two new members will add significantly to our growing medium and heavy duty research track. STEPS Board members indicated this was an important new direction for us at the advisory board meeting in December. Other medium and heavy duty trucking companies are being pursued, along with major fleet operators, to fully develop ourresearch in the "non-LDV" areas.

New Natural Gas Infrastructure Project Awarded by ARB
Amy Jaffe and team have secured an award from the ARB, for a project entitled, "Potential to Build Current Natural Gas Infrastructure to Accommodate the Future Conversion to Near-Zero Transportation Technology." The award is co-funding for the National Center for Sustainable Transportation. The goal of this project is to investigate how the near-term development of natural gas infrastructure, in the medium and heavy-duty sector, can be implemented to include technology that can best facilitate the long-term conversion to near-zero technology.

New graduates
The STEPS team congratulates Yu Pei, who completed her MS in Transportation, Technology and Policy in December and Allen Lee, who completed his MS in Civil and Environmental Engineering in March and is now interning with BMW.

Former CA Assemblymember Nancy Skinner Joins UC Davis as Senior Policy Fellow on Energy and Transportation Policy
Former California state legislator Nancy Skinner is bringing her expertise on energy and climate policy to UC Davis, working with energy, transportation, and policy centers in West Village. The three-term state assemblymember will serve as a senior policy fellow for the UC energy and transportation programs, including

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the Energy Efficiency Center, Institute of Transportation Studies, and the Policy Institute for Energy, Environment and the Economy. Read more…

ITS-Davis Director Dan Sperling Appointed 2015 Chair of Prestigious Transportation Research Board
Dan Sperling, director of the UC Davis Institute of Transportation Studies (ITS-Davis), has been appointed the 2015 chair of the Transportation Research Board's Executive Committee, which provides independent scientific advice to the nation on transportation issues. The appointment was announced at the 94th annual meeting of the Transportation Research Board, held January 11-15 in Washington, D.C. and attended by 12,000 transportation professionals from across the United States and abroad. The Transportation Research Board is a major division of the National Research Council, the private, nonprofit institution that serves as the operating arm of the National Academy of Sciences and the National Academy of Engineering and as an independent adviser to the U.S. government. Read more…

Two UC Davis Students Awarded Prestigious Women's Transportation Seminar Scholarships
Women's Transportation Seminar (WTS) Sacramento, an organization dedicated to furthering the careers of women in the transportation industry, awarded two UC Davis students with scholarships at the annual WTS-Sacramento Awards and Scholarship dinner. The event recognizes the accomplishments of women in the transportation industry, while also supporting promising students through scholarships and awards. Read more…

Professor for the Future Fellowship awarded
We are pleased to share that Jeff Kessler, TTP PhD candidate was awarded a fellowship through the *Professors for the Future* program. Learn more about the program…

The impact of the economic crisis and policy actions on GHG emissions from road transport in Spain
STEPS was pleased to host Natalia Sobrino, PhD candidate at Centro de Investigación del Transporte Transport Research Centre Universidad Politécnica de Madrid, this quarter. Read more…

NEXT QUARTER'S TASKS, DELIVERABLES and DUE DATES:

✓ Major Papers & Reports

Draft Released: "Strategies for Transitioning to Low-carbon Emission Trucks in the United States"
In April, the STEPS and National Center for Sustainable Transportation (NCST) draft white paper, "Strategies for Transitioning to Low-carbon Emission Trucks in the United States" was released for exclusive review by STEPS members for comments and feedback. STEPS and NCST will host a webinar on April 30, release a revised draft version at the May 12-13 STEPS symposium, and after careful review release to the public this summer.

The final white papers synthesizing results on **CCS** and **Integrative Scenarios for Low Carbon, Sustainable Futures** will be released this year. The revised schedule and status of draft paper releases and public webinars is:

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SCHEDULE of NextSTEPS/STEPS WHITE PAPERS and REPORTS				
Draft Release Date to Consortium	**Public Webinar date**	**White Paper**	**Leaders**	**Status**
4/23/2014	5/16/2014	Biofuels	**Lew Fulton**, Nathan Parker, Geoff Morrison, Julie Witcover, Dan Sperling	Paper released and webinar completed.
5/29/2014	6/19/2014	Electric Vehicles (PEV Market Update)	**Tom Turrentine**, Ken Kurani	PEV Market Report released and webinar and white paper completed; additional white paper synthesizing PEV research results is under development
exec summ released 5/29/2014; draft white paper released 7/9/2014	7/30/2014	Hydrogen	**Joan Ogden**, Chris Yang, Mike Nicholas, Lew Fulton	Paper released and webinar completed.
2/18/2015	Three part series: 3/11/2015, 4/2/2015 and TBA	Natural Gas	**Amy Jaffe**, Rosa Dominquez-Faus	Paper released and 2/3 webinars completed.
draft white paper circulated for comments 4/13/2015	4/30/2015	**Non-LDV Subsectors**	**Lew Fulton**, Marshall Miller	Draft paper circulated for comments and webinar scheduled for 4/30.
2015	2015	**CCS**	**Joan Ogden**	Draft paper underway.
2015	2015	**Integrative Scenarios for Low Carbon, Sustainable Futures**	**Joan Ogden, Lew Fulton, Sonia Yeh, Chris Yang**	Draft paper underway, being reviewed internally.

✓ Save the Dates

- **STEPS 2030 Targets Workshop and Spring Symposium**: May 12-13, 2015 at UC Davis
- **STEPS Advisory Board Meeting:** August 18, 2015, preceding the August 18-21 Asilomar Conference, in Pacific Grove, CA
- **STEPS3 Fall Symposium**: December 10-11, 2015 at UC Davis

Invite only (let Paul Gruber know if you are interested, pwgruber@ucdavis.edu):

Workshop #1 (July 13, 2015)	**Bio-fuels, bio-methane, bio-diesel** – production and marketing and renewable hydrogen from wind and solar PV
Workshop #2 (Sept. 18, 2015)	**Medium and heavy-duty trucks** for long-haul and ports - natural gas and H2 - alternative powertrains including fuel cells
Workshop #3 (Dec. 8, 2015)	**Light-duty ZEV technologies & infrastructure** – batteries, supercapacitors, smart charging, fuel cells, hydrogen infrastructure

***

Thank you for your support and engagement in research of sustainable transportation energy pathways.

To: Newbold, Steve[Newbold.Steve@epa.gov]; Marten, Alex[Marten.Alex@epa.gov]; Griffiths, Charles[Griffiths.Charles@epa.gov]; Wolverton, Ann[Wolverton.Ann@epa.gov]; Kopits, Elizabeth[Kopits.Elizabeth@epa.gov]
From: McGartland, Al
Sent: Mon 4/13/2015 9:15:30 AM
Subject: Fwd: Pricing Climate Risk Mitigation
Pizer et al Science 2014.pdf
ATT00001.htm
Aldy Nature Climate Change 2015.pdf
ATT00002.htm

Sorry for any duplication.

Sent from my iPhone

Begin forwarded message:

From: "Aldy, Joseph" <Joseph_Aldy@hks.harvard.edu>
To: "McGartland, Al" <McGartland.Al@epa.gov>
Subject: Pricing Climate Risk Mitigation

Al,

I hope you are well. I have recently published a commentary in Nature Climate Change titled "Pricing Climate Risk Mitigation" (see attached). In this commentary, I discuss why adaptation and geoengineering should be considered in the estimation of the social cost of carbon. In particular, I suggest that "adaptation response functions" and "geoengineering response functions" should be incorporated in integrated assessment models focused on generating social cost of carbon estimates. I also describe a research agenda that could inform such an effort. I would welcome any thoughts you may have on this. In the commentary, I also cite the recent Science policy forum article that I co-authored with Billy Pizer and others, which I have attached for your reference.

Best,

Joe

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COMMENTARY:

Pricing climate risk mitigation

Joseph E. Aldy

Adaptation and geoengineering responses to climate change should be taken into account when estimating the social cost of carbon.

At the September 2014 United Nations Climate Summit, 73 countries and more than 1,000 companies advocated pricing carbon[1]. Economists have long called for pricing carbon to reflect the social damages associated with the impacts of carbon dioxide emissions on the global climate[2,3]. Such an approach generally reflects the polluter pays principle — as elaborated in the 1992 Rio declaration on environment and development, with its emphasis on the use of economic instruments to internalize environmental costs[4]. Scholars have also called for the organization of international negotiations around agreement on a carbon price to provide the basis for emission commitments[5,6].

The meaning of carbon pricing

For some policymakers, setting a price on carbon that reflects the cost of carbon pollution can inform the 'objective' of climate policy. For example, the US government uses an estimate of the social cost of carbon (SCC) — the present value of monetized damages associated with an incremental ton of carbon dioxide emissions — to evaluate standards for fuel economy, appliance efficiency and carbon emissions[7]. As some laws require regulations to reflect a weighting of benefits and costs, the application of the SCC could determine the ambition of energy and climate policies.

For other policymakers, pricing carbon is an 'instrument' of climate policy — such as carbon dioxide cap-and-trade programmes or a carbon tax. For example, the European Union emissions trading scheme and the British Columbia carbon tax impose a price that carbon dioxide-emitters must bear. Of course, these two interpretations can be mutually reinforcing. In a benefit–cost framework, a policy that maximizes net social benefits would equate the SCC with the price borne by emitters under a tax or cap-and-trade instrument[8].

Whether the SCC determines the objective of policy, informs the design of a pricing instrument, or serves as a focal point in international negotiations, it will play an important role in the future of climate change policy. The social damages of carbon emissions will depend on the impacts of a warming world, such as sea-level rise, extreme weather events and changes in agricultural productivity, as well as potential catastrophic harms, migration, conflict and so on[9]. The SCC will also vary with alternative efforts to mitigate climate change risks, such as adaptation and geoengineering. Thus, it is important to conceptualize the SCC in the context of the full suite of risk management policies for climate change.

Managing risks posed by climate change

Policymakers, individuals and businesses can use three general approaches to mitigate the risks posed by climate change. First, they can halt the atmospheric accumulation of greenhouse gases, thereby preventing the problem through emission abatement. Second, they can avoid some climate change impacts by making investments in adaptation and resilience. Third, they can attempt to 'fix' the problem through geoengineering, such as solar radiation management strategies.

This multipronged approach to mitigating climate risk has emerged only recently in the debate over climate change policy. In the 1990s, international and domestic climate change policy focused almost exclusively on emission abatement. In the early 2000s, adaptation joined emission abatement in multilateral negotiations as well as development policy. In recent years, scholars have raised the prospect of geoengineering paired with emission abatement to avoid potentially catastrophic climate change[10–12]. Putting a price on carbon for emission abatement that fails to account for adaptation and geoengineering risks could leave too few resources for these options, which have potentially high returns in reducing climate change damages.

Role of adaptation and geoengineering

Pricing carbon within a comprehensive risk management framework requires continued work and advances in our understanding of climate change damages. Scholars from an array of disciplines have raised questions about the damage functions in the integrated assessment models that generate SCC estimates[9,13,14]. Improving the knowledge base on climate change impacts is a necessary foundation for evaluating the risk mitigation impacts of emission abatement, adaptation and geoengineering.

The status quo integrated assessment model approach produces an estimate of SCC without consideration of geoengineering and typically with incomplete or ad hoc attempts to represent adaptation [15]. Of the more than 400,000 SCC estimates produced by the US government in its 2013 report[15], 160 scenarios had a SCC in excess of US$1,000 per ton — or nearly US$10,000 in annual climate damages per US household — for its residential energy consumption. It is difficult to imagine that if the world were in such a dire state there would be no increase in adaptation investment or geoengineering deployment to offset at least some of these impacts.

Many individuals and businesses have strong incentives to mitigate their exposure to risks related to climate change. If the impacts of climate change become more severe, then they will increase their private adaptation investments. Moreover, governments are likely to increase outlays for resilience and adaptation if climate risks become more pronounced.

Adaptation will not fully offset the increase in damages, but it is likely to offset some climate change risk. As a result, the integrated assessment framework for evaluating the damages of an incremental emission of carbon dioxide should be expanded to include an 'adaptation response function'. Such a function (or system of functions) would represent how adaptation actions by governments and private agents respond to climate change, how adaptation affects the residual damages associated with another ton of carbon dioxide in the air, and how much this adaptation costs. This adaptation response

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function would result in lower monetized damages — because adaptation reduces the impacts of a changing climate — and an opportunity cost for these adaptation investments. If adaptation investments occur only when their returns (benefits of climate risk reduction) exceed their costs, then on net this adaptation function approach would result in a lower SCC than the status quo approach. If private agents, however, make adaptation investments that are privately welfare-improving, but impose local negative externalities (for example, damming a waterway), then the SCC could increase when accounting for adaptation response.

Similarly, a 'geoengineering response function' could be incorporated into integrated assessment models. Such a function would be likely to focus on state behaviour and, possibly, multilateral coordination. This response function could represent a future multilateral governance regime, especially if such a regime provided clear guidance on the use of geoengineering. Alternatively, the response function could model the incentives and behaviour of various countries likely to react to adverse climate impacts through unilateral geoengineering actions. Just as in the case of adaptation response, a geoengineering response would be likely to reduce some climate risks (for example, temperature-related impacts) at the cost of designing and implementing the geoengineering actions. It is important to recognize that these costs would include those associated with launching the geoengineering solution (for example, injecting reflective particles into the stratosphere) as well as possible unintended side effects. Based on the first-order effects, accounting for geoengineering response would be likely to reduce the SCC — again, through lower impacts net of the direct cost of implementing geoengineering — but the unintended side effects may increase social losses and could potentially offset the social gains.

Constructing such response functions requires, at a minimum, research on three dimensions of the problem. First, greater spatial and temporal resolution in estimating impacts can inform the consideration of adaptation and the incentives for any given state to launch geoengineering. Second, the construction of such response functions should explicitly enable uncertainty analysis. Just as there are uncertainties in how emissions translate into impacts, meaningful uncertainties characterize the form, timing and efficacy of adaptation and geoengineering responses. Third, these functions could inform a richer application of game theory, drawing from international relations and economics, to understand the likely reactions of countries to a changing climate and the prospects for building a credible international climate policy architecture. As the incentives for free-riding differ dramatically across these three general approaches[16], explicit modelling of behaviour may be important in constructing the response functions.

Policy implications

A conventional economic approach to this kind of risk management problem would call for evaluating the returns (say, in reduced damages) associated with incremental investments along each of these three approaches. A policy that maximizes the risk reduction for a given expenditure of resources would equate the marginal return on emission abatement with the marginal return on adaptation, and with the marginal return on geoengineering. This is simply an extension of the same cost-effectiveness analysis that underlies the case for putting a common price on carbon across all emission sources to maximize emission reductions for a given expenditure of resources on abatement. Even if there is no explicit policy effort to equate the marginal returns with actions along these three approaches, the avoided damages associated with emission abatement are likely to be affected by adaptation and geoengineering responses that could occur in the future.

The use of a SCC enhances the transparency of public decision-making and can facilitate the identification of opportunities to mitigate climate change risks. The failure to meaningfully slow the growth in global greenhouse-gas emissions in recent decades suggests that driving emission abatement through carbon pricing is important, but only part of the risk management portfolio. There will be hard decisions in the future. Policymakers will need rigorous tools that account for all available options for the risk management of climate change to inform these decisions. ❐

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ENVIRONMENTAL ECONOMICS

Using and improving the social cost of carbon

Regular, institutionalized updating and review are essential

By **William Pizer,[1,2]*† Matthew Adler,[1] Joseph Aldy,[2,3] David Anthoff,[4] Maureen Cropper,[2,5] Kenneth Gillingham,[6] Michael Greenstone,[7] Brian Murray,[1] Richard Newell,[1,2] Richard Richels,[8] Arden Rowell,[9] Stephanie Waldhoff,[10] Jonathan Wiener[1,2]**

The social cost of carbon (SCC) is a crucial tool for economic analysis of climate policies. The SCC estimates the dollar value of reduced climate change damages associated with a one-metric-ton reduction in carbon dioxide (CO_2) emissions. Although the conceptual basis, challenges, and merits of the SCC are well established, its use in government cost-benefit analysis (CBA) is relatively new. In light of challenges in constructing the SCC, its newness in government regulation, and the importance of updating, we propose an institutional process for regular SCC review and revision when used in government policy-making and suggest how scientists might contribute to improved SCC estimates.

POLICY

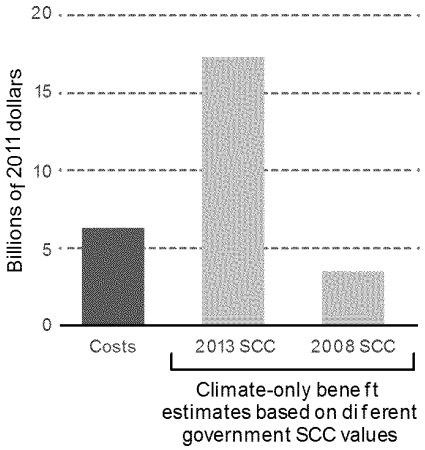
Although regulations issued by U.S. federal agencies have been subject to CBA for four decades, those analyses largely ignored economic benefits of carbon reduction until a federal court held in 2008 that carbon emission reductions have nonzero value. After a brief period during which different U.S. agencies used different SCC numbers, an interagency working group established a single set of government-wide values in 2009 and 2010, with an update in 2013 (*1*).

Such updates arise because the science, impact estimates, and socioeconomic models used to develop the SCC continue to evolve, as do expert opinions about how it should be synthesized. The results for CBA are consequential (see the graph). Using the most recent central value of interagency SCC estimates, a proposed U.S. rule on emissions from existing power plants would pass a CBA on climate benefits alone (*2*); using the central value SCC from a single agency in 2008 (*3*), it would not.

Estimating the SCC in a particular year, say 2015, involves four steps: (i) projecting a future path of global greenhouse gas (GHG) emissions; (ii) translating this emissions path, along with an alternative that adds 1 ton in 2015, into alternate scenarios of climate change; (iii) estimating physical impacts of these climate changes on humans and ecosystems; and (iv) monetizing these impacts and discounting future monetary damages back to 2015. The SCC is the difference in damage valuations with and without the extra ton of CO_2 in 2015.

Integrated assessment models [IAMs; e.g., DICE (*4*), FUND (*5*), and PAGE (*6*)], perform all four steps. Underlying step (i) are assumptions about future climate change policies and their effects on GHG emissions and about population, GDP growth, and technology. In step (ii), a simplified representation of the climate system translates emissions to metrics of climate change (e.g., change in global average temperature). Steps (iii) and (iv) require a damage function that relates climate change metrics to climate impacts and to valuations. Valuation of impacts often aggregates and/or extrapolates detailed climate impact studies and relies on population and economic assumptions from step (i) to project the level of human and economic activity exposed to these impacts in the future.

Costs and benefits of emissions reductions



Benefits of regulations vary. Estimated costs and climate change benefits of emission reductions in 2020 from proposed U.S. power plant regulations using 2008 (*3*) and 2013 (*2*) government SCC estimates. Estimates from table 18 in (*2*) using a 3% discount rate averaged over state and regional approaches. SCC estimate from table V-3 in (*3*), rising 2.4% per year to $8.67 in 2020, multiplied by avoided emissions estimates averaged over state and regional approaches from table 10 in (*2*), and inflation adjusted using the implicit GDP price index from the U.S. Bureau of Economic Analysis.

DIFFICULT CHOICES. Constructing an SCC for government CBA requires specific choices, beginning with the selection of which IAMs to include. Models vary in terms of breadth of use, degree of public access and available peer review, and incorporation of latest scientific results. New IAMs may emerge. How should a government select among models? Should selection evolve over time? Should models be weighted? If so, how?

Next, one must choose what, if any, assumptions to harmonize across models. Such assumptions may be important for consistency between the SCC and other elements of a government CBA, to reflect important uncertainties, or to address possibly outdated assumptions.

This harmonization requires more tough choices. For example, the SCC will measure incremental policy benefits relative to a baseline or range of baselines, which must be explicitly selected. One must decide whether emissions are forecast on the basis of an ambitious climate policy (such as the scenario in which polluters are already forced to pay the estimated SCC), a scenario where only policies already on the books remain in place, or something in between.

There are also credible differences on analytic and ethical grounds regarding the appropriate discount rate. Previous government guidance for CBA suggested discount rates of 3 and 7% for most projects, with possibly lower rates for phenomena (like climate change) with important intergenerational effects (*7*). Such differences have enormous implications; federal SCC estimates tripled as the discount rate changes from 5 to 3% (*1*). For practical CBA, it is important to have distinct SCC estimates for different discount rates that can be paired with cost estimates based on a particular discount rate(s).

Each IAM will have its own internal discount rate determined by model parameters and socioeconomic forecasts. Low discount rates typically follow from low economic growth (*8*), and economic growth is tied to climate impacts. Given this connection, how problematic is it to impose a discount rate in the SCC that is different from the rate used within the IAM itself?

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Should socioeconomic scenarios in the IAM be made consistent with the selected SCC discount rate, or vice-versa?

Finally, one must choose how much weight to give to climate change impacts outside the jurisdiction considering the SCC. In the United States, some have questioned the legality of using global SCC estimates (*9*). Unless a relevant statute clearly requires otherwise, the President and agencies have latitude to choose between domestic and global SCC values for regulatory analysis [including the authority to interpret silent or ambiguous statutes under the Chevron doctrine (*10*)]. Key U.S. statutes (e.g., Clean Air Act and National Environmental Policy Act) refer to global impacts in some sections and do not preclude a Presidential judgment that U.S. interests are best served via a global SCC.

Traditionally, regulatory CBA has used domestic impacts. However, unlike virtually all other regulated pollutants and risks, GHG emissions are overwhelmingly a problem of the global commons. A global SCC, used worldwide to determine policy, would maximize global net benefits. U.S. emissions cause the bulk of their damages beyond U.S. borders, and U.S. damages will largely depend on mitigation choices in other countries where emissions are larger and growing (*11*).

Beyond the moral, ethical, and security issues this raises, there is a strategic foreign relations question. The United States is engaged in international negotiations in which U.S. emission reductions are part of a deal for abatement by other countries. Benefits to each country are determined by the global effort. Even if the U.S. government cares only about domestic impacts, this potential to leverage foreign mitigation supports a domestic SCC estimate augmented by the expected foreign leverage. Our view is that these are compelling reasons to focus on a global SCC but, more important, to make a strategic choice and to conduct periodic review.

A PROCESS TO UPDATE THE SCC. Current U.S. government practice is vague regarding when and how a process of reviewing and updating the SCC might occur, which makes it difficult for stakeholders and researchers to anticipate future reviews and to plan for useful engagement in the process. A regularized and institutionalized process would allow both groups to align their activities more sensibly.

We see four components to an improved institutional process. First, revisions to the SCC should follow a regular schedule. A 5-year cycle would balance the need to respond to evolving research with the need for a thorough process.

Second, SCC revisions should continue to be an interagency process, led by an appropriate group within the Executive Office of the President. This emphasizes the need for consistent values across the whole of government and allows the process to draw on expertise from multiple agencies, as well as reflecting the strategic considerations noted above. The process should include public notice and comment.

> ***"Current U.S. . . . practice is vague regarding when and how . . . reviewing and updating the SCC might occur."***

Third, government SCC estimates should be regularly reviewed by the National Academy of Science's National Research Council (NRC). This would enhance the scientific credibility of the SCC and provide an avenue for experts to suggest changes for the next iteration. Such review could begin with the current estimates.

Finally, the entire process should be institutionalized through an executive order or an Office of Management and Budget (OMB) memorandum or circular. This would communicate the aforementioned components and achieve reasonably stable expectations about future practice. Moreover, a regular procedure with high-quality external review would help reduce any potential politicization of the SCC.

A regularized process for updating the SCC allows researchers to direct efforts toward policy-relevant issues. First, there is research on socioeconomic and emissions scenarios, climate science, and physical impacts, which are necessary inputs to IAMs and SCC estimates. Second, there is translation of physical impacts into human and ecosystem consequences, monetization of those consequences, and synthesis of this information into a consistent modeling framework to estimate the SCC. We believe there are especially appealing opportunities in the second area, which has not been as strongly supported as the physical science research.

Currently, estimates of human and ecosystem consequences of climate change, particularly in less-studied regions and impact categories, come from a small number of studies. Recent work suggests that temperature change may have different—and larger—impacts in poorer countries (*12*). Estimating damage from extreme climate change is a research area with particularly high value (*13*). Increased efforts to synthesize such studies for use in IAMs can facilitate their incorporation into SCC estimates.

SCC estimates could be improved by increasing opportunities for peer review of IAM development. This could be through model intercomparison projects focused specifically on the SCC, special journal issues to compare sector-by-sector impact valuations, and the NRC review process proposed earlier. This will require redirection of research time and funding, adjustments more easily planned in conjunction with a regularized updating schedule.

As the world makes progress in GHG mitigation, governments will need decision-making processes and information tools that reflect important trade-offs. That requires a regularized, transparent, and credible process that ensures that the SCC is reliable, well-supported, and up to date.

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From: Stock, James
Sent: Thur 2/12/2015 7:54:32 PM
Subject: FW: Paper on IAMs and climate policy
Metcalf Stock REEP Draft v5.pdf

Elizabeth,

Attached is a draft of a paper for a REEP symposium on the use of integrated assessment models for climate policy that Gib Metcalf I have written (the other two papers are by John Weyant and by Bob Pindyck). I'd be very interested in your reactions.

Thanks and best regards,

Jim

The Role of Integrated Assessment Models in Climate Policy: A User's Guide and Assessment

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February 12, 2015

Abstract

This paper considers the role of integrated assessment models (IAMs) in the construction of climate policy. We focus on questions involving the role of IAMs in estimating the social cost of carbon (SCC), how best to handle the considerable scientific uncertainty underlying the IAMs from the perspective of estimating the SCC, and whether an IAM-based SCC should be abandoned and replaced by expert judgment or another substitute. The perspective we adopt in tackling these questions is rooted in the specific needs of the existing U.S. institutions responsible for making and implementing climate policy, specifically regulatory agencies within the Executive Branch and Congress should it choose to take up climate legislation.

Our discussion has three premises. First, policy makers need a numerical value and an uncertainty range for the SCC for policy evaluation and implementation. Second, whatever the true value of the SCC is, it is not zero. Third, considerable uncertainty surrounds the current state of scientific knowledge about the current and future costs of climate change. The evolving nature of the science and the ultimate goal of informing first-best policy suggests to us that the official SCC – the SCC used for regulatory analysis by the U.S. Government – should not be thought of as a single number or even a range of numbers, but more broadly as a process that yields updated estimates of those numbers and ranges. Viewed in this way, the ultimate goal of the process is scientific credibility, public acceptance, and political and legal viability.

Keywords: Climate Change, Social Cost of Carbon, Integrated Assessment Models, Climate Policy

JEL Codes: Q54, Q58

This paper was written for a symposium on the use of integrated assessment models for climate policy in the *Review of Environmental Economics and Policy*. The authors gratefully acknowledge the help of …
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The Role of Integrated Assessment Models in Climate Policy: A User's Guide and Assessment

I. Introduction

Greenhouse gas emissions are a textbook case of a global externality. The starting point for any policy to address this market failure is an assessment of the monetized social marginal damages from emissions – the net damages arising from one additional ton of emissions in any given year. The classic prescription for an externality of this type is to set a price on emissions equal to the social marginal damages. This can be done in the form of a Pigouvian tax (Pigou, 1932) or by establishing property rights to pollution through cap and trade systems (see the seminal treatment by Dales, 1968) where the equilibrium trading price of emissions is set by the intersection of demand for emissions and the fixed supply of emission allowances set by policy. Whether a price on emissions is set by a tax or through a cap and trade system, optimal policy design requires knowledge of the social marginal monetized damages from greenhouse gas emissions. In the case of CO_2 emissions, this marginal monetized externality value is known as the Social Cost of Carbon (SCC).[1,2]

While theoretically straightforward, computing the SCC is empirically highly challenging on a number of dimensions. To date, academic researchers have relied heavily on integrated assessment models (IAMs) both to explore the pathways through which greenhouse gas emissions accumulate in the atmosphere and oceans and to assess natural and economic impacts. The current U.S. Government estimate of the SCC, or more precisely its central SCC value and three alternative estimates, were computed by the Interagency Working Group using three well known IAMS, initially in 2010 and using updated versions of those IAMs in 2013.[3]

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[1] There is a vast literature on the pros and cons of using taxes as opposed to cap and trade systems to reduce greenhouse gas emissions going back to Weitzman (1974) . Weitzman's analysis focuses on efficiency given the policy maker's ex ante uncertainty over marginal abatement costs. More recent analyses have focused more on the political benefits and costs of different policy approaches. See, for example, Metcalf (2007) and Stavins (2007) for one contrasting set of views. Another strand of the literature focuses on the Pigouvian prescription to set a price on emissions equal to the social cost of carbon. Bovenberg and de Mooij (1994) along with Parry (1995) noted that in the presence of pre-existing distortions the optimal price on emissions would likely fall short of the social marginal damages from emissions and sparked a large literature on the so-called "Double Dividend Hypothesis"; for recent contributions and references see Goulder (2013) and Jorgenson et al. (2013). These papers and nearly all subsequent theoretical work on policy design whether in a first or second best world assume that the monetized externality of a ton of carbon emissions (the social cost of carbon) is known.

[2] The Social Cost of Carbon can be converted to other greenhouse gases using CO_2-equivalent methods such as global warming potentials, although those conversions are approximate, for example because of different residence times (and thus different time paths of damages) of different gases.

[3] Greenstone, Kopits, and Woolverton (2013) provide an overview and discussion of the interagency process used to develop the SCC in 2010.

Recently Pindyck (2013) criticized the use of IAMs for evaluating climate policy, arguing that the models are built on assumptions that do not allow sufficient precision to estimate a SCC for policy purposes, and proposed that an IAM-based SCC be replaced with an SCC that reflects the combined opinion of a panel of experts. At a general level, Pindyck's challenge is an addition to the large literature on how best to conduct policy under uncertainty, including model uncertainty. In the case of the SCC, this general problem of decision-making under uncertainty interacts with the specific institutional structure of climate policy in the United States.

This paper considers the role of the SCC in climate policy, the role of IAMs in estimating the SCC, how best to handle the considerable scientific uncertainty underlying the IAMs from the perspective of estimating the SCC, and whether an IAM-based SCC should be abandoned and replaced by expert judgment or another substitute. The perspective we adopt in tackling these questions is rooted in the specific needs of the existing U.S. institutions responsible for making climate policy, specifically regulatory agencies within the Executive Branch and Congress should it choose to take up climate legislation. Our discussion has three premises.

First, policy makers need a numerical value and an uncertainty range for the SCC for policy evaluation and implementation. In a regulatory context, the Office of Management and Budget (OMB) requires agencies to conduct cost-benefit analysis of major newly proposed regulations. These and other climate policies implemented by regulation under existing law are second best; first-best policies would require Congressional action. But setting the appropriate stringency of both first- and second-best policies depends on the monetized externality value of carbon emissions, that is, on the SCC.

Second, whatever the true value of the SCC is, it is not zero. In 2008, the U.S. Court of Appeals for the Ninth Circuit struck down the 2007 changes to the CAFE standards in part because it found that the National Highway and Transportation Authority had been arbitrary and capricious when it argued that the monetary benefits of greenhouse gas reductions were too uncertain to permit their use in regulatory analysis.[4] Thus a specific, nonzero, value is needed; moreover, so that this value is neither arbitrary nor capricious, it should be based on the best available science.

Third, considerable uncertainty surrounds the current state of scientific knowledge about the current and future costs of climate change. Although research is progressing rapidly on some fronts, we argue below that some important aspects of the uncertainty, such as the appropriate discount factor to use or the damages induced by extreme events far outside the range of historical human experience

[4] Ninth Circuit Court of Appeals, Ctr. for Biological Diversity, 508 F.3d (9th Cir. 2007) as replaced by 538 F.3d 1200 (9th Cir. 2008); also see the discussion in NHTSA's revised proposed CAFE rule, 73 *Federal Register* 24361-2.

(such as melting of ice sheets), are unlikely to be resolved within the time frame necessary for making important and costly decisions on climate policy.

As we argue below, the evolving nature of the science and the ultimate goal of informing first-best policy leads us to conclude that the official SCC – the SCC used for regulatory analysis by the U.S. Government – should not be thought of as a single number or range of numbers, but more broadly as a process that yields updated estimates of those numbers and ranges. Viewed in this way, the ultimate goal of the process is scientific credibility, public acceptance, and political and legal viability. Accordingly, we suggest that the process that results in an official SCC should satisfy five criteria:

1) The estimate of the SCC should use the best available science and should be accompanied by quantified measures reflecting the uncertainty in the existing science, for example by providing a range in addition to a central focal estimate;
2) The method by which the SCC is computed should be transparent, replicable, and broadly explainable and understandable to non-experts;
3) The methodology should be subject to expert review and should incorporate regular updating;
4) The process should provide guidance to researchers to identify key sensitivities and areas where future research would be most productive for improving estimates of the SCC;
5) The process should not risk being viewed by the courts as arbitrary and capricious and it should be as isolated as possible from political influences.

While enhancing precision in the estimate of the SCC is desirable, improving precision is a process and we should expect that uncertainty about the SCC will persist for an extended period of time. Policy-making under uncertainty is the norm, and in this sense climate policy and the SCC is no different. Given the long time horizon for climate policy, however, both the policies and the analytical basis for those policies need to be able to incorporate and to adjust to newly available information.[5]

As we discuss in more detail below, we conclude that the process followed by the Interagency Working Group to estimate the SCC in 2010 and 2013, including its use of IAMs, fares well on many of these criteria. This said, room remains for improvement, in particular incorporating into the SCC process formal external expert review and a schedule for regular updating. In addition, the attention received by the official SCC has successfully shown a spotlight on aspects of IAMs with considerable scientific uncertainty, such as the damage functions and the largely-unmodeled consequences of large-scale

[5] Interestingly, most models of optimal climate policy do not incorporate the stochastic nature of knowledge acquisition or climate outcomes, an understandable simplification given the computational challenges posed by optimal updating. A recent example of a study in which the carbon price changes as information is acquired (in this case, information about large-scale abrupt changes) is Cai, Judd, and Lontzek (2013).

abrupt changes, and we point to vibrant new strands of research that could help to improve the IAMs and thus inform future revisions to the SCC. But an ongoing, transparent, scientifically-based process which uses improved IAMs or their successors is, in our view, more consistent with the democratic process and current regulatory requirements than alternatives such as different agencies using different values (as was done before the centralized efforts of OMB and the Interagency Working Group), failure to adopt any value (thereby implicitly adopting the clearly incorrect value of zero), or an expert panel charged with reaching a numerical judgment without reference to numerical models.

Before developing these arguments, we first provide a brief history of the use of IAMs in U.S. climate policy, then examine the current official SCC and its uses. We then turn to the question of alternative processes for developing the SCC. We conclude that while the Interagency Working Group Process so far (including its use of IAMs) is sound and better than the alternatives, it is important to institutionalize a process for the ongoing improvement of the SCC consistent with the five criteria above.

II. IAMS and the Use of the SCC in Climate Policy

Nordhaus (2013b) defines integrated assessment models as "approaches that integrate knowledge from two or more domains into a single framework" (p. 1070). Nordhaus's definition is broad and includes a variety of models that, by themselves, do not generate estimates of the SCC.[6] Models that can be used to estimate the SCC combine a model of the economy with a model of the atmosphere and ocean (and possibly land) that allows the researcher to track geophysical and economic variables of interest. An IAM constructed to address climate change must be able to track emissions, the concentration of greenhouse gases in the atmosphere as well as other carbon sinks, temperature and other climate impacts arising from increased concentrations of greenhouse gases in the atmosphere, and damages resulting from those climate impacts. Emissions follows from economic behavior, and policies scenarios can be posited to affect emissions along a number of dimensions. Figure 1 (adapted from Nordhaus, 2013b) illustrates the modules (rectangles) and model inputs/outputs (parallelogram) of a generic IAM. Not all IAM's contain all of the elements in Figure 1. For example, we

[6] The U.S. National Energy Modeling System (NEMS) is a good example of this latter type of model. NEMS is comprised of a number of modules representing energy supply (e.g. oil and gas, coal, renewable fuels), energy demand (residential, commercial, industrial, and transportation) and conversion modules (e.g. electricity, petroleum markets, international energy) and can produce detailed scenarios of future energy pathways. While it can be used to generate future emission scenarios under different policy assumptions, it lacks the climate, ecosystem, and damage modules that would be necessary to develop estimates of the SCC.

are not aware of any IAM that contains an explicit political response module that models how policy makers react to climate change damages through policy actions that lead to emission reductions.[7]

Early Regulatory Applications of the SCC. Prior to the Interagency Working Group's effort, estimates of damages from greenhouse gas emissions were incorporated into regulatory analyses in an ad hoc way that varied across agencies and rules. Some examples illustrate the evolution of thinking as well as differing agency views on SCC estimates.

The March 2006 National Highway Transportation Safety Administration (NHTSA) Final Regulatory Impact Analysis setting forth fuel economy standards for Model Year 2008-2011 light trucks states that

> "[t]he agency continues to view the value of reducing emissions of carbon dioxide and other greenhouse gases as too uncertain to support their explicit valuation and inclusion among the savings in environmental externalities from reducing gasoline production and use. There is extremely wide variation in published estimates of damage costs from greenhouse gas emissions, costs for controlling or avoiding their emissions, and costs of sequestering emissions that do occur, the three major sources for developing estimates of economic benefits from reducing emissions of greenhouse gases. ... As a consequence, the agency has elected to include no economic value for reducing greenhouse gas emissions … among the benefits of reducing gasoline use via more stringent fuel economy regulation." U.S. Department of Transportation (2006), pp VIII-64 – 65.

In 2008, the U.S. Ninth Circuit Court of Appeals held that, by failing to monetize the benefits of GHB emissions reductions, NHTSA had acted arbitrarily and capriciously, and for this and other reasons remanded the rule to NHTSA to set new standards. The court stated that, "[w]hile the record shows that there is a range of values, the value of carbon emissions reduction is certainly not zero."[8]

Accordingly, in May 2008 NHTSA issued a proposed rule for MY 2011-15 passenger cars and light trucks that incorporated a SCC value of $7 per ton CO_2e (2006 dollars). NHTSA arrived at this result by averaging a high value of $14 per ton (based on estimates from the IPCC's Fourth Assessment Report and adjusted forward to 2011) with a low value of zero. This latter estimate is based on measuring damages to the U.S. economy only: "Although this finding suggests that the *global* value of economic benefits from reducing carbon dioxide emissions is unlikely to be zero, it does not necessarily rule out

[7] IAM modeling exercises typically model political response as part of a given scenario. Reference case scenarios in which no action is taken to address climate change assumes one implicit political response while optimal policy scenarios posit a different political response that sets an implicit or explicit price on greenhouse gas emissions at the optimal rate.

[8] *Center For Biological Diversity v. Nat'l Highway Traffic Safety Admin.*, 538 F.3d 1200 (9th Cir. 2008). This opinion replaced an earlier 2007 opinion (508 F.3d).

low or zero values for the benefit to the U.S. itself from reducing emissions" (U.S. Department of Transportation, 2008a, p. 24414, emphasis in original).

In the Agency's final environmental impact statement for the MY 2011-2015 fuel economy standards released five months later, SCC estimates of $2 per ton CO_2e (based on domestic benefits only) and $33 per ton (based on global benefits) were used U.S. Department of Transportation (2008b). The Agency based its increase in global benefits from $14 to 33 per ton on new and updated estimates of the SCC contained in Tol (2008). It also used a positive value for U.S.-only benefits based on an assessment of the ratio of U.S. to global benefits of emission reductions.

In its proposed rule for regulating greenhouse gas emissions under the Clean Air Act, the U.S. Environmental Protection Agency (2008) used four values of the SCC in a side analysis to estimate benefits of reducing emissions. EPA used global benefit estimates of $40 and $68 per ton CO_2e based on discount rates of 3 and 2 percent, respectively and domestic benefit estimates of $1 and $4 (again for discount rates of 3 and 2 percent) based on a meta-analysis building on Tol (2008).[9] In all cases these estimates are for emission reductions in 2007 and are measured in year 2006 dollars. Despite reporting benefit estimates that include a SCC estimate, the EPA made clear that the agency was not endorsing a particular SCC value.[10]

In an effort to better understand the externalities associated with energy production and consumption, Congress directed the Department of Treasury in 2005 to commission a study by the National Academy of Sciences to investigate this issue. A committee was formed to undertake this task and included in its statement of task the following activity: "[d]evelop an approach for estimating externalities related to greenhouse gas emissions and climate change. Estimate externalities related to those changes" (National Research Council, 2009, p. 18). The committee concluded after an extensive survey of the literature that the SCC could range by two orders of magnitude – from $1 to $100 per ton CO_2-equivalent – depending on the choice of discount rate for discounting future damages from climate change and the degree of damages from climate change (see Table 1). The report states that "at this point only order-of-magnitude estimates appear warranted" (p. 218).

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[9] EPA's global SCC of $40 and $68 (depending on the discount rate) differ from NHTSA's estimate of $33 despite the underlying data in both cases coming from Tol (2008). NHTSA averaged the 125 estimates in the Tol meta-analysis while EPA focused on studies concluded since 1995 and separated out estimates of the SCC according to the underlying discount rate. Without criticizing the work either of NHTSA or EPA, the divergent SCC estimates speak to the value of an official SCC number (or set of numbers).

[10] "Presentation of these values does not represent, and should not be interpreted to represent, any determination by EPA as to what the social cost of carbon should be for purposes of calculating benefits pursuant to the Clean Air Act." U.S. EPA (2008), p. 44446.

While unsatisfying from the perspective of not providing a SCC number for use in regulatory impact analysis, the NRC study highlighted two of the key modeling choices (discount rate and damage function) that drive estimates of the SCC, issues we return to below.

The Interagency Working Group and the Current SCC. The Interagency Working Group used three widely known and respected IAMs to develop an official SCC.[11] The Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) model has been used extensively by the IPCC; its developer, Richard Tol, as noted above, has carried out several meta-analyses on the social cost of carbon relying on his and other modelers' work. The Policy Analysis of the Greenhouse Effect (PAGE) model, developed by Chris Hope was most prominently used in the analysis of the *Stern Review* (2007). The Dynamic Integrated Climate and Economy (DICE) model, developed by William Nordhaus, is especially transparent given Nordhaus's posting of the model on his website along with the various books he has written documenting and using the model (Nordhaus and Boyer, 2000; Nordhaus, 2008; Nordhaus, 2013a).

After reviewing the literature, the Interagency Working Group ran the three models using five scenarios (sets of assumptions about emissions, economic growth, population growth and other socioeconomic assumptions) with 10,000 draws each from a Roe-Baker distribution of equilibrium climate sensitivity (ECS) calibrated to assumptions taken from the IPCC's Fourth Assessment Report. The ECS measures the long-term equilibrium increase in global average surface temperature due to a doubling of greenhouse gas concentrations in the atmosphere from pre-industrial era levels and is a critical parameter in climate models. For each of three assumed discount rates (2.5, 3 and 5 percent), the 150,000 model runs were generated (3 models x 5 economic scenarios x 10,000 runs) and the results were pooled with equal weight given to each model and scenario. For each run, marginal damages were constructed as the present discounted value of the change in per capita consumption from the reference case arising from a shock to emissions in a given year. The Interagency Working Group reported mean values of marginal damages for each year for the 150,000 runs associated for each discount rate. In addition it reported the 95th percentile value from the 3 percent discount rate runs as one way to take into account potentially large tail impacts of climate change.

The 2013 SCC update replicated the methodology of the 2010 report but used updated versions of the FUND, PAGE, and DICE models. Table 2 shows estimates of the SCC for 2020 and 2050 from the

[11] This section draws heavily on Interagency Working Group on Social Cost of Carbon (2010) and Greenstone, Kopits, and Woolverton (2013).

two reports. Focusing on the 2020 estimates from the 2013 technical update, moving from a discount rate of 5 percent to 3 percent nearly quadruples the SCC and more than quintuples it when going to a 2.5 percent rate. The SCC at the 95th percentile of the distribution with a discount rate of 3 percent is triple the mean value. Similar patterns hold for the other years. The central estimate of the SCC in 2020 increases by 65 percent between the 2010 report and the 2013 technical update, reflecting among other things updating to the damage functions and explicit representation of sea level rise in two of the models.

All three models used in the 2013 Interagency Working Group's calculations exhibit mean SCC estimates greater than the median for all the scenarios and discount rates, a consequence of a long right tail of the distribution of the SCC across simulations (see Tables A2-A4 in the 2013 report). While there is variation in the estimates based on the scenario under consideration, the greater variation occurs across equilibrium climate sensitivity (as evidenced by the range of estimates for any particular model, discount rate, and scenario), discount rates, and model.

The variation across models is particularly striking. The estimates from the FUND model are considerably lower on average reflecting lower damages at all temperature levels (at least in the 2010 analysis; see figures 1A and 1B). While the 2013 update does not provide information about damages as a function of temperature change, the FUND model consistently provides lower estimates of damages at any percentile for each scenario-discount rate combination. By taking simple averages across models and economic scenarios, the Interagency Working Group took no position on the relative merits of competing models or the likelihood of differing economic scenarios, an issue to which we return below.

Current Uses of the SCC. Currently the SCC is used as an input into official cost-benefit analyses of proposed regulations, as part of legal challenges to government actions, and as a measure of the costs of climate change in the public discussion about climate policy. We turn to examples of each of these three uses.

In June 2014, the U.S. Environmental Protection Agency (2014) released its regulatory impact analysis for proposed guidelines on carbon emissions from existing power plants (EPA's Clean Power Plan). EPA's summary of the estimated monetized benefits of the proposed rule includes four estimates of the benefits of reduced carbon dioxide emissions using the four estimates from the Interagency Working Group's 2013 technical update: mean averages at 2.5, 3.0, and 5.0 percent discount rates and the 95th percentile value from the distribution of estimated SCC's from the 3 percent discount rate run.

Unlike previous NHTSA or EPA analyses, but consistent with the multiple prior uses of the Interagency Working Group's estimates,[12] there is no attempt to disentangle global from U.S. benefits noting the

> distinctive nature of the climate change problem. Emissions of greenhouse gases contribute to damages around the world, even when they are released in the United States, and the world's economies are now highly interconnected. Therefore, the SCC estimates incorporate the worldwide damages caused by carbon dioxide emissions in order to reflect the global nature of the problem, and we expect other governments to consider the global consequences of their greenhouse gas emissions when setting their own domestic policies. (EPA, 2014, p. ES-14)

In keeping with numerous other cost-benefit analyses of energy/environmental regulations since OMB's adoption of the 2010 Interagency Working Group report, the 2014 RIA explicitly defers to the Interagency Working Group's estimate of the SCC. The RIA uses the Working Group's central value, the mean of the distribution of SCC estimates from runs where a 3 percent discount rate is assumed (Tables ES-8, 9, and 10 of the RIA).

The SCC appears in legal decisions as well. For example, the SCC played a central role in a June 2014 U.S. District Court judge's decision to rescind the U.S. Bureau of Land Management's (BLM) granting of a lease to Arch Coal to expand coal mining in an area of the Gunnison National Forest in Colorado (Jackson, 2014). In its quantification of the benefits and costs of the lease expansion, BLM had excluded any costs associated with the release of methane and other greenhouse gases arguing that "[s]tandardized protocols designed to measure factors that may contribute to climate change, and to quantify climatic impacts, are presently unavailable" (p. 17 of decision). The judge in the case explicitly rejected that claim finding that "… a tool is and was available: the social cost of carbon protocol," (p. 17) going on to describe the Interagency Working Group TSD. The decision notes that while the preliminary EIS had contained estimates of the climate impacts using the Interagency Working Group's SCC estimates, monetized climate impacts were excluded from the FEIS apparently in response to an email from a BLM economist who argued that the use of SCC was "controversial" citing the wide range of estimates both in the Interagency TSD as well as other sources. In effect, the existence of uncertainty over the SCC led BLM to replace a positive value for the SCC in the quantitative analysis it undertook with a value of zero. The judge deemed that decision "arbitrary and capricious" (p. 19 of decision). This decision marks a significant milestone in legitimizing the Interagency SCC by overturning a federal

[12] For example, prior regulatory uses of the SCC for cost-benefit analysis include multiple energy efficiency rules under the Energy Independence and Security Act, Sewage Sludge Incineration Emission Standards (75 *Federal Register* 63260), and Fuel Efficiency Standards for Medium- and Heavy-Duty Vehicles (75 *Federal Register* 74152).

agency decision on the grounds that the working group's SCC estimates were not employed in the benefit cost analysis.[13]

The SCC also plays an important role in the public discussion of the costs of climate change and the monetized benefits of emissions reductions. A leading example concerns public discussions about what the appropriate value of a carbon tax might be. The American Opportunity Carbon Fee Act, a bill introduced by Senators Whitehouse and Schatz in 2014, proposes a carbon fee starting at $42 per ton in 2015. According to the accompanying press release, "The price of the fee follows the Obama Administration's central estimate of the 'social cost of carbon,' the value of the harms caused by carbon pollution including falling agricultural productivity, human health hazards, and property damages from flooding."[14] Introduced in the lame duck session of the 113th Congress, the bill did not generate widespread public debate. Notably, however, at least some conservative commentators accepted the linkage of the fee to the SCC, but emphasized that because of interactions with the rest of the tax system, leakage, and without future international coordination the optimal tax would be less than the SCC (Murphy, 2014). In this aspect at least, the public discussion echoes the academic literature which points out that in practice the optimal carbon tax depends not just on the external cost of marginal carbon emissions but on its implementation and how it interacts with the rest of the tax code.

III. IAMs: A Starting Point for Improving SCC Estimates or Fundamentally Flawed?

The central question of this symposium is whether IAMs constitute an acceptable basis for estimating the SCC or whether an alternative approach is needed. We break this question down into two pieces. The first, which we address in this section, is an assessment of the scientific shortcomings of existing IAMs and whether there is reason to think that these shortcomings will be addressed in a time frame consistent with the formulation of climate policy. The second piece of the question, which we address in the next section, is whether a better alternative exists in the context of the existing institutional and legal structure of climate policy formulation and implementation. Given space limitations, these comments are necessarily high-level.

The paper by Weyant (forthcoming) in this symposium provides a detailed description and history of the evolution of IAMs over the past 30 years. What is clear from a reading of Weyant's paper as well as the survey of IAMs in Nordhaus (2013b) is that IAMs and their role in SCC calculations have helped focus the attention of researchers on key areas of scientific uncertainty that drive many of the results in SCC calculations. Given the complexity of modeling climate change and its interaction with the

[13] The judge finalized his decision in September and neither BLM nor Arch Coal appealed the decision (Sierra Club, 2014).

[14] http://www.whitehouse.senate.gov/news/release/sens-whitehouse-and-schatz-introduce-carbon-fee-legislation

global economy, it is encouraging that the critically important areas of sensitivity can be narrowed down to a handful. Especially important are 1) equilibrium climate sensitivity; 2) damage functions; 3) treatment of catastrophic events; and 4) the discount rate. There are, of course, other areas where research progress would be quite valuable but these four areas stand out. As we think about the value of future research in each of these areas, we are struck by how fundamentally different these four areas are in terms of how optimistic we can be about pinning down our understanding of these key inputs. Because the equilibrium climate sensitivity is the province of geophysical climate science, we stick to the economic focus of this journal (and our own expertise) and focus on the final three issues in turn.

***Damage functions*.** The early damage functions in IAMs come from top-down cross-sectional analysis of the relation between the level of GDP and temperature, and thus associate warming with a shift in the level of future GDP, that is, a downward parallel shift in the path of GDP. In part because of the public importance of the SCC, current literature has undertaking a critical reexamination of these damage functions. Indeed disentangling temperature effects from other effects in top-down cross-sectional levels regressions faces significant identification challenges. As a result, this literature has focused on different identification strategies. One is to use short-run variation in the weather to examine effects on GDP growth; see for example Dell, Jones, and Olken (2012) and Deryugina and Hsiang (2014). Because weather variations are plausibly exogenous, after suitable conditioning on geographic variables, they allow estimates with greater internal validity than cross-sectional GDP regressions. On the negative side, the short-run nature of weather makes it challenging to analyze the effects of adaptation or to estimate with much confidence whether there are long-term effects on economic growth rates, not just levels, of weather or climate shocks. An alternative approach is to construct bottom-up estimates of damages. While a much larger undertaking than the bottom-down approach, a bottom-up approach is potentially amenable to more compelling identification strategies. For example, the property damage estimates in Koop et al. (2014) combined an insurance company compilation of built property values on the U.S. East Coast, elevation maps, and actual and simulated hurricane tracks to estimate the property damage cost of increased sea level rise and possibly stronger storms with more easterly tracks. Additional recent bottom-up research in the weather literature focuses on the effect of temperatures on labor productivity, health, crime, political unrest, and other elements of the total cost of climate change (see the survey by Dell, Jones, and Olken, 2014). And because the planet is now experiencing the early effects of climate change, new data are being generated that can be used to estimate damage functions, at least for the relatively small changes experienced so far. Most of the work in this area is quite new, the

literature is growing very quickly, and the available data are expanding. All this makes us optimistic that this literature is on a path towards substantially better-identified estimates of damage functions in IAMs.

Climate catastrophes. As discussed in National Research Council (2013), the Earth's climate history suggests the existence of "tipping points," that is, thresholds beyond which major changes occur that may be self-reinforcing and are likely to be irreversible over relevant time scales. Some of these changes, such as the rapid decline in late-summer Arctic sea ice, are already under way,[15] while others, such as the release of methane from thawing Arctic permafrost, could reinforce GHG warming but are considered unlikely to occur in this century.[16] The Weitzman (2009) dismal theorem focused the attention of the climate economics community on the potentially critical role of large-scale events that are abrupt on geological scale – so-called climate catastrophes – for formulating climate policy. The main thrust of the dismal theorem is that, with concave utility, society should be willing to pay substantial sums now to avoid worst-case catastrophic outcomes, what Pindyck (2011) and Weitzman (2011) have called "climate insurance." [17]

This literature points to an important element of GHG emissions externalities being the possibility of worst-case outcomes. The challenge is how to turn this into a monetary value; as the review in the previous section indicates, a number (or a range of numbers) is in the end needed in the regulatory and political process. The Interagency Working Group's estimate of the SCC does not explicitly model or account for climate catastrophes.[18] Because the climate catastrophe channel is largely distinct from the "local" damage function estimates arising from warming within the scope of human experience, a reasonable question is whether the climate catastrophe cost should be computed separately for the SCC, or whether it should be computed within IAMs. This is essentially a technical

[15] Joughin, Smith, and Medley (2014) and Rignot et al. (2014).
[16] National Research Council (2013).
[17] The details of Weitzman's theorem are sensitive to functional form assumptions but the broader point that risk aversion induces a willingness to pay a potentially large sum for insurance is not. See, for example Newbold and Daigneault (2009), Ackerman et al. (2010), Pindyck (2011, 2013), Nordhaus (2011, 2012), Litterman (2013), Millner (2013), and Weitzman (2011, 2014).
[18] While the Interagency Working Group modeled worst-case outcomes, and attempted to capture severe risks by reporting a high value of the SCC based on the 95th percentile value of the SCC drawn from a distribution of runs with a 3 percent discount rate, the analytical framework for those severe outcomes was obtained from large draws of the ECS combined with the standard IAM damage functions. Because those damage functions were calibrated from historical cross-country temperature comparisons they do not do justice to the mass extinctions, population disruptions, and land loss associated with some of the abrupt large-scale events such as the melting of the Greenland ice sheet.

question on which we do not have strong views. If the two effects are additive, then separate computations could be justified, but this additivity would need to be demonstrated. Given the sensitivity of the "normal warming" estimate and, presumably, of the interaction between tipping points and the ECS, one can imagine that the two effects would not be additive. In any event, Weyant's paper in this symposium makes it clear that there is much research to be done before IAMs are capable of addressing catastrophic risk. Still, in our view it would be a mistake simply to focus on tail events given the likelihood of disruption to particularly vulnerable communities over the next few decades from climate change. The "normal warming" costs are still highly likely to be economically meaningful and are particularly salient.

Discount rates. Climate change involves damages that extend many hundreds of years into the future. While there have been advances in our understanding of long term discount rates on the order of a century (see, for example, Giglio, Maggiori, and Stroebel, 2014) it is not clear that an appropriate framework exists for empirically identifying discount rates over the several centuries used to estimate the SCC. One then has two choices: use existing data and – with some assumptions – adapt results to a time span that is an order of magnitude longer than the span over which estimates were made, or adopt an explicitly ethical and normative perspective, along the lines of Stern (2007). Neither approach is entirely satisfying, and our reading of the literature is that it is unresolved on basic issues, such as whether to use market rates, consumption-based (Ramsey) discounting, whether discounting should be horizon-dependent, or whether a normative approach should be adopted. To us, it seems that these basic issues reflect fundamentally different perspectives or philosophies and it is hard to see how debates over discount rates will be resolved soon.[19]

These observations suggest that uncertainty in the three key areas of damage functions, climate catastrophes, and discount rates is likely to persist, so that estimates of the SCC will continue to exhibit considerable uncertainty over the foreseeable future. One could interpret this conclusion as implying that IAMs should be abandoned for some other method for estimating the SCC, but we interpret it differently. Uncertainty is rife in economic and scientific research; after all that is why new research is undertaken. While the current vigorous research in these areas is unlikely to result in a lasting consensus on the right damage function, for example, it is reasonable to expect that this research will

[19] For various perspectives on discounting see Nordhaus (2013a), Arrow et al. (2013), Litterman (2013), and Barro (2015).

serve to characterize, and in some cases tighten substantially, the range of technical uncertainty associated with these and other issues within IAMs. With a better quantification of uncertainty, one that is based on ongoing research, the IAMs can better serve to quantify, and we think narrow, the range of uncertainty of the SCC as well as provide an increasingly solid scientific basis for the various steps in the calculation. The idea of abandoning IAMs as the basis for the SCC, just as a burgeoning body of research promises to improve them and their measures of uncertainty, strikes us as misguided.

IV. The SCC as a Process, not a Number

Given the scientific uncertainty inherent in the current generation of IAMs, should the IAM-based SCC be replaced, as Pindyck (2013) has suggested, with another approach? We can think of at least five alternative approaches to that taken by the Interagency Working Group. We assess these alternatives using the five criteria laid out in the introduction: using the best available science and quantifying uncertainty; transparency, replicability, and comprehension; being subject to expert review and regular updating; providing guidance for ongoing research; and not being arbitrary and capricious and isolating the process from political pressure.

The first alternative approach would be to say that scientific work is so incomplete, and uncertainty so vast, that the Government simply should not use a SCC until more research is completed. We consider this position to be indefensible: while there is debate over how large the SCC is, the overwhelming evidence is that the costs of climate change are real and significant and that whatever the true value of the SCC is, it is not zero. Using a value of zero in cost-benefit analysis would restrict climate regulations to ones justified solely by their co-benefits. Because it is inconsistent with the best available science, abandoning the SCC because of uncertainty has already been rejected by the courts as arbitrary and capricious, as discussed above.[20]

A second alternative is to drop an official SCC but to allow agencies to provide their own individual SCCs and thereby comply with the court requirement for an SCC. This alternative also is a step backwards and fails in multiple dimensions, including transparency and being explainable. The inherent

[20] A more nuanced version of this argument is that uncertainty about a model, or about key policy parameters (such as the SCC), could warrant taking a conservative approach to its implementation. Brainard (1967) provided an early articulation of this view in the context of monetary policy, suggesting that uncertainty would lead to caution when the policy has costs. Brainard's (1967) result is special, however. Giannoni (2002), for example, considers a monetary model in which optimal policy guards against particularly bad models by responding more aggressively to shocks, not less, than when there is no model uncertainty; also see Hansen and Sargent (2007) and Cai, Judd, and Lentza (2013). In any event, this more nuanced argument does not imply biasing the estimate of the SCC towards zero, rather it concerns whether the policy path should be more conservative or more aggressive in the face of uncertainty.

redundancy also makes it administratively complex, less likely to use the best available science, and a poor use of limited government resources.

A third alternative to constructing an official SCC for policy purpose takes a "revealed preference" approach. Policy design in a number of political jurisdictions has led to a cost of carbon being implicitly or explicitly mandated. Examples include British Columbia's carbon tax, California's cap and trade system, the EU's emissions trading system, and South Korea's recently enacted cap and trade system. The official SCC would then be some average of a selected set of existing programs under the theory that the policy process has chosen the socially appropriate SCC. This approach has the virtue of being explainable – the U.S. is just following suit – and could be updated when other jurisdictions change their SCC. But it fails on most of the other criteria, such as using the best available science, being subject to peer review, conveying uncertainty, and providing guidance to researchers for further improvements. Indeed, this approach only works under the heroic assumption that the political process manages to absorb the relevant scientific evidence while ignoring all costs of mitigation, especially those falling on politically important interest groups. A political revealed preference approach seems quite unlikely to approximate the true SCC.

A fourth alternative is that the U.S. government would construct and maintain its own official integrated assessment model for U.S. policy purposes, instead of using (as did the Interagency Working Group) leading peer-reviewed models. This might be done, for example, by adding models of the physical processes in the ocean, atmosphere, and land cover to existing modules in the Energy Information Administration's annual integrated energy market model, the National Energy Modeling System (NEMS), and by enhancing the NEMS international energy activity module. The advantage of this approach is that there would be "in-house" modeling capabilities and expertise within the Federal government to build and maintain the model and to improve it as new research and insights into climate change emerges. If properly implemented and funded, this approach would do well by many of the five criteria, including using the best available science, quantifying uncertainty, periodic updating, external review, and providing guidance to researchers. The disadvantage, however, is that expertise would have to be built up within the federal workforce to build the model and there is no assurance that sufficient capacity would be in place to carry out such an ambitious undertaking and to keep up with scientific developments. Perhaps more important, it is not clear that a federal IAM would be sufficiently transparent and explainable that the public would have confidence in making policy from that model only; in the end, this alternative has the Federal government making myriads of modeling judgments which will inevitably be viewed as subject to political influence. While the NEMS model has high

credibility, the NEMS modeling judgments (such as how best to aggregate time periods and electricity generation regions) to balance output detail against computational feasibility are far less controversial, and have far less reaching ramifications, than the judgments involved in building a climate damages module for different regions of the world. And in the end an in-house model could be subject to political pressure – or appear to be subject to pressure – even if it were housed at an independent agency or a national laboratory – through the budget process which necessarily reflects the political positions of the Executive Branch and Congressional appropriators.

The fifth approach, which is proposed by Pindyck in his paper in this symposium and in Pindyck (2013), is to base the SCC on expert judgment. For example, the U.S. Government could contract with the National Research Council to constitute a standing panel of experts which would deliberate on the SCC, reach an initial estimate, and convene again every five years to consider whether a new SCC value is warranted based on how the judgment of the members has evolved in the interim. If implemented properly, this process could be based on the best available science as interpreted by the experts, it would entail regular updating, the experts could convey their judgment both of the SCC and its quantified uncertainty, and the experts could convey their views to researchers about what additional research is needed. But in our view this proposal falls short on the other criteria, especially if (as Pindyck's proposal would, it seems, have it) there is a side constraint that the experts are prohibited from using IAMs. If the experts are not allowed to use IAMs, then that presumably would disqualify many experts who have devoted much of their careers to developing IAMs, since their expert judgments would be heavily informed by the IAMs on which they have labored. Presumably those experts who focus on climate catastrophes/climate insurance calculations would also be precluded from using IAMs, which close off one line of quantifying that insurance value. One suspects that some of these experts would object to these preclusions which they would feel, in their expert judgment, are not scientifically warranted: Excel is OK, DICE is not? In any event it is hard to see how a panel of experts, precluded from using a class of models, would result in an estimate that is transparent, replicable, and uses the best available scientific information. Moreover, as a practical matter, it is hard to see how a judgmental expert panel would not be subject to political influences, since a standard institutional practice is to balance panels of experts not by weighting by scientific credibility but by ensuring representation of a spectrum of views. And – at the risk of being accused of practicing law without a license – it is also hard

for us to see how a panel-of-experts approach, with the side constraint of not using a class of scientific tools, would be viewed by the courts as other than arbitrary and capricious.[21]

In the end, each of these alternative approaches fails to meet many of our five procedural criteria. As the discussion of the panel-of-experts approach makes clear, we find it hard to imagine a successful process for estimating the SCC that does not involve the use of IAMs. The science behind climate change is extraordinarily complex and the interaction between the climatic and economic outcomes calls for the use of both physical and economic models. This is the very essence of IAMs. To us, it is unescapable that integrated modeling must play some role in the analysis.

What about the process followed by the Interagency Working Group? In our view, that process does reasonably well on the five criteria, but room remains for further improvement. Conditional on the models, the computational approach is straightforward and follows from economic and statistical principles. One can always argue with specific modeling choices the working group made. In particular weighting the three models and different economic scenarios equally in its averaging suggests all models/scenarios have equal credibility. The difference across the models is, however, so striking that it begs expert review and judgment of these models (and other potential models for consideration in the process) to put appropriate weight on whichever models are included in the analysis.

Setting aside issues of weighting model runs, the process itself is scientifically sound. The process itself is transparent and readily understandable given the care with which the 2010 Technical Support Document was written, and the rarely-satisfied Government Accountability Office (2014) found the process to be consistent with federal standards for internal control. As a by-product of the results it reported, the Interagency Working Group made clear the importance of key parameters, most notably discount rate, distribution of ECS, and damage function choices. This gives useful feedback to the research community.

But we believe the process has room for improvement on three related criteria. First, the TSD indicates that the estimate will be reviewed from time to time as new science becomes available, but there is no explicit process for that review and for the production of new estimates. Second, while there have been multiple opportunities for the public to comment officially on the SCC and the TSD, there is no formal framework for external expert review. Third, although the Interagency Working Group made

[21] Pindyck's argument is based in part on his view that the panel should focus only on catastrophic risks. We argued above that the research on non-catastrophic damages is steadily improving and that damage functions are increasingly calibrated to real-world data. Another argument for focusing on non-catastrophic risk is the need in the international climate negotiations to demonstrate credibility about developed country concerns with near-term damages to the most vulnerable developing countries. A social cost of carbon process that ignored non-catastrophic damages would undermine on-going efforts to build and sustain that credibility.

several decisions that protected it from political influence,[22] the process is organized by the Executive Office of the President and, regardless of whether there is in fact political influence, the process is likely to retain the perception of political influence. These issues are addressed by the recommendations of Pizer et al. (2014), who suggest a regular revision schedule (e.g. every 5 years); that the process should be similar to the interagency process used for the 2010 and 2013 analyses; that the estimates should be regularly reviewed by National Research Council, a branch of the National Academy of Sciences; and that the process should be codified through an Office of Management and Budget (OMB) memo or circular. We agree with these recommendations, which would transform the SCC from being a single number, or snapshot of the research, into a stable process for revision. It would be essential that the expert scientific review be coordinated so that NRC recommendations can be incorporated into the subsequent updating process. In addition to enhancing transparency, providing expert review, and providing guidance for further research, regular oversight by the National Research Council provides additional protection from political influence since attempts at political influence would presumably be called out by the review panel. Still, an issue that could be explored is whether additional steps are warranted to further protect the process from political influence, for example housing the technical work associated with the models at a national laboratory or an independent agency such as the Energy Information Administration.

V. Conclusion

These remarks lead to several conclusions. Given its importance in regulatory implementation and the public debate, an official SCC must be as credible as possible; we propose five criteria aimed at ensuring that credibility. To the point of this symposium, the SCC must have a numerical value and be associated with numerical measures of uncertainty, and we cannot see how that can be done credibly without sophisticated computer models that incorporate climate and economic considerations, that is, without IAMs. Complicating all this, the horizon over which the uncertainty surrounding the costs of climate change is resolved extends beyond the horizon in which climate policy decisions must be made, and moreover estimates of the SCC will change as new science becomes available. These conclusions

[22] For example, although the Interagency Working Group was headed by the Executive Office of the President through the Council of Economic Advisers and the Office of Management and Budget, it mainly consisted of numerous agencies representing disparate interests and expertise. The decision to use leading peer-reviewed models instead of just one model, or an internally-developed model, also provided a layer of insulation from political influences.

imply climate policy must be sufficiently sophisticated that it can adapt to evolving science and evolving estimates of the SCC. This will require a challenging degree of sophistication in climate policy.

To date the SCC has been used in ways that are important but, to the best of our knowledge, its numerical value has never been determinative for major regulations. The cost-benefit analyses for energy efficiency regulations typically find them justified from the energy savings alone, and in the largest rule in which the official SCC has been used, the EPA's Clean Power Plan, the rule would have positive net benefits even if the SCC were zero given the health co-benefits of reducing particulate emissions. For these applications of the SCC so far, climate benefits have been secondary. But, as the Whitehouse-Schatz carbon fee bill makes clear, the SCC must be able to stand on its own as a measure of the price of carbon in meaningful market-based policies for reducing GHG emissions. It is hard to see how that can happen without sophisticated integrated frameworks for computing marginal climate damages, that is, without IAMs. The task, then, of the research community is to continue the exciting and important new work on improving our understanding of climate damages, large-scale abrupt geophysical changes and their economic consequences, and long-term discount rates.

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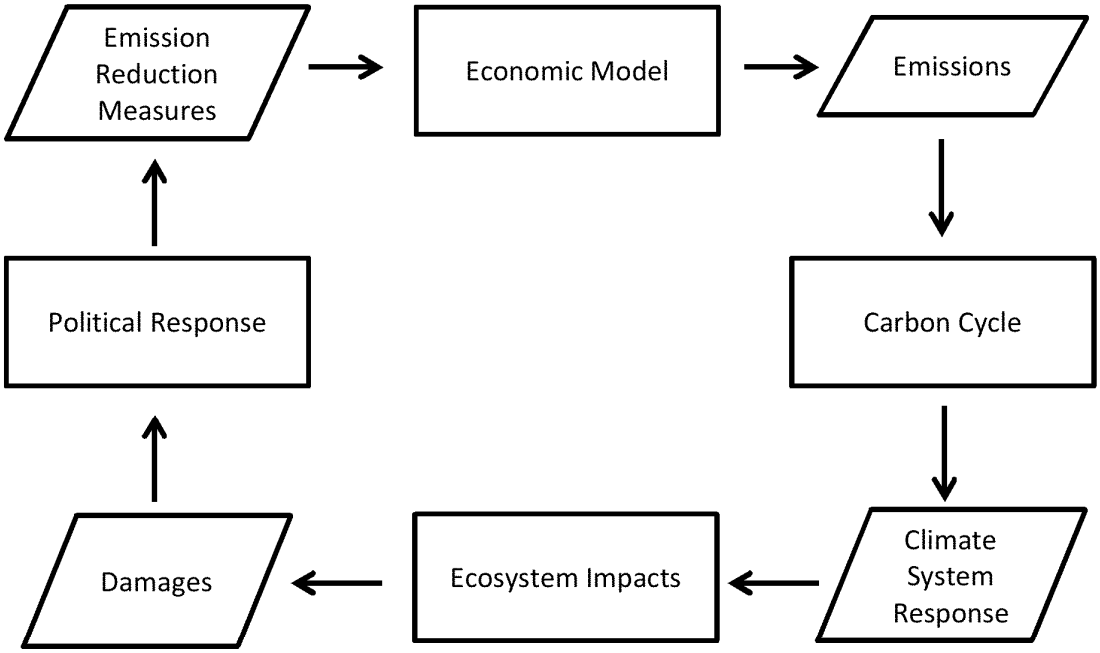

Figure 1. Integrated Assessment Model Schematic

Table 1. Indicative Damages from Greenhouse Gas Emissions: NRC Study

	Damages from Climate Change	
Discount Rate	Relatively Low	Higher
1.5 percent	10	100
3.0 percent	3	30
4.5 percent	1	10
Source: NRC (2009)		

Table 2. Interagency Working Group SCC Estimates

Discount Rate Year	5.0% Mean	3.0% Mean	2.5% Mean	3.0% 95th Percentile
2020	$7	$26	$42	$80
2020(rev)	12	43	64	128
2050	16	45	65	136
2050(rev)	27	71	98	221
Source: Interagency Working Group (2010, 2013). Table reports estimates of the social cost of carbon measured in 2007$ per metric ton. "rev" indicates revised estimates from the 2013 technical update.				

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From: Wolverton, Ann
Sent: Thur 2/12/2015 2:59:14 PM
Subject: a couple of recent NBER papers of potential interest to the climate team

"Climate Sensitivity Uncertainty: When is Good News Bad?"
NBER Working Paper No. w20900

MARK FREEMAN, Loughborough University
Email: m.c.freeman@lboro.ac.uk
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Climate change is real and dangerous. Exactly how bad it will get, however, is uncertain. Uncertainty is particularly relevant for estimates of one of the key parameters: equilibrium climate sensitivity — how eventual temperatures will react as atmospheric carbon dioxide concentrations double. Despite significant advances in climate science and increased confidence in the accuracy of the range itself, the "likely" range has been 1.5-4.5°C for over three decades. In 2007, the Intergovernmental Panel on Climate Change (IPCC) narrowed it to 2-4.5°C, only to reverse its decision in 2013, reinstating the prior range. In addition, the 2013 IPCC report removed prior mention of 3°C as the "best estimate." We interpret the implications of the 2013 IPCC decision to lower the bottom of the range and excise a best estimate. Intuitively, it might seem that a lower bottom would be good news. Here we ask: When might apparently good news about climate sensitivity in fact be bad news? The lowered bottom value also implies higher uncertainty about the temperature increase, a definite bad. Under reasonable assumptions, both the lowering of the lower bound and the removal of the "best estimate" may well be bad news.

"Assessing the Energy-Efficiency Gap"
NBER Working Paper No. w20904

TODD GERARDEN, Harvard University, Resources for the Future
Email: gerarden@rff.org
RICHARD G. NEWELL, Duke University - Nicholas School of Environment, National Bureau of Economic Research (NBER), Resources for the Future
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ROBERT N. STAVINS, Harvard University - Harvard Kennedy School (HKS), Resources for the Future, National Bureau of Economic Research (NBER)
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Energy-efficient technologies offer considerable promise for reducing the financial costs and environmental damages associated with energy use, but these technologies appear not to be adopted by consumers and businesses to the degree that would apparently be justified, even on a purely financial basis. We present two complementary frameworks for understanding this so-called "energy paradox" or "energy-efficiency gap." First, we build on the previous literature by dividing potential explanations for the energy-efficiency gap into three categories: market failures, behavioral anomalies, and model and measurement errors. Second, we posit that it is useful to think in terms of the fundamental elements of cost-minimizing energy-efficiency decisions. This provides a decomposition that organizes thinking around four questions. First, are product offerings and pricing economically efficient? Second, are energy operating costs inefficiently priced and/or understood? Third, are product choices cost-minimizing in present

value terms? Fourth, do other costs inhibit more energy-efficient decisions? We review empirical evidence on these questions, with an emphasis on recent advances, and offer suggestions for future research.

To: Klemick, Heather[Klemick.Heather@epa.gov]; Evans, DavidA[Evans.DavidA@epa.gov]; Shadbegian, Ron[Shadbegian.Ron@epa.gov]; McGartland, Al[McGartland.Al@epa.gov]; Kopits, Elizabeth[Kopits.Elizabeth@epa.gov]; Bowen, Jennifer[Bowen.Jennifer@epa.gov]; Simon, Nathalie[Simon.Nathalie@epa.gov]; Ferris, Ann[Ferris.Ann@epa.gov]; Snyder, Brett[Snyder.Brett@epa.gov]; Marten, Alex[Marten.Alex@epa.gov]; Simpson, David[Simpson.David@epa.gov]; Griffiths, Charles[Griffiths.Charles@epa.gov]; Sargent, Keith[Sargent.Keith@epa.gov]; Moore, Chris[Moore.Chris@epa.gov]; Sheriff, Glenn[Sheriff.Glenn@epa.gov]; Pasurka, Carl[Pasurka.Carl@epa.gov]; Dockins, Chris[Dockins.Chris@epa.gov]; Garbaccio, Richard[Garbaccio.Richard@epa.gov]; Newbold, Steve[Newbold.Steve@epa.gov]
Cc: McGee, Natasha[McGee.Natasha@epa.gov]
From: Wolverton, Ann
Sent: Thur 1/29/2015 3:56:10 PM
Subject: climate and international team meeting
Skeleton Agenda -jan2915.doc

Rule-Related:

Non-Responsive

Other items

Non-Responsive

Non-Responsive

Upcoming Seminars of Potential Interest

-

Feb 4, 12:45 pm RFF Seminar, William Pizer and Joseph Aldy, *Toward a Global Climate Agreement: Comparing Countries' Levels of Effort*. Note: Registration is required.

Agenda for Climate and International Team Meeting – January 29, 2015

Rule-Related:

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Other items

Non-Responsive

Upcoming Seminars of Potential Interest

Feb 4, 12:45 pm RFF Seminar, William Pizer and Joseph Aldy, *Toward a Global Climate Agreement: Comparing Countries' Levels of Effort*. Note: Registration is required.

To: McGartland, Al[McGartland.Al@epa.gov]; Newbold, Steve[Newbold.Steve@epa.gov]; Wheeler, William[Wheeler.William@epa.gov]; Wolverton, Ann[Wolverton.Ann@epa.gov]; Griffiths, Charles[Griffiths.Charles@epa.gov]; Simon, Nathalie[Simon.Nathalie@epa.gov]
Cc: Kopits, Elizabeth[Kopits.Elizabeth@epa.gov]; Marten, Alex[Marten.Alex@epa.gov]
From: Dockins, Chris
Sent: Fri 1/23/2015 2:57:05 PM
Subject: RE: Discounting

Thanks, Al. I have a conflicting meeting at 10, but quickly...

Ex 5

- C

From: McGartland, Al
Sent: Friday, January 23, 2015 9:46 AM
To: Dockins, Chris; Newbold, Steve; Wheeler, William; Wolverton, Ann; Griffiths, Charles; Simon, Nathalie
Cc: Kopits, Elizabeth; Marten, Alex
Subject: RE: Discounting

Hi everyone --- please do not feel pressure to attend this meeting. We have a meeting with Joel coming up and we could probably do this by email Ex 5

Ex 5

Ex 5

-----Original Appointment-----
From: McGartland, Al
Sent: Thursday, January 22, 2015 6:26 PM
To: McGartland, Al; Dockins, Chris; Newbold, Steve; Wheeler, William; Wolverton, Ann; Griffiths, Charles; Simon, Nathalie
Cc: Kopits, Elizabeth; Marten, Alex
Subject: Discounting
When: Friday, January 23, 2015 10:00 AM-11:00 AM (UTC-05:00) Eastern Time (US & Canada).
Where:

To: McGartland, Al[McGartland.Al@epa.gov]; Dockins, Chris[Dockins.Chris@epa.gov]; Newbold, Steve[Newbold.Steve@epa.gov]; Wheeler, William[Wheeler.William@epa.gov]; Wolverton, Ann[Wolverton.Ann@epa.gov]; Simon, Nathalie[Simon.Nathalie@epa.gov]
Cc: Kopits, Elizabeth[Kopits.Elizabeth@epa.gov]; Marten, Alex[Marten.Alex@epa.gov]
From: Griffiths, Charles
Sent: Fri 1/23/2015 2:54:20 PM
Subject: RE: Discounting

Yes. Chris and I will be happy to put together a set of slides for discussion.

Charles

****
Charles Griffiths
National Center for Environmental Economics
Room 4334B, WJC West, Mail Code 1809T
U.S. Environmental Protection Agency
1200 Pennsylvania Avenue, N.W.
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****

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Cc: Kopits, Elizabeth; Marten, Alex
Subject: Discounting
When: Friday, January 23, 2015 10:00 AM-11:00 AM (UTC-05:00) Eastern Time (US & Canada).
Where:

To: Kopits, Elizabeth[Kopits.Elizabeth@epa.gov]; Li, Jia[Li.Jia@epa.gov]
Cc: Wolverton, Ann[Wolverton.Ann@epa.gov]; Griffiths, Charles[Griffiths.Charles@epa.gov]; Shouse, Kate[Shouse.Kate@epa.gov]; Fawcett, Allen[Fawcett.Allen@epa.gov]; Marten, Alex[Marten.Alex@epa.gov]; McGartland, Al[McGartland.Al@epa.gov]
From: Newbold, Steve
Sent: Wed 1/14/2015 4:47:11 PM
Subject: RE: New Stanford study showing SCC six times higher than USG estimates

Hi gang,

I read this paper last night and took some notes on it this morning, so I'm pasting them below in case they may be of some use to us later.

Notes on Moore FC, Diaz DB. 2015 Temperature impacts on economic growth warrant stringent mitigation policy. Nature Climate Change. doi:10.1038/nclimate2481

The authors develop a modified version of DICE to accommodate a damage function based on the results of Dell et al. and compare the results to a (a close replication of) the traditional version of DICE.

Results from Dell et al. are summarized as follows:

Effect of 1 dec C temp increase on GDP growth rates in poor countries = -1.171 pp (percentage points) and in rich countries = -0.152 pp. Effect of 1 deg C temp increase on economic output in poor countries = -0.426% and in rich countries = 0.371%.

"To implement these parameters in an IAM, we develop a two-region version of DICE (DICE-2R). We then modify the damage pathway so that warming affects either TFP growth or capital depreciation as per results in Dell et al. (gro-DICE). We present results of the TFP pathway here..."

So DICE-2R is meant to closely mimic the standard version of DICE as developed by Nordhaus, and gro-DICE is a modified version of DICE-2R that incorporates the results of Dell et al.

The authors note that the growth rate sensitivities estimated by Dell et al. are based on transient weather shocks and so should be interpreted as short run impacts. They claim that the long run impacts could be either larger ("owing to intensification") or smaller ("owing to adaptation"). In this paper the authors assume that the long run effects are zero and that the short run impacts decay exponentially at a rate of 10% per year.

Ex 5

"Figure 1 shows the trajectory of per-capita GDP under business as usual for the reference (no climate

damages), DICE-2R and gro-DICE models. Temperatures exceed 4.5 deg C by 2100, causing economic losses in both models with damages. Impacts in DICE-2R are modest because impacts are transient and offset by sustained growth in TFP, labour and capital: the difference from reference GDP is less than 12% in both poor and rich regions by 2100. In contrast, the growth effects in gro-DICE compound over the century, leading to much larger impacts. The average annual growth rate in poor regions is cut from 3.2% to 2.6%, which means that by 2100 per-capita GDP is 40% below reference. The much smaller growth effects in rich countries, combined with the fact that warming slightly improves economic output, means the gro-DICE and DICE-2R timepaths are very similar in the rich region."

Ex 5

Ex 5

OK, back to the article itself:

Ex 5

****
Steve Newbold
U.S. EPA
National Center for Environmental Economics (NCEE)
EPA West, 4316T, MC 1809T
1200 Pennsylvania Ave NW
Washington, DC 20004
(202) 566-2293
****

-----Original Message-----
From: Kopits, Elizabeth
Sent: Tuesday, January 13, 2015 8:20 AM
To: Li, Jia
Cc: Wolverton, Ann; Griffiths, Charles; Shouse, Kate; Fawcett, Allen; Marten, Alex; Newbold, Steve
Subject: RE: New Stanford study showing SCC six times higher than USG estimates

FYI - More press on this paper. Includes comment from Billy....

POLICY:
Researchers say the social cost of carbon will be 6 times the Obama administration's estimate Evan Lehmann, E&E reporter
Published: Tuesday, January 13, 2015

Climate change could have much larger impacts on the economy than the U.S. government is anticipating, according to an analysis released yesterday that suggests the social cost of carbon should be six times higher.

A paper by two Stanford University researchers argues that the true cost of releasing greenhouse gases is about $220 a ton because rising temperatures could badly hinder a nation's economic growth over decades or centuries. The Obama administration estimates that the social cost of carbon is $37 a ton.

The paper, published yesterday in the journal Nature Climate Change, adds to a growing number of voices calling for improvements to the complicated process of establishing the cost estimate, which is used to measure the benefits of regulations. A dozen federal agencies set the price using three computer models that project emission rates, economic activity and climate damages.

The Stanford paper bases its findings on prior research showing that the economic health of a country suffers during periods of high temperatures. Heat can harm agricultural and industrial output, while increasing political instability. In that way, the Stanford analysis subscribes to emerging calls among experts to incorporate new observations into the trio of models that date back to the 1990s.

"The social cost of carbon is almost certainly larger of what's being used so far," said co-author Frances Moore, a doctoral candidate at Stanford's School of Earth Sciences.

In a key departure from the government's analysis, the paper uses the previous empirical research to assert that climate impacts could damage a nation's economic growth rate over time, rather than just harassing its year-to-year economic output.

That could mean that nations face permanent malfunctions, like economic declines in labor, capital and technology from severe weather and other "temperature shocks." The authors say these bigger impacts have a "compounding effect" that is more damaging to the economy than temporary strains from heat on agricultural output and more expensive air conditioning costs.

"So the economy is kind of permanently lower," Moore said. "If you have repeated shocks, in that case, they accumulate over time. That's why even very, very small reductions in growth rates have these really big effects over time."

It's an 'overestimate'

The social cost of carbon is used in the cost-benefit analysis of some federal regulations. If the impact of emissions is deemed expensive for society, it could justify more aggressive policies to reduce their release by industry. Opponents of climate action criticized the Obama administration for raising the social cost of carbon in 2013 by almost 50 percent.

William Pizer, a Duke University professor and former Obama administration official who has worked on the estimate, applauded the Stanford researchers for applying updated observations into their carbon estimates. He and several other former Obama advisers say the administration should improve its use of updated science when establishing the price.

But Pizer also questioned the methodology of the Stanford analysis. The empirical research it relied on tracked short-term temperature spikes and their impacts on nations' economies -- not long-term trends that might show permanent economic reductions.

"To me, it just seems like it has to be an overestimate," Pizer said of the Stanford result of $220.

"I think it's great they're doing this," he added. "I just think this is another data point that someone needs to weigh as they're trying to figure out what the right social cost of carbon is. But this isn't like a definitive new answer."

Moore acknowledged the uncertainties in her research. For example, she noted that there's not enough evidence to know if climate change will continue to have outsized impacts on poorer countries or if as their economies grow they'll be able to adapt and decrease their damage.

A grimmer outcome consists of "biophysical temperature thresholds" -- the idea that the heat will prevent large economic advances. Both scenarios effect the speed and aggressiveness with which emissions should be reduced -- and the price of their social cost of carbon.

Moore hopes the new research will help inform the administration that a larger spectrum of damages should be considered when establishing the monetary estimate.

-----Original Message-----
From: Kopits, Elizabeth
Sent: Monday, January 12, 2015 3:39 PM
To: Li, Jia
Cc: Wolverton, Ann; Griffiths, Charles; Shouse, Kate; Fawcett, Allen; Marten, Alex; Newbold, Steve
Subject: RE: New Stanford study showing SCC six times higher than USG estimates

I hadn't. Thanks for sending. Here's the Nature Climate Change article.

-----Original Message-----
From: Li, Jia
Sent: Monday, January 12, 2015 2:26 PM
To: Kopits, Elizabeth; Shouse, Kate; Fawcett, Allen; Marten, Alex; Newbold, Steve
Subject: New Stanford study showing SCC six times higher than USG estimates

FYI - you may have seen the study

http://www.rtcc.org/2015/01/12/social-cost-of-carbon-six-times-higher-than-thought-study/

Sent from my iPhone

To: Cropper, Maureen[mcropper@econ.umd.edu]
From: Kopits, Elizabeth
Sent: Tue 7/7/2015 1:14:11 PM
Subject: RE: Who Performed the Computations for the SCC?

Hi Maureen,

Great to hear from you. The actual runs were done by us – Alex Marten, Steve Newbold, Charles Griffiths, and me.

All is well here. Non-Responsive

Non-Responsive

Hope to talk/see you soon.

Best,

Elizabeth

From: Cropper, Maureen [mailto:mcropper@econ.umd.edu]
Sent: Tuesday, July 07, 2015 9:04 AM
To: Kopits, Elizabeth
Subject: Who Performed the Computations for the SCC?
Importance: High

Elizabeth,

Who performed the actual computations for the SCC? Were they performed by EPA staff or someone else?

I hope all is well with you!

With best wishes,
Maureen

To: Marten, Alex[Marten.Alex@epa.gov]; Newbold, Steve[Newbold.Steve@epa.gov]; Griffiths, Charles[Griffiths.Charles@epa.gov]; Wolverton, Ann[Wolverton.Ann@epa.gov]; McGartland, Al[McGartland.Al@epa.gov]
From: Kopits, Elizabeth
Sent: Wed 5/6/2015 5:54:35 PM
Subject: FW: Paper on IAMs and climate policy
DP62_Metcalf-Stock.pdf

FYI. Here is Jim's paper written for the same REEP symposium as the Pindyck paper that was sent around a few weeks ago.

From: Stock, James [mailto:james_stock@harvard.edu]
Sent: Wednesday, May 06, 2015 1:47 PM
To: Kopits, Elizabeth
Cc: Metcalf, Gilbert E.
Subject: RE: Paper on IAMs and climate policy

Here is the most recent version, which is lightly changed from what we sent you in Feb. I think we are still waiting on editors comments so there will be another round of revisions.

non-responsive

Jim

From: Kopits, Elizabeth [mailto:Kopits.Elizabeth@epa.gov]
Sent: Wednesday, May 06, 2015 1:44 PM
To: Stock, James
Cc: Metcalf, Gilbert E.
Subject: RE: Paper on IAMs and climate policy

Hi Jim,

I am sorry to be so slow in responding to this. I am just getting back to work **Non-Responsive**

Non-Responsive and gradually making my way through my inbox. Is this REEP symposium finalized yet? I am very interested to read your paper – is the version you sent me in February still the most recent/final? Someone sent me an April version of Pindyck's paper so I just looked at that as well.

Best,

Elizabeth

From: Stock, James [mailto:james_stock@harvard.edu]
Sent: Thursday, February 12, 2015 2:55 PM
To: Kopits, Elizabeth
Cc: Metcalf, Gilbert E.
Subject: FW: Paper on IAMs and climate policy

Elizabeth,

Attached is a draft of a paper for a REEP symposium on the use of integrated assessment models for climate policy that Gib Metcalf I have written (the other two papers are by John Weyant and by Bob Pindyck). I'd be very interested in your reactions.

Thanks and best regards,

Jim

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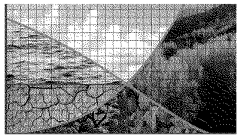

Harvard Environmental Economics Program

DEVELOPING INNOVATIVE ANSWERS TO TODAY'S COMPLEX ENVIRONMENTAL CHALLENGES

March 2015
Discussion Paper 15-62

The Role of Integrated Assessment Models in Climate Policy: A User's Guide and Assessment

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The Harvard Environmental Economics Program

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HEEP and the closely-affiliated Harvard Project on Climate Agreements are grateful for additional support from the Belfer Center for Science and International Affairs and the Hui Research Fund for Generating Powerful Ideas at the Ash Center for Democratic Governance and Innovation —both located at the Harvard Kennedy School; and Christopher P. Kaneb (Harvard AB 1990).

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The Role of Integrated Assessment Models in Climate Policy: A User's Guide and Assessment

Gilbert E. Metcalf
Department of Economics
Tufts University and NBER

James Stock
Department of Economics
Harvard University and NBER

February 2015

Abstract

This paper considers the role of integrated assessment models (IAMs) in the construction of climate policy. We focus on questions involving the role of IAMs in estimating the social cost of carbon (SCC), how best to handle the considerable scientific uncertainty underlying the IAMs from the perspective of estimating the SCC, and whether an IAM-based SCC should be abandoned and replaced by expert judgment or another substitute. The perspective we adopt in tackling these questions is rooted in the specific needs of the existing U.S. institutions responsible for making and implementing climate policy, specifically regulatory agencies within the Executive Branch and Congress should it choose to take up climate legislation.

Our discussion has three premises. First, policy makers need a numerical value and an uncertainty range for the SCC for policy evaluation and implementation. Second, whatever the true value of the SCC is, it is not zero. Third, considerable uncertainty surrounds the current state of scientific knowledge about the current and future costs of climate change. The evolving nature of the science and the ultimate goal of informing first-best policy suggests to us that the official SCC – the SCC used for regulatory analysis by the U.S. Government – should not be thought of as a single number or even a range of numbers, but more broadly as a process that yields updated estimates of those numbers and ranges. Viewed in this way, the ultimate goal of the process is scientific credibility, public acceptance, and political and legal viability.

Keywords: Climate Change, Social Cost of Carbon, Integrated Assessment Models, Climate Policy

JEL Codes: Q54, Q58

This paper was written for a symposium on the use of integrated assessment models for climate policy in the *Review of Environmental Economics and Policy*. The authors gratefully acknowledge comments from Joe Aldy, Bob Pindyck, and Marty Weitzman. Contact information: gmetcalf@tufts.edu and james_stock@harvard.edu.

The Role of Integrated Assessment Models in Climate Policy: A User's Guide and Assessment

I. Introduction

Greenhouse gas emissions are a textbook case of a global externality. The starting point for any policy to address this market failure is an assessment of the monetized social marginal damages from emissions – the net damages arising from one additional ton of emissions in any given year. The classic prescription for an externality of this type is to set a price on emissions equal to the social marginal damages. This can be done in the form of a Pigouvian tax (Pigou, 1932) or by establishing property rights to pollution through cap and trade systems (see the seminal treatment by Dales, 1968) where the equilibrium trading price of emissions is set by the intersection of demand for emissions and the fixed supply of emission allowances set by policy. Whether a price on emissions is set by a tax or through a cap and trade system, optimal policy design requires knowledge of the social marginal monetized damages from greenhouse gas emissions. In the case of CO_2 emissions, this marginal monetized externality value is known as the Social Cost of Carbon (SCC).[1]

While theoretically straightforward, estimating the value of the SCC is highly challenging on a number of dimensions. To date, academic researchers have relied heavily on integrated assessment models (IAMs) both to explore the pathways through which greenhouse gas emissions accumulate in the atmosphere and oceans and to assess natural and economic impacts. The current U.S. Government estimate of the SCC, or more precisely its central SCC value and three alternative estimates, were computed by the Interagency Working Group using three well known IAMS, initially in 2010 and using updated versions of those IAMs in 2013.[2]

The three papers in this symposium consider the challenge of estimating the SCC using IAMs, given the very large amount of uncertainty underlying many aspects of the IAM-based calculations.

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[1] There is a vast literature on the pros and cons of using taxes as opposed to cap and trade systems to reduce greenhouse gas emissions going back to Weitzman (1974). Weitzman's analysis focuses on efficiency given the policy maker's ex ante uncertainty over marginal abatement costs. More recent analyses have focused more on the political benefits and costs of different policy approaches. See, for example, Metcalf (2007) and Stavins (2007) for one contrasting set of views. Another strand of the literature focuses on the Pigouvian prescription to set a price on emissions equal to the social cost of carbon. Bovenberg and de Mooij (1994) along with Parry (1995) noted that in the presence of pre-existing distortions the optimal price on emissions would likely fall short of the social marginal damages from emissions and sparked a large literature on the so-called "Double Dividend Hypothesis"; for recent contributions and references see Goulder (2013) and Jorgenson et al. (2013). These papers and nearly all subsequent theoretical work on policy design whether in a first or second best world assume that the monetized externality of a ton of carbon emissions (the social cost of carbon) is known.

[2] Greenstone, Kopits, and Woolverton (2013) provide an overview and discussion of the interagency process used to develop the SCC in 2010.

Weyant's paper reviews IAMs and argues that much of the uncertainty in the use of IAMs represents less the flaws of the models and more the fundamental uncertainty in scientific and economic knowledge of key model features and inputs. Weyant also stresses the importance of the research community improving how it reports and handles the wide range of uncertainty from IAM-based calculations. Pindyck's paper also focuses on the uncertainty in the IAMs but reaches a quite different conclusion, echoing the earlier criticism in Pindyck (2013) that the models are "of little or no value for evaluating alternative climate change policies and estimating the SCC" (p. 870) and that the models suggest "a level of knowledge and precision that is nonexistent, and allows the modeler to obtain almost any desired result because key inputs can be chosen arbitrarily" (ibid). Pindyck proposes that an IAM-based SCC be replaced with an SCC that reflects the combined opinion of a panel of experts.

This paper considers the role of the SCC in climate policy, the role of IAMs in estimating the SCC, how best to handle the considerable scientific uncertainty underlying the IAMs from the perspective of estimating the SCC, and whether an IAM-based SCC should be abandoned and replaced by expert judgment or another substitute. The perspective we adopt in tackling these questions is rooted in the specific needs of the existing U.S. institutions responsible for making climate policy, specifically regulatory agencies within the Executive Branch and Congress should it choose to take up climate legislation. Our discussion has three premises.

First, policy makers need a numerical value and an uncertainty range for the SCC for policy evaluation and implementation. In a regulatory context, the Office of Management and Budget (OMB) requires agencies to conduct cost-benefit analysis of major newly proposed regulations. These and other climate policies implemented by regulation under existing law are second best; first-best policies would require Congressional action. But setting the appropriate stringency of both first- and second-best policies depends on the monetized externality value of carbon emissions, that is, on the SCC.

Second, whatever the true value of the SCC is, it is not zero. In 2008, the U.S. Court of Appeals for the Ninth Circuit struck down the 2007 changes to the CAFE standards in part because it found that the National Highway and Transportation Authority had been arbitrary and capricious when it argued that the monetary benefits of greenhouse gas reductions were too uncertain to permit their use in regulatory analysis.[3] Thus a specific, nonzero, value is needed; moreover, so that this value is neither arbitrary nor capricious, it should be based on the best available science.

[3] Ninth Circuit Court of Appeals, Ctr. for Biological Diversity, 508 F.3d (9th Cir. 2007) as replaced by 538 F.3d 1200 (9th Cir. 2008); also see the discussion in NHTSA's revised proposed CAFE rule, 73 *Federal Register* 24361-2.

Third, considerable uncertainty surrounds the current state of scientific knowledge about the current and future costs of climate change. Although research is progressing rapidly on some fronts, we argue below that some important aspects of the uncertainty, such as the appropriate discount factor to use or the damages induced by extreme events far outside the range of historical human experience (such as melting of ice sheets), are unlikely to be resolved within the time frame necessary for making important and costly decisions on climate policy.

As we argue below, the evolving nature of the science and the ultimate goal of informing first-best policy leads us to conclude that the official SCC – the SCC used for regulatory analysis by the U.S. Government – should not be thought of as a single number or range of numbers, but more broadly as a process that yields updated estimates of those numbers and ranges. Viewed in this way, the ultimate goal of the process is scientific credibility, public acceptance, and political and legal viability. Accordingly, we suggest that the process that results in an official SCC should satisfy five criteria[4]:

1) The estimate of the SCC should use the best available science and should be accompanied by quantified measures reflecting the uncertainty in the existing science, for example by providing a range in addition to a central focal estimate;
2) The method by which the SCC is computed should be transparent, replicable, and broadly explainable and understandable to non-experts;
3) The methodology should be subject to expert review and should incorporate regular updating;
4) The process should provide guidance to researchers to identify key sensitivities and areas where future research would be most productive for improving estimates of the SCC;
5) The process should not risk being viewed by the courts as arbitrary and capricious and it should be as isolated as possible from political influences.

While enhancing precision in the estimate of the SCC is desirable, improving precision is a process and we should expect that uncertainty about the SCC will persist for an extended period of time. Policy-making under uncertainty is the norm, and in this sense climate policy and the SCC is no different. Given the long time horizon for climate policy, however, both the policies and the analytical basis for those policies need to be able to incorporate and to adjust to newly available information.[5]

---

[4] Our criteria are consistent with but not directly tied to the principles for regulatory design and review laid out in guidance such as Executive Order 12866 which sets out objectives and criteria for regulatory planning and review.

[5] Interestingly, most models of optimal climate policy do not incorporate the stochastic nature of knowledge acquisition or climate outcomes, an understandable simplification given the computational challenges posed by optimal updating. A recent example of a study in which the carbon price changes as information is acquired (in this case, information about large-scale abrupt changes) is Cai, Judd, and Lontzek (2013).

These observations lead us to three conclusions. First, as we discuss in more detail below, in our view the process followed by the Interagency Working Group to estimate the SCC in 2010 and 2013, including its use of IAMs, fares well on many of these criteria. While it is certainly possible to imagine alternatives to the IAM-based process run by the U.S. government, the Interagency Working Group Process is more consistent with these criteria than alternatives such as different agencies using different values (as was done before the centralized efforts of OMB and the Interagency Working Group), failure to adopt any value (thereby implicitly adopting the clearly incorrect value of zero), or an expert panel charged with reaching a numerical judgment without reference to numerical models. This said, room remains for improving the current process. One such improvement is incorporating into the SCC process formal external expert review, and another is providing a schedule for regular updating, both suggestions recently made by Pizer et al. (2014).

Second, an ongoing challenge of the SCC process is how best to communicate the uncertainty surrounding estimates of the SCC while still providing a numerical value and range that can be used in the policy process. As Weitzman (2015) puts it, climate change is an application to which IAMs are likely to give "fuzzier" answers than usual cost-benefit analysis. In our view, a key challenge for the SCC process is balancing the tension that the SCC is subject to considerable uncertainty on the one hand, but on the other that the range of uncertainty does not plausibly include zero and that the policy process needs a SCC value and range that can be useful and actionable. We do not propose a single novel communications method for solving this problem, but do think that a process that meets the five criteria above has the best chance of tackling this communications problem in an ongoing way.

Third, the value of the SCC – whether computed using IAMs or in some other fashion that incorporates the best available science – will for the foreseeable future be provisional and subject to change. For example, the attention received by the official SCC has shown a spotlight on aspects of IAMs with considerable scientific uncertainty, such as the damage functions and the largely-unmodeled consequences of large-scale abrupt changes, and we point to vibrant new strands of research that could help to improve the IAMs and thus inform future revisions to the SCC. This combination of ongoing uncertainty and evolving estimates of the SCC requires a degree of sophistication in the public debate and in climate policies not normally required in other policy arenas.

Before developing these arguments, we first provide a brief history of the use of IAMs in U.S. climate policy, then examine the current official SCC and its uses. We then turn to the question of alternative processes for developing the SCC. We conclude that while the Interagency Working Group

process so far (including its use of IAMs) is sound and better than the alternatives, it is important to institutionalize a process for the ongoing improvement of the SCC consistent with the five criteria above.

II. IAMS and the Use of the SCC in Climate Policy

Nordhaus (2013b) defines integrated assessment models as "approaches that integrate knowledge from two or more domains into a single framework" (p. 1070). Nordhaus's definition is broad and includes a variety of models that, by themselves, do not generate estimates of the SCC.[6] Models that can be used to estimate the SCC combine a model of the economy with a model of the atmosphere and ocean (and possibly land) that allows the researcher to track geophysical and economic variables of interest. An IAM constructed to address climate change must be able to track emissions, the concentration of greenhouse gases in the atmosphere as well as other carbon sinks, temperature and other climate impacts arising from increased concentrations of greenhouse gases in the atmosphere, and damages resulting from those climate impacts. Emissions follows from economic behavior, and policies scenarios can be posited to affect emissions along a number of dimensions. Figure 1 (adapted from Nordhaus, 2013b) illustrates the modules (rectangles) and model inputs/outputs (parallelogram) of a generic IAM. Not all IAM's contain all of the elements in Figure 1. For example, we are not aware of any IAM that contains an explicit political response module that models how policy makers react to climate change damages through policy actions that lead to emission reductions.[7]

Early Regulatory Applications of the SCC. Prior to the Interagency Working Group's effort, estimates of damages from greenhouse gas emissions were incorporated into regulatory analyses in an ad hoc way that varied across agencies and rules. Some examples illustrate the evolution of thinking as well as differing agency views on SCC estimates.

The March 2006 National Highway Transportation Safety Administration (NHTSA) Final Regulatory Impact Analysis setting forth fuel economy standards for Model Year 2008-2011 light trucks states that

[6] The U.S. National Energy Modeling System (NEMS) is a good example of this latter type of model. NEMS is comprised of a number of modules representing energy supply (e.g. oil and gas, coal, renewable fuels), energy demand (residential, commercial, industrial, and transportation) and conversion modules (e.g. electricity, petroleum markets, international energy) and can produce detailed scenarios of future energy pathways. While it can be used to generate future emission scenarios under different policy assumptions, it lacks the climate, ecosystem, and damage modules that would be necessary to develop estimates of the SCC.

[7] IAM modeling exercises typically model political response as part of a given scenario. Reference case scenarios in which no action is taken to address climate change assumes one implicit political response while optimal policy scenarios posit a different political response that sets an implicit or explicit price on greenhouse gas emissions at the optimal rate.

> "[t]he agency continues to view the value of reducing emissions of carbon dioxide and other greenhouse gases as too uncertain to support their explicit valuation and inclusion among the savings in environmental externalities from reducing gasoline production and use. There is extremely wide variation in published estimates of damage costs from greenhouse gas emissions, costs for controlling or avoiding their emissions, and costs of sequestering emissions that do occur, the three major sources for developing estimates of economic benefits from reducing emissions of greenhouse gases. ... As a consequence, the agency has elected to include no economic value for reducing greenhouse gas emissions … among the benefits of reducing gasoline use via more stringent fuel economy regulation." U.S. Department of Transportation (2006), pp VIII-64 – 65.

In 2008, the U.S. Ninth Circuit Court of Appeals held that, by failing to monetize the benefits of GHG emissions reductions, NHTSA had acted arbitrarily and capriciously, and for this and other reasons remanded the rule to NHTSA to set new standards. The court stated that, "[w]hile the record shows that there is a range of values, the value of carbon emissions reduction is certainly not zero."[8]

Accordingly, in May 2008 NHTSA issued a proposed rule for MY 2011-15 passenger cars and light trucks that incorporated a SCC value of $7 per ton CO_2e (2006 dollars). NHTSA arrived at this result by averaging a high value of $14 per ton (based on estimates from the IPCC's Fourth Assessment Report and adjusted forward to 2011) with a low value of zero. This latter estimate is based on measuring damages to the U.S. economy only: "Although this finding suggests that the *global* value of economic benefits from reducing carbon dioxide emissions is unlikely to be zero, it does not necessarily rule out low or zero values for the benefit to the U.S. itself from reducing emissions" (U.S. Department of Transportation, 2008a, p. 24414, emphasis in original).

In the Agency's final environmental impact statement for the MY 2011-2015 fuel economy standards released five months later, SCC estimates of $2 per ton CO_2e (based on domestic benefits only) and $33 per ton (based on global benefits) were used U.S. Department of Transportation (2008b). The Agency based its increase in global benefits from $14 to 33 per ton on new and updated estimates of the SCC contained in Tol (2008). It also used a positive value for U.S.-only benefits based on an assessment of the ratio of U.S. to global benefits of emission reductions.

In its proposed rule for regulating greenhouse gas emissions under the Clean Air Act, the U.S. Environmental Protection Agency (2008) used four values of the SCC in a side analysis to estimate benefits of reducing emissions. EPA used global benefit estimates of $40 and $68 per ton CO_2e based on discount rates of 3 and 2 percent, respectively and domestic benefit estimates of $1 and $4 (again for

[8] *Center For Biological Diversity v. Nat'l Highway Traffic Safety Admin.*, 538 F.3d 1200 (9th Cir. 2008). This opinion replaced an earlier 2007 opinion (508 F.3d).

discount rates of 3 and 2 percent) based on a meta-analysis building on Tol (2008).[9] In all cases these estimates are for emission reductions in 2007 and are measured in year 2006 dollars. Despite reporting benefit estimates that include a SCC estimate, the EPA made clear that the agency was not endorsing a particular SCC value.[10]

In an effort to better understand the externalities associated with energy production and consumption, Congress directed the Department of Treasury in 2005 to commission a study by the National Academy of Sciences to investigate this issue. A committee was formed to undertake this task and included in its statement of task the following activity: "[d]evelop an approach for estimating externalities related to greenhouse gas emissions and climate change. Estimate externalities related to those changes" (National Research Council, 2009, p. 18). The committee concluded after an extensive survey of the literature that the SCC could range by two orders of magnitude – from $1 to $100 per ton CO_2-equivalent – depending on the choice of discount rate for discounting future damages from climate change and the degree of damages from climate change (see Table 1). The report states that "at this point only order-of-magnitude estimates appear warranted" (p. 218).

While unsatisfying from the perspective of not providing a SCC number for use in regulatory impact analysis, the NRC study highlighted two of the key modeling choices (discount rate and damage function) that drive estimates of the SCC, issues we return to below.

The Interagency Working Group and the Current SCC. The Interagency Working Group used three widely known and respected IAMs to develop an official SCC.[11] The Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) model has been used extensively by the IPCC; its developer, Richard Tol, as noted above, has carried out several meta-analyses on the social cost of carbon relying on his and other modelers' work. The Policy Analysis of the Greenhouse Effect (PAGE) model, developed by Chris Hope was most prominently used in the analysis of the *Stern Review* (2007) . The Dynamic Integrated Climate and Economy (DICE) model, developed by William Nordhaus, is especially

[9] EPA's global SCC of $40 and $68 (depending on the discount rate) differ from NHTSA's estimate of $33 despite the underlying data in both cases coming from Tol (2008). NHTSA averaged the 125 estimates in the Tol meta-analysis while EPA focused on studies concluded since 1995 and separated out estimates of the SCC according to the underlying discount rate. Without criticizing the work either of NHTSA or EPA, the divergent SCC estimates speak to the value of an official SCC number (or set of numbers).

[10] "Presentation of these values does not represent, and should not be interpreted to represent, any determination by EPA as to what the social cost of carbon should be for purposes of calculating benefits pursuant to the Clean Air Act." U.S. EPA (2008), p. 44446.

[11] This section draws heavily on Interagency Working Group on Social Cost of Carbon (2010) and Greenstone, Kopits, and Woolverton (2013).

transparent given Nordhaus's posting of the model on his website along with the various books he has written documenting and using the model (Nordhaus and Boyer, 2000; Nordhaus, 2008; Nordhaus, 2013a).

After reviewing the literature, the Interagency Working Group ran the three models using five scenarios (sets of assumptions about emissions, economic growth, population growth and other socioeconomic assumptions) with 10,000 draws each from a Roe-Baker distribution of equilibrium climate sensitivity (ECS) calibrated to assumptions taken from the IPCC's Fourth Assessment Report. The ECS measures the long-term equilibrium increase in global average surface temperature due to a doubling of greenhouse gas concentrations in the atmosphere from pre-industrial era levels and is a critical parameter in climate models. For each of three assumed discount rates (2.5, 3 and 5 percent), the 150,000 model runs were generated (3 models x 5 economic scenarios x 10,000 runs) and the results were pooled with equal weight given to each model and scenario. For each run, marginal damages were constructed as the present discounted value of the change in per capita consumption from the reference case arising from a shock to emissions in a given year.[12] The Interagency Working Group reported mean values of marginal damages for each year for the 150,000 runs associated for each discount rate. In addition it reported the 95th percentile value from the 3 percent discount rate runs as one way to take into account potentially large tail impacts of climate change.

The 2013 SCC update replicated the methodology of the 2010 report but used updated versions of the FUND, PAGE, and DICE models. Table 2 shows estimates of the SCC for 2020 and 2050 from the two reports. Focusing on the 2020 estimates from the 2013 technical update, moving from a discount rate of 5 percent to 3 percent nearly quadruples the SCC and more than quintuples it when going to a 2.5 percent rate. The SCC at the 95th percentile of the distribution with a discount rate of 3 percent is triple the mean value. Similar patterns hold for the other years. The central estimate of the SCC in 2020 increases by 65 percent between the 2010 report and the 2013 technical update, reflecting among other things updating to the damage functions and explicit representation of sea level rise in two of the models.

[12] This approach could be extended to estimate the social cost of other greenhouse gases (e.g. methane). Directly measuring the social cost through modeling would be preferable to a social cost computed as the social cost of carbon times the global warming potential for other greenhouse gases. Global warming potential (GWP) measures the radiative forcing of a greenhouse gas over a specified time period (usually 100 years) that is equivalent to a given amount of carbon dioxide. Schmalensee (1993) and Reilly et al. (1999), among others, highlight the problems with using a GWP measure in lieu of an explicit analysis of marginal impacts of emissions of various greenhouse gases.

All three models used in the 2013 Interagency Working Group's calculations exhibit mean SCC estimates greater than the median for all the scenarios and discount rates, a consequence of a long right tail of the distribution of the SCC across simulations (see Tables A2-A4 in the 2013 report). While there is variation in the estimates based on the scenario under consideration, the greater variation occurs across equilibrium climate sensitivity (as evidenced by the range of estimates for any particular model, discount rate, and scenario), discount rates, and model.

The variation across models is particularly striking. The estimates from the FUND model are considerably lower on average reflecting lower damages at all temperature levels (at least in the 2010 analysis; see figures 1A and 1B). While the 2013 update does not provide information about damages as a function of temperature change, the FUND model consistently provides lower estimates of damages at any percentile for each scenario-discount rate combination. By taking simple averages across models and economic scenarios, the Interagency Working Group took no position on the relative merits of competing models or the likelihood of differing economic scenarios, an issue to which we return below.

Current Uses of the SCC. Currently the SCC is used as an input into official cost-benefit analyses of proposed regulations, as part of legal challenges to government actions, and as a measure of the costs of climate change in the public discussion about climate policy. We turn to examples of each of these three uses.

In June 2014, the U.S. Environmental Protection Agency (2014) released its regulatory impact analysis for proposed guidelines on carbon emissions from existing power plants (EPA's Clean Power Plan). EPA's summary of the estimated monetized benefits of the proposed rule includes four estimates of the benefits of reduced carbon dioxide emissions using the four estimates from the Interagency Working Group's 2013 technical update: mean averages at 2.5, 3.0, and 5.0 percent discount rates and the 95th percentile value from the distribution of estimated SCC's from the 3 percent discount rate run. Unlike previous NHTSA or EPA analyses, but consistent with the multiple prior uses of the Interagency Working Group's estimates,[13] there is no attempt to disentangle global from U.S. benefits noting the

> distinctive nature of the climate change problem. Emissions of greenhouse gases contribute to damages around the world, even when they are released in the United States, and the world's economies are now highly interconnected. Therefore, the SCC estimates incorporate the worldwide damages caused by carbon dioxide emissions in order to reflect the global nature of the problem, and we expect other governments to

[13] For example, prior regulatory uses of the SCC for cost-benefit analysis include multiple energy efficiency rules under the Energy Independence and Security Act, Sewage Sludge Incineration Emission Standards (75 *Federal Register* 63260), and Fuel Efficiency Standards for Medium- and Heavy-Duty Vehicles (75 *Federal Register* 74152).

> consider the global consequences of their greenhouse gas emissions when setting their own domestic policies. (EPA, 2014, p. ES-14)

In keeping with numerous other cost-benefit analyses of energy/environmental regulations since OMB's adoption of the 2010 Interagency Working Group report, the 2014 Regulatory Impact Assessment (RIA) explicitly defers to the Interagency Working Group's estimate of the SCC. The RIA uses the Working Group's central value, the mean of the distribution of SCC estimates from runs where a 3 percent discount rate is assumed (Tables ES-8, 9, and 10 of the RIA).

The SCC appears in legal decisions as well. For example, the SCC played a central role in a June 2014 U.S. District Court judge's decision to rescind the U.S. Bureau of Land Management's (BLM) granting of a lease to Arch Coal to expand coal mining in an area of the Gunnison National Forest in Colorado (Jackson, 2014). In its quantification of the benefits and costs of the lease expansion, BLM had excluded any costs associated with the release of methane and other greenhouse gases arguing that "[s]tandardized protocols designed to measure factors that may contribute to climate change, and to quantify climatic impacts, are presently unavailable" (p. 17 of decision). The judge in the case explicitly rejected that claim finding that "… a tool is and was available: the social cost of carbon protocol," (p. 17) going on to describe the Interagency Working Group Technical Support Document. The decision notes that while the preliminary environmental impact statement had contained estimates of the climate impacts using the Interagency Working Group's SCC estimates, monetized climate impacts were excluded from the final environmental impact statement apparently in response to an email from a BLM economist who argued that the use of SCC was "controversial" citing the wide range of estimates both in the Interagency Technical Support Document as well as other sources. In effect, the existence of uncertainty over the SCC led BLM to replace a positive value for the SCC in the quantitative analysis it undertook with a value of zero. The judge deemed that decision "arbitrary and capricious" (p. 19 of decision). This decision marks a significant milestone in legitimizing the Interagency SCC by overturning a federal agency decision on the grounds that the working group's SCC estimates were not employed in the benefit cost analysis.[14]

The SCC also plays an important role in the public discussion of the costs of climate change and the monetized benefits of emissions reductions. A leading example concerns public discussions about what the appropriate value of a carbon tax might be. The American Opportunity Carbon Fee Act, a bill introduced by Senators Whitehouse and Schatz in 2014, proposes a carbon fee starting at $42 per ton in

[14] The judge finalized his decision in September and neither BLM nor Arch Coal appealed the decision (Sierra Club, 2014).

2015. According to the accompanying press release, "The price of the fee follows the Obama Administration's central estimate of the 'social cost of carbon,' the value of the harms caused by carbon pollution including falling agricultural productivity, human health hazards, and property damages from flooding."[15] Introduced in the lame duck session of the 113th Congress, the bill did not generate widespread public debate. Notably, however, at least some conservative commentators accepted the linkage of the fee to the SCC, but emphasized that because of interactions with the rest of the tax system, leakage, and without future international coordination the optimal tax would be less than the SCC (Murphy, 2014). In this aspect at least, the public discussion echoes the academic literature which points out that in practice the optimal carbon tax depends not just on the external cost of marginal carbon emissions but on its implementation and how it interacts with the rest of the tax code.

III. IAMs: A Starting Point for Improving SCC Estimates or Fundamentally Flawed?

The central question of this symposium is whether IAMs constitute an acceptable basis for estimating the SCC or whether an alternative approach is needed. We break this question down into two pieces. The first, which we address in this section, is an assessment of the scientific shortcomings of existing IAMs and whether there is reason to think that these shortcomings will be addressed in a time frame consistent with the formulation of climate policy. The second piece of the question, which we address in the next section, is whether a better alternative exists in the context of the existing institutional and legal structure of climate policy formulation and implementation.

The paper by Weyant (forthcoming) in this symposium provides a detailed description and history of the evolution of IAMs over the past 30 years. What is clear from a reading of Weyant's paper as well as the survey of IAMs in Nordhaus (2013b) is that IAMs and their role in SCC calculations have helped focus the attention of researchers on key areas of scientific uncertainty that drive many of the results in SCC calculations. Given the complexity of modeling climate change and its interaction with the global economy, it is encouraging that the critically important areas of sensitivity can be narrowed down to a handful. Especially important are 1) equilibrium climate sensitivity; 2) damage functions; 3) treatment of catastrophic events; and 4) the discount rate. There are, of course, other areas where research progress would be quite valuable but these four areas stand out. As we think about the value of future research in each of these areas, we are struck by how fundamentally different these four areas are in terms of how optimistic we can be about pinning down our understanding of these key inputs.

[15] http://www.whitehouse.senate.gov/news/release/sens-whitehouse-and-schatz-introduce-carbon-fee-legislation

Because the equilibrium climate sensitivity is the province of geophysical climate science, we stick to the economic focus of this journal (and our own expertise) and focus on the final three issues in turn.[16]

***Damage functions*.** The early damage functions in IAMs come from top-down cross-sectional analysis of the relation between the level of GDP and temperature, and thus associate warming with a shift in the level of future GDP, that is, a downward parallel shift in the path of GDP. In part because of the public importance of the SCC, current literature has undertaking a critical reexamination of these damage functions. Indeed disentangling temperature effects from other effects in top-down cross-sectional levels regressions faces significant identification challenges. As a result, this literature has focused on different identification strategies. One is to use short-run variation in the weather to examine effects on GDP growth; see for example Dell, Jones, and Olken (2012) and Deryugina and Hsiang (2014). Because weather variations are plausibly exogenous, after suitable conditioning on geographic variables, they allow estimates with greater internal validity than cross-sectional GDP regressions. On the negative side, the short-run nature of weather makes it challenging to analyze the effects of adaptation or to estimate with much confidence whether there are long-term effects on economic growth rates, not just levels, of weather or climate shocks. An alternative approach is to construct bottom-up estimates of damages. While a much larger undertaking than the top-down approach, a bottom-up approach is potentially amenable to more compelling identification strategies. For example, the property damage estimates in Koop et al. (2014) combined an insurance company compilation of built property values on the U.S. East Coast, elevation maps, and actual and simulated hurricane tracks to estimate the property damage cost of increased sea level rise and possibly stronger storms with more easterly tracks. Additional recent bottom-up research in the weather literature focuses on the effect of temperatures on labor productivity, health, crime, political unrest, and other elements of the total cost of climate change (see the survey by Dell, Jones, and Olken, 2014). And because the planet is now experiencing the early effects of climate change, new data are being generated that can be used to estimate damage functions, at least for the relatively small changes experienced so far. Most of the work in this area is quite new, the literature is growing very quickly, and the available data are expanding. All this makes us optimistic that this literature is on a path towards substantially better-identified estimates of damage functions in IAMs.

[16] It is worth noting, however, that despite some 35 years of research, there has been little progress in narrowing the likely range of estimates of climate sensitivity (Weitzman, 2015).

Climate catastrophes. As discussed in National Research Council (2013), the Earth's climate history suggests the existence of "tipping points," that is, thresholds beyond which major changes occur that may be self-reinforcing and are likely to be irreversible over relevant time scales. Some of these changes, such as the rapid decline in late-summer Arctic sea ice, are already under way,[17] while others, such as the release of methane from thawing Arctic permafrost, could reinforce GHG warming but are considered unlikely to occur in this century.[18] The Weitzman (2009) dismal theorem focused the attention of the climate economics community on the potentially critical role of large-scale events that are abrupt on geological scale – so-called climate catastrophes – for formulating climate policy. The main thrust of the dismal theorem is that, with concave utility, society should be willing to pay substantial sums now to avoid worst-case catastrophic outcomes, what Pindyck (2011) and Weitzman (2011) have called "climate insurance." [19]

This literature points to an important element of GHG emissions externalities being the possibility of worst-case outcomes. The challenge is how to turn this into a monetary value; as the review in the previous section indicates, a number (or a range of numbers) is in the end needed in the regulatory and political process. The Interagency Working Group's estimate of the SCC does not explicitly model or account for climate catastrophes.[20] Because the climate catastrophe channel is largely distinct from the "local" damage function estimates arising from warming within the scope of human experience, a reasonable question is whether the climate catastrophe cost should be computed separately for the SCC, or whether it should be computed within IAMs. This is essentially a technical question on which we do not have strong views. If the two effects are additive, then separate computations could be justified, but this additivity would need to be demonstrated. Given the sensitivity of the "normal warming" estimate and, presumably, of the interaction between tipping points and the ECS, one can imagine that the two effects would not be additive. In any event, Weyant's paper in this

[17] Joughin, Smith, and Medley (2014) and Rignot et al. (2014).
[18] National Research Council (2013).
[19] The details of Weitzman's theorem are sensitive to functional form assumptions but the broader point that risk aversion induces a willingness to pay a potentially large sum for insurance is not. See, for example Newbold and Daigneault (2009), Ackerman et al. (2010), Pindyck (2011, 2013), Nordhaus (2011, 2012), Litterman (2013), Millner (2013), and Weitzman (2011, 2014).
[20] While the Interagency Working Group modeled worst-case outcomes, and attempted to capture severe risks by reporting a high value of the SCC based on the 95th percentile value of the SCC drawn from a distribution of runs with a 3 percent discount rate, the analytical framework for those severe outcomes was obtained from large draws of the ECS combined with the standard IAM damage functions. Because those damage functions were calibrated from historical cross-country temperature comparisons they do not do justice to the mass extinctions, population disruptions, and land loss associated with some of the abrupt large-scale events such as the melting of the Greenland ice sheet.

symposium makes it clear that there is much research to be done before IAMs are capable of addressing catastrophic risk. Still, in our view it would be a mistake simply to focus on tail events given the likelihood of disruption to particularly vulnerable communities over the next few decades from climate change. The "normal warming" costs are still highly likely to be economically meaningful and are particularly salient.

Discount rates. Climate change involves damages that extend many hundreds of years into the future. While there have been advances in our understanding of long term discount rates on the order of a century (see, for example, Giglio, Maggiori, and Stroebel, 2014) it is not clear that an appropriate framework exists for empirically identifying discount rates over the several centuries used to estimate the SCC. One then has two choices: use existing data and – with some assumptions – adapt results to a time span that is an order of magnitude longer than the span over which estimates were made, or adopt an explicitly ethical and normative perspective, along the lines of Stern (2007). Neither approach is entirely satisfying, and our reading of the literature is that it is unresolved on basic issues, such as whether to use market rates, consumption-based (Ramsey) discounting, whether discounting should be horizon-dependent, or whether a normative approach should be adopted. To us, it seems that these basic issues reflect fundamentally different perspectives or philosophies and it is hard to see how debates over discount rates will be resolved soon.[21]

These observations suggest that uncertainty in the three key areas of damage functions, climate catastrophes, and discount rates is likely to persist, so that estimates of the SCC will continue to exhibit considerable uncertainty over the foreseeable future. One could interpret this conclusion as implying that IAMs should be abandoned for some other method for estimating the SCC, but we interpret it differently. Uncertainty is rife in economic and scientific research; after all that is why new research is undertaken. While the current vigorous research in these areas is unlikely to result in a lasting consensus on the right damage function, for example, it is reasonable to expect that this research will serve to characterize, and in some cases tighten substantially, the range of technical uncertainty associated with these and other issues within IAMs. With a better quantification of uncertainty, one that is based on ongoing research, the IAMs can better serve to quantify, and we think narrow, the range of uncertainty of the SCC as well as provide an increasingly solid scientific basis for the various steps in the

[21] For various perspectives on discounting see Nordhaus (2013a), Arrow et al. (2013), Litterman (2013), and Barro (2015).

calculation. The idea of abandoning IAMs as the basis for the SCC, just as a burgeoning body of research promises to improve them and their measures of uncertainty, strikes us as misguided.

IV. The SCC as a Process, not a Number

Given the scientific uncertainty inherent in the current generation of IAMs, should the IAM-based SCC be replaced, as Pindyck (2013) has suggested, with another approach? We can think of at least five alternative approaches to that taken by the Interagency Working Group. We assess these alternatives using the five criteria laid out in the introduction: using the best available science and quantifying uncertainty; transparency, replicability, and comprehension; being subject to expert review and regular updating; providing guidance for ongoing research; and not being arbitrary and capricious and isolating the process from political pressure.

The first alternative approach would be to say that scientific work is so incomplete, and uncertainty so vast, that the Government simply should not use a SCC until more research is completed. We consider this position to be indefensible: while there is debate over how large the SCC is, the overwhelming evidence is that the costs of climate change are real and significant and that whatever the true value of the SCC is, it is not zero. Using a value of zero in cost-benefit analysis would restrict climate regulations to ones justified solely by their co-benefits. Because it is inconsistent with the best available science, abandoning the SCC because of uncertainty has already been rejected by the courts as arbitrary and capricious, as discussed above.[22]

A second alternative is to drop an official SCC but to allow agencies to provide their own individual SCCs and thereby comply with the court requirement for an SCC. This alternative also is a step backwards and fails in multiple dimensions, including transparency and being explainable. The inherent redundancy also makes it administratively complex, less likely to use the best available science, and a poor use of limited government resources.

A third alternative to constructing an official SCC for policy purpose takes a "revealed preference" approach. Policy design in a number of political jurisdictions has led to a cost of carbon

[22] A more nuanced version of this argument is that uncertainty about a model, or about key policy parameters (such as the SCC), could warrant taking a conservative approach to its implementation. Brainard (1967) provided an early articulation of this view in the context of monetary policy, suggesting that uncertainty would lead to caution when the policy has costs. Brainard's (1967) result is special, however. Giannoni (2002), for example, considers a monetary model in which optimal policy guards against particularly bad models by responding more aggressively to shocks, not less, than when there is no model uncertainty; also see Hansen and Sargent (2007) and Cai, Judd, and Lentza (2013). In any event, this more nuanced argument does not imply biasing the estimate of the SCC towards zero, rather it concerns whether the policy path should be more conservative or more aggressive in the face of uncertainty.

being implicitly or explicitly mandated. Examples include British Columbia's carbon tax, California's cap and trade system, the EU's emissions trading system, and South Korea's recently enacted cap and trade system. The official SCC would then be some average of a selected set of existing programs under the theory that the policy process has chosen the socially appropriate SCC. This approach has the virtue of being explainable – the U.S. is just following suit – and could be updated when other jurisdictions change their SCC. But it fails on most of the other criteria, such as using the best available science, being subject to peer review, conveying uncertainty, and providing guidance to researchers for further improvements. Indeed, this approach only works under the heroic assumption that the political process manages to absorb the relevant scientific evidence while ignoring all costs of mitigation, especially those falling on politically important interest groups. A political revealed preference approach seems quite unlikely to approximate the true SCC.

A fourth alternative is that the U.S. government would construct and maintain its own official integrated assessment model for U.S. policy purposes, instead of using (as did the Interagency Working Group) leading peer-reviewed models. This might be done, for example, by adding models of the physical processes in the ocean, atmosphere, and land cover to existing modules in the Energy Information Administration's annual integrated energy market model, the National Energy Modeling System (NEMS), and by enhancing the NEMS international energy activity module. The advantage of this approach is that there would be "in-house" modeling capabilities and expertise within the Federal government to build and maintain the model and to improve it as new research and insights into climate change emerges. If properly implemented and funded, this approach would do well by many of the five criteria, including using the best available science, quantifying uncertainty, periodic updating, external review, and providing guidance to researchers. The disadvantage, however, is that expertise would have to be built up within the federal workforce to build the model and there is no assurance that sufficient capacity would be in place to carry out such an ambitious undertaking and to keep up with scientific developments. Perhaps more important, it is not clear that a federal IAM would be sufficiently transparent and explainable that the public would have confidence in making policy from that model only; in the end, this alternative has the Federal government making myriads of modeling judgments which will inevitably be viewed as subject to political influence. While the NEMS model has high credibility, the NEMS modeling judgments (such as how best to aggregate time periods and electricity generation regions) to balance output detail against computational feasibility are far less controversial, and have far less reaching ramifications, than the judgments involved in building a climate damages module for different regions of the world. And in the end an in-house model could be subject to political

pressure – or appear to be subject to pressure – even if it were housed at an independent agency or a national laboratory – through the budget process which necessarily reflects the political positions of the Executive Branch and Congressional appropriators.[23]

The fifth approach, which is proposed by Pindyck in his paper in this symposium and in Pindyck (2013), is to base the SCC on expert judgment. For example, the U.S. Government could contract with the National Research Council to constitute a standing panel of experts which would deliberate on the SCC, reach an initial estimate, and convene again every five years to consider whether a new SCC value is warranted based on how the judgment of the members has evolved in the interim. If implemented properly, this process could be based on the best available science as interpreted by the experts, it would entail regular updating, the experts could convey their judgment both of the SCC and its quantified uncertainty, and the experts could convey their views to researchers about what additional research is needed. But in our view this proposal falls short on the other criteria, especially if (as Pindyck's proposal would, it seems, have it) there is a side constraint that the experts are prohibited from using IAMs. If the experts are not allowed to use IAMs, then that presumably would disqualify many experts who have devoted much of their careers to developing IAMs, since their expert judgments would be heavily informed by the IAMs on which they have labored. Presumably those experts who focus on climate catastrophes/climate insurance calculations would also be precluded from using IAMs, which close off one line of quantifying that insurance value. One suspects that some of these experts would object to these preclusions which they would feel, in their expert judgment, are not scientifically warranted: Excel is OK, DICE is not? In any event it is hard to see how a panel of experts, precluded from using a class of models, would result in an estimate that is transparent, replicable, and uses the best available scientific information. Moreover, as a practical matter, it is hard to see how a judgmental expert panel would not be subject to political influences, since a standard institutional practice is to balance panels of experts not by weighting by scientific credibility but by ensuring representation of a spectrum of views. And – at the risk of being accused of practicing law without a license – it is also hard for us to see how a panel-of-experts approach, with the side constraint of not using a class of scientific tools, would be viewed by the courts as other than arbitrary and capricious.[24]

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[23] An official government model would also go against the norm of using the peer reviewed literature in regulatory impact analysis rather than independent government analysis. We thank Joe Aldy for pointing this out.

[24] Pindyck's argument is based in part on his view that the panel should focus only on catastrophic risks. We argued above that the research on non-catastrophic damages is steadily improving and that damage functions are increasingly calibrated to real-world data. Another argument for focusing on non-catastrophic risk is the need in the international climate negotiations to demonstrate credibility about developed country concerns with near-

In the end, each of these alternative approaches fails to meet many of our five procedural criteria. As the discussion of the panel-of-experts approach makes clear, we find it hard to imagine a successful process for estimating the SCC that does not involve the use of IAMs. The science behind climate change is extraordinarily complex and the interaction between the climatic and economic outcomes calls for the use of both physical and economic models. This is the very essence of IAMs. To us, it is unescapable that integrated modeling must play some role in the analysis.

What about the process followed by the Interagency Working Group? In our view, that process does reasonably well on the five criteria, but room remains for further improvement. Conditional on the models, the computational approach is straightforward and follows from economic and statistical principles. One can always argue with specific modeling choices the working group made. In particular weighting the three models and different economic scenarios equally in its averaging suggests all models/scenarios have equal credibility. The difference across the models is, however, so striking that it begs expert review and judgment of these models (and other potential models for consideration in the process) to put appropriate weight on whichever models are included in the analysis.

Setting aside issues of weighting model runs, the process itself is scientifically sound. The process itself is transparent and readily understandable given the care with which the 2010 Technical Support Document was written, and the rarely-satisfied Government Accountability Office (2014) found the process to be consistent with federal standards for internal control. As a by-product of the results it reported, the Interagency Working Group made clear the importance of key parameters, most notably discount rate, distribution of ECS, and damage function choices. This gives useful feedback to the research community.

But we believe the process has room for improvement on three related criteria. First, the Technical Support Document indicates that the estimate will be reviewed from time to time as new science becomes available, but there is no explicit process for that review and for the production of new estimates. Second, while there have been multiple opportunities for the public to comment officially on the SCC and the Technical Support Document, there is no formal framework for external expert review. Third, although the Interagency Working Group made several decisions that protected it from political influence,[25] the process is organized by the Executive Office of the President and, regardless of whether

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term damages to the most vulnerable developing countries. A social cost of carbon process that ignored non-catastrophic damages would undermine on-going efforts to build and sustain that credibility.

[25] For example, although the Interagency Working Group was headed by the Executive Office of the President through the Council of Economic Advisers and the Office of Management and Budget, it mainly consisted of numerous agencies representing disparate interests and expertise. The decision to use leading peer-reviewed

there is in fact political influence, the process is likely to retain the perception of political influence. These issues are addressed by the recommendations of Pizer et al. (2014), who suggest a regular revision schedule (e.g. every 5 years); that the process should be similar to the interagency process used for the 2010 and 2013 analyses; that the estimates should be regularly reviewed by National Research Council, a branch of the National Academy of Sciences; and that the process should be codified through an Office of Management and Budget (OMB) memo or circular. We agree with these recommendations, which would transform the SCC from being a single number, or snapshot of the research, into a stable process for revision. It would be essential that the expert scientific review be coordinated so that NRC recommendations can be incorporated into the subsequent updating process. In addition to enhancing transparency, providing expert review, and providing guidance for further research, regular oversight by the National Research Council provides additional protection from political influence since attempts at political influence would presumably be called out by the review panel. Still, an issue that could be explored is whether additional steps are warranted to further protect the process from political influence, for example housing the technical work associated with the models at a national laboratory or an independent agency such as the Energy Information Administration.

V. Conclusion

These remarks lead to several conclusions. Given its importance in regulatory implementation and the public debate, an official SCC must be as credible as possible; we propose five criteria aimed at ensuring that credibility. To the point of this symposium, the SCC must have a numerical value and be associated with numerical measures of uncertainty, and we cannot see how that can be done credibly without sophisticated computer models that incorporate climate and economic considerations, that is, without IAMs. Complicating all this, the horizon over which the uncertainty surrounding the costs of climate change is resolved extends beyond the horizon in which climate policy decisions must be made, and moreover estimates of the SCC will change as new science becomes available. These conclusions imply climate policy must be sufficiently sophisticated that it can adapt to evolving science and evolving estimates of the SCC. This will require a challenging degree of sophistication in climate policy.

To date the SCC has been used in ways that are important but, to the best of our knowledge, its numerical value has never been determinative for major regulations. The cost-benefit analyses for energy efficiency regulations typically find them justified from the energy savings alone, and in the

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models instead of just one model, or an internally-developed model, also provided a layer of insulation from political influences.

largest rule in which the official SCC has been used, the EPA's Clean Power Plan, the rule would have positive net benefits even if the SCC were zero given the health co-benefits of reducing particulate emissions. For these applications of the SCC so far, climate benefits have been secondary. But, as the Whitehouse-Schatz carbon fee bill makes clear, the SCC must be able to stand on its own as a measure of the price of carbon in meaningful market-based policies for reducing GHG emissions. It is hard to see how that can happen without sophisticated integrated frameworks for computing marginal climate damages, that is, without IAMs. The task, then, of the research community is to continue the exciting and important new work on improving our understanding of climate damages, large-scale abrupt geophysical changes and their economic consequences, and long-term discount rates.

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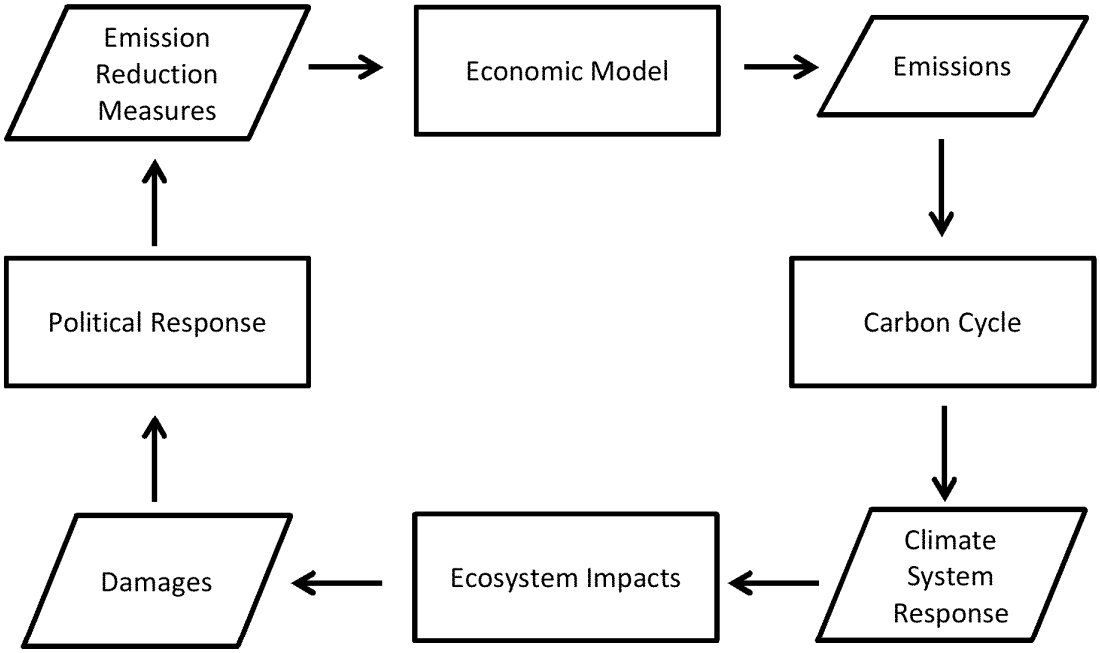

Figure 1. Integrated Assessment Model Schematic

Table 1. Indicative Damages from Greenhouse Gas Emissions: NRC Study

	Damages from Climate Change	
Discount Rate	Relatively Low	Higher
1.5 percent	10	100
3.0 percent	3	30
4.5 percent	1	10
Source: NRC (2009)		

Table 2. Interagency Working Group SCC Estimates

Discount Rate Year	5.0% Mean	3.0% Mean	2.5% Mean	3.0% 95th Percentile
2020	$7	$26	$42	$80
2020(rev)	12	43	64	128
2050	16	45	65	136
2050(rev)	27	71	98	221

Source: Interagency Working Group (2010, 2013). Table reports estimates of the social cost of carbon measured in 2007$ per metric ton. "rev" indicates revised estimates from the 2013 technical update.

To: Stock, James[james_stock@harvard.edu]
Cc: Metcalf, Gilbert E.[Gilbert.Metcalf@tufts.edu]
From: Kopits, Elizabeth
Sent: Wed 5/6/2015 5:44:05 PM
Subject: RE: Paper on IAMs and climate policy

Hi Jim,

I am sorry to be so slow in responding to this non-responsive

non-responsive

non-responsive Is this REEP symposium finalized yet? I am very interested to read your paper – is the version you sent me in February still the most recent/final? Someone sent me an April version of Pindyck's paper so I just looked at that as well.

Best,

Elizabeth

From: Stock, James [mailto:james_stock@harvard.edu]
Sent: Thursday, February 12, 2015 2:55 PM
To: Kopits, Elizabeth
Cc: Metcalf, Gilbert E.
Subject: FW: Paper on IAMs and climate policy

Elizabeth,

Attached is a draft of a paper for a REEP symposium on the use of integrated assessment models for climate policy that Gib Metcalf I have written (the other two papers are by John Weyant and by Bob Pindyck). I'd be very interested in your reactions.

Thanks and best regards,

Jim

To: Jenkins, Robin[Jenkins.Robin@epa.gov]; Snyder, Brett[Snyder.Brett@epa.gov]; McGartland, Al[McGartland.Al@epa.gov]; Marten, Alex[Marten.Alex@epa.gov]
From: Ferris, Ann
Sent: Thur 7/23/2015 7:10:05 PM
Subject: FW: SBCA Newsletter - July 2015

Fyi.

The next issue of the JBCA will be available online in the coming weeks. Articles will include the following:

- "Pricing Lives for Corporate and Governmental Risk Decisions" - W. Kip Viscusi
- "Valuing Regulations Affecting Addictive or Habitual Goods" - David M. Cutler, Amber Jessup, Donald Kenkel, and Martha A. Starr
- "Estimating the Job Impacts of Environmental Regulation" - Anna Belova, Wayne B. Gray, Joshua Linn, Richard D. Morgenstern, and William Pizer
- "Challenges in including BCA in Planning Approval Processes: Coal Mine Projects in New South Wales, Australia" - Robert Gillespie and Jeff Bennett
- "Benefit-Cost Analysis in the States: Status, Impact, and Challenges" - Darcy White and Gary VanLandingham
- "The Energy Efficiency Gap in EPA's Benefit-Cost Analysis of Vehicle Greenhouse Gas Regulations: A Case Study" - Gloria Hefland and Reid Dorsey-Palmateer

From: Society for Benefit-Cost Analysis [mailto:sbcainfo@uw.edu]
Sent: Thursday, July 23, 2015 2:55 PM
To: Ferris, Ann
Subject: SBCA Newsletter - July 2015

Problems displaying this message? View it on the web.

July 2015 News and Updates

Join Us | **Save the Date: 2016 Conference and Workshops**

The Society for Benefit-Cost Analysis Eighth Annual Conference and Meeting will take place on March 16–18, 2016 in Washington, D.C., with pre-conference professional development workshops on Wednesday and the conference on Thursday and Friday.

The conference will again be held at the George Washington University (but with more space to fit our growing attendance!).

The call for submissions will be going out in the coming weeks; please watch your inbox and the SBCA website for more details and updates. Registration will open in December.

2016 Program Committee:

- Susan Dudley, Chair (GW Regulatory Studies Center)
- Richard Belzer (Regulatory Checkbook)
- Sandra Hoffmann (U.S. Department of Agriculture)
- Lynn Karoly (RAND Corporation)
- Don Kenkel (Cornell University)
- Clark Nardinelli (U.S. Food and Drug Administration)
- Emile Quinet (Ecole des Ponts-Paris)
- Stuart Shapiro (Rutgers University)
- Anne Smith (NERA Economic Consulting)
- Craig Thornton (Econometrica, Inc.)
- Gary VanLandingham (The Pew Charitable Trusts)
- Jack Wells (retired - U.S. Department of Transportation)

Please feel free to contact SBCA Executive Director Erika Dowd with any suggestions or questions related to the conference.

Read more on our website

Welcome to Our Newest Organizational Affiliates

- Fisheries and Oceans Canada
- University of Chicago Harris School of Public Policy

We thank all of our affiliates and invite your organization to join as

well. More information is available on our website and the full list of 2015 affiliates is below.

Next Issue of *Journal of Benefit-Cost Analysis* Coming Soon

The next issue of the JBCA will be available online in the coming weeks. Articles will include the following:

- "Pricing Lives for Corporate and Governmental Risk Decisions" - W. Kip Viscusi
- "Valuing Regulations Affecting Addictive or Habitual Goods" - David M. Cutler, Amber Jessup, Donald Kenkel, and Martha A. Starr
- "Estimating the Job Impacts of Environmental Regulation" - Anna Belova, Wayne B. Gray, Joshua Linn, Richard D. Morgenstern, and William Pizer
- "Challenges in including BCA in Planning Approval Processes: Coal Mine Projects in New South Wales, Australia" - Robert Gillespie and Jeff Bennett
- "Benefit-Cost Analysis in the States: Status, Impact, and Challenges" - Darcy White and Gary VanLandingham
- "The Energy Efficiency Gap in EPA's Benefit-Cost Analysis of Vehicle Greenhouse Gas Regulations: A Case Study" - Gloria Hefland and Reid Dorsey-Palmateer

We are also thrilled to announce that all issues of JBCA Volumes 1–5 (2010–2014) are now available as **permanent free access** on the JBCA website. We hope you enjoy reading and downloading these articles free of charge. To access future issues, please join the SBCA and/or subscribe to the Journal.

For more details about the upcoming issue, please watch the JBCA page on our website for announcements and sign up for Table of Contents alerts.

SBCA Survey Update

Thank you to all who provided your thoughtful feedback in our recent survey. We are working on analyzing the responses and will be looking at ways to incorporate your input and suggestions into our work going forward. We appreciate your time!

Contribute to Our Online Resource Listings

As a service to our members and the field, SBCA provides listings of useful resources on our website, including:

- Career Listings and Funding Opportunities
- Professional Development and Training
- Benefit-Cost Analysis Databases

In addition to visiting these pages, we hope you will contribute to them by submitting relevant resources. Please contact the SBCA Executive Director with any suggestions or questions.

You may also share resource information, discussion topics, and relevant announcements to our LinkedIn group page.

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- Exxon Mobil*
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- Industrial Economics, Incorporated*
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- University of Kentucky Department of Economics
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Please visit our membership page for information about becoming a 2015 Organizational Affiliate and a list of past Affiliates.

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To: Marten, Alex[Marten.Alex@epa.gov]
Cc: Sarofim, Marcus[Sarofim.Marcus@epa.gov]; Wolverton, Ann[Wolverton.Ann@epa.gov]; Griffiths, Charles[Griffiths.Charles@epa.gov]; Newbold, Steve[Newbold.Steve@epa.gov]; Shouse, Kate[Shouse.Kate@epa.gov]; McGartland, Al[McGartland.Al@epa.gov]
From: Fawcett, Allen
Sent: Wed 6/24/2015 6:29:27 PM
Subject: Re: Start on list of potential candidates for NAS SCC committee

Ex 5

On Jun 24, 2015, at 2:20 PM, Marten, Alex <Marten.Alex@epa.gov> wrote:

This time with the list. And Marcus' questions.

Beyond climate sensitivity the climate science questions in the charge are below.

Ex 5

Climate Science

Ex 5

Ex 5

Hi Alex, Elizabeth,

Could you also forward the original list?

Ex 5

Ex 5

-Marcus

--

Alex L. Marten
phone: (202) 566-2301
email: marten.alex@epa.gov

From: Kopits, Elizabeth
Sent: Tuesday, June 23, 2015 12:48 PM
To: Marten, Alex; Wolverton, Ann; Griffiths, Charles; Newbold, Steve; Shouse, Kate
Cc: McGartland, Al; Fawcett, Allen
Subject: Start on list of potential candidates for NAS SCC committee

Hi all,

I have started to pull together some names we could potentially forward to the NAS for consideration. See attached list and notes. Please let me know what you think, including views on whether any should be deleted or added. Also, please let me know if you have a preference for how we organize/transmit our suggestions, e.g.:

Ex 5

Ex 5

While there is no firm deadline, it would be great to have your thoughts soon (Thursday?) so we can send some suggestions along to Josh by the end of the week/early next week. If it would be helpful to have a short meeting to discuss let me know and I will send an invite.

Thanks,

Elizabeth

<potential committee suggestions.docx>

ENVIRONMENTAL ECONOMICS

Using and improving the social cost of carbon

Regular, institutionalized updating and review are essential

By **William Pizer,[1,2]*† Matthew Adler,[1] Joseph Aldy,[2,3] David Anthoff,[4] Maureen Cropper,[2,5] Kenneth Gillingham,[6] Michael Greenstone,[7] Brian Murray,[1] Richard Newell,[1,2] Richard Richels,[8] Arden Rowell,[9] Stephanie Waldhoff,[10] Jonathan Wiener[1,2]**

The social cost of carbon (SCC) is a crucial tool for economic analysis of climate policies. The SCC estimates the dollar value of reduced climate change damages associated with a one-metric-ton reduction in carbon dioxide (CO_2) emissions. Although the conceptual basis, challenges, and merits of the SCC are well established, its use in government cost-benefit analysis (CBA) is relatively new. In light of challenges in constructing the SCC, its newness in government regulation, and the importance of updating, we propose an institutional process for regular SCC review and revision when used in government policy-making and suggest how scientists might contribute to improved SCC estimates.

POLICY

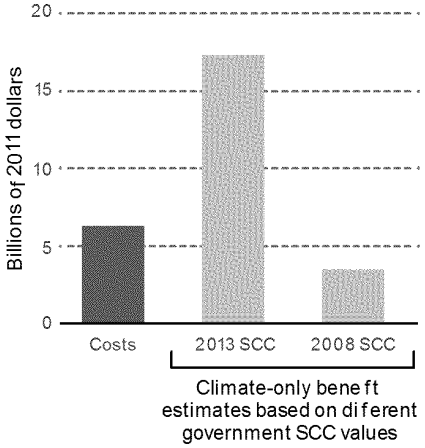
Although regulations issued by U.S. federal agencies have been subject to CBA for four decades, those analyses largely ignored economic benefits of carbon reduction until a federal court held in 2008 that carbon emission reductions have nonzero value. After a brief period during which different U.S. agencies used different SCC numbers, an interagency working group established a single set of government-wide values in 2009 and 2010, with an update in 2013 (*1*).

Such updates arise because the science, impact estimates, and socioeconomic models used to develop the SCC continue to evolve, as do expert opinions about how it should be synthesized. The results for CBA are consequential (see the graph). Using the most recent central value of interagency SCC estimates, a proposed U.S. rule on emissions from existing power plants would pass a CBA on climate benefits alone (*2*); using the central value SCC from a single agency in 2008 (*3*), it would not.

Estimating the SCC in a particular year, say 2015, involves four steps: (i) projecting a future path of global greenhouse gas (GHG) emissions; (ii) translating this emissions path, along with an alternative that adds 1 ton in 2015, into alternate scenarios of climate change; (iii) estimating physical impacts of these climate changes on humans and ecosystems; and (iv) monetizing these impacts and discounting future monetary damages back to 2015. The SCC is the difference in damage valuations with and without the extra ton of CO_2 in 2015.

Integrated assessment models [IAMs; e.g., DICE (*4*), FUND (*5*), and PAGE (*6*)], perform all four steps. Underlying step (i) are assumptions about future climate change policies and their effects on GHG emissions and about population, GDP growth, and technology. In step (ii), a simplified representation of the climate system translates emissions to metrics of climate change (e.g., change in global average temperature). Steps (iii) and (iv) require a damage function that relates climate change metrics to climate impacts and to valuations. Valuation of impacts often aggregates and/or extrapolates detailed climate impact studies and relies on population and economic assumptions from step (i) to project the level of human and economic activity exposed to these impacts in the future.

Costs and benefits of emissions reductions



Benefits of regulations vary. Estimated costs and climate change benefits of emission reductions in 2020 from proposed U.S. power plant regulations using 2008 (*3*) and 2013 (*2*) government SCC estimates. Estimates from table 18 in (*2*) using a 3% discount rate averaged over state and regional approaches. SCC estimate from table V-3 in (*3*), rising 2.4% per year to $8.67 in 2020, multiplied by avoided emissions estimates averaged over state and regional approaches from table 10 in (*2*), and inflation adjusted using the implicit GDP price index from the U.S. Bureau of Economic Analysis.

DIFFICULT CHOICES. Constructing an SCC for government CBA requires specific choices, beginning with the selection of which IAMs to include. Models vary in terms of breadth of use, degree of public access and available peer review, and incorporation of latest scientific results. New IAMs may emerge. How should a government select among models? Should selection evolve over time? Should models be weighted? If so, how?

Next, one must choose what, if any, assumptions to harmonize across models. Such assumptions may be important for consistency between the SCC and other elements of a government CBA, to reflect important uncertainties, or to address possibly outdated assumptions.

This harmonization requires more tough choices. For example, the SCC will measure incremental policy benefits relative to a baseline or range of baselines, which must be explicitly selected. One must decide whether emissions are forecast on the basis of an ambitious climate policy (such as the scenario in which polluters are already forced to pay the estimated SCC), a scenario where only policies already on the books remain in place, or something in between.

There are also credible differences on analytic and ethical grounds regarding the appropriate discount rate. Previous government guidance for CBA suggested discount rates of 3 and 7% for most projects, with possibly lower rates for phenomena (like climate change) with important intergenerational effects (*7*). Such differences have enormous implications; federal SCC estimates tripled as the discount rate changes from 5 to 3% (*1*). For practical CBA, it is important to have distinct SCC estimates for different discount rates that can be paired with cost estimates based on a particular discount rate(s).

Each IAM will have its own internal discount rate determined by model parameters and socioeconomic forecasts. Low discount rates typically follow from low economic growth (*8*), and economic growth is tied to climate impacts. Given this connection, how problematic is it to impose a discount rate in the SCC that is different from the rate used within the IAM itself?

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Should socioeconomic scenarios in the IAM be made consistent with the selected SCC discount rate, or vice-versa?

Finally, one must choose how much weight to give to climate change impacts outside the jurisdiction considering the SCC. In the United States, some have questioned the legality of using global SCC estimates (*9*). Unless a relevant statute clearly requires otherwise, the President and agencies have latitude to choose between domestic and global SCC values for regulatory analysis [including the authority to interpret silent or ambiguous statutes under the Chevron doctrine (*10*)]. Key U.S. statutes (e.g., Clean Air Act and National Environmental Policy Act) refer to global impacts in some sections and do not preclude a Presidential judgment that U.S. interests are best served via a global SCC.

Traditionally, regulatory CBA has used domestic impacts. However, unlike virtually all other regulated pollutants and risks, GHG emissions are overwhelmingly a problem of the global commons. A global SCC, used worldwide to determine policy, would maximize global net benefits. U.S. emissions cause the bulk of their damages beyond U.S. borders, and U.S. damages will largely depend on mitigation choices in other countries where emissions are larger and growing (*11*).

Beyond the moral, ethical, and security issues this raises, there is a strategic foreign relations question. The United States is engaged in international negotiations in which U.S. emission reductions are part of a deal for abatement by other countries. Benefits to each country are determined by the global effort. Even if the U.S. government cares only about domestic impacts, this potential to leverage foreign mitigation supports a domestic SCC estimate augmented by the expected foreign leverage. Our view is that these are compelling reasons to focus on a global SCC but, more important, to make a strategic choice and to conduct periodic review.

A PROCESS TO UPDATE THE SCC. Current U.S. government practice is vague regarding when and how a process of reviewing and updating the SCC might occur, which makes it difficult for stakeholders and researchers to anticipate future reviews and to plan for useful engagement in the process. A regularized and institutionalized process would allow both groups to align their activities more sensibly.

We see four components to an improved institutional process. First, revisions to the SCC should follow a regular schedule. A 5-year cycle would balance the need to respond to evolving research with the need for a thorough process.

Second, SCC revisions should continue to be an interagency process, led by an appropriate group within the Executive Office of the President. This emphasizes the need for consistent values across the whole of government and allows the process to draw on expertise from multiple agencies, as well as reflecting the strategic considerations noted above. The process should include public notice and comment.

> ***"Current U.S. . . . practice is vague regarding when and how . . . reviewing and updating the SCC might occur."***

Third, government SCC estimates should be regularly reviewed by the National Academy of Science's National Research Council (NRC). This would enhance the scientific credibility of the SCC and provide an avenue for experts to suggest changes for the next iteration. Such review could begin with the current estimates.

Finally, the entire process should be institutionalized through an executive order or an Office of Management and Budget (OMB) memorandum or circular. This would communicate the aforementioned components and achieve reasonably stable expectations about future practice. Moreover, a regular procedure with high-quality external review would help reduce any potential politicization of the SCC.

A regularized process for updating the SCC allows researchers to direct efforts toward policy-relevant issues. First, there is research on socioeconomic and emissions scenarios, climate science, and physical impacts, which are necessary inputs to IAMs and SCC estimates. Second, there is translation of physical impacts into human and ecosystem consequences, monetization of those consequences, and synthesis of this information into a consistent modeling framework to estimate the SCC. We believe there are especially appealing opportunities in the second area, which has not been as strongly supported as the physical science research.

Currently, estimates of human and ecosystem consequences of climate change, particularly in less-studied regions and impact categories, come from a small number of studies. Recent work suggests that temperature change may have different—and larger—impacts in poorer countries (*12*). Estimating damage from extreme climate change is a research area with particularly high value (*13*). Increased efforts to synthesize such studies for use in IAMs can facilitate their incorporation into SCC estimates.

SCC estimates could be improved by increasing opportunities for peer review of IAM development. This could be through model intercomparison projects focused specifically on the SCC, special journal issues to compare sector-by-sector impact valuations, and the NRC review process proposed earlier. This will require redirection of research time and funding, adjustments more easily planned in conjunction with a regularized updating schedule.

As the world makes progress in GHG mitigation, governments will need decision-making processes and information tools that reflect important trade-offs. That requires a regularized, transparent, and credible process that ensures that the SCC is reliable, well-supported, and up to date.

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*The views and opinions expressed in this paper are those of the authors alone. E-mail: william.pizer@duke.edu.

REFERENCES AND NOTES

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ACKNOWLEDGMENTS

The authors acknowledge Duke's Nicholas Institute for Environmental Policy Solutions and the Center for Law, Economics, and Public Policy for sponsoring the workshop where these ideas were developed and the Global Technology Strategy Program for supporting S.W. We appreciate many useful intellectual contributions from the workshop audience.

10.1126/science.1259774

ED_000584A_00000472

To: Marten, Alex[Marten.Alex@epa.gov]; Sarofim, Marcus[Sarofim.Marcus@epa.gov]
Cc: Shouse, Kate[Shouse.Kate@epa.gov]
From: Li, Jia
Sent: Thur 3/12/2015 6:18:47 PM
Subject: RE: SBCA conference

Hi Alex:

That will be great!

Cheers,

Jia

From: Marten, Alex
Sent: Thursday, March 12, 2015 11:32 AM
To: Li, Jia; Sarofim, Marcus
Cc: Shouse, Kate
Subject: RE: SBCA conference

Thanks Jia. I was looking through the sessions yesterday and was certainly intrigued by the one you are participating in. I hope to be there if my schedule allows.

--

Alex L. Marten
phone: (202) 566-2301
email: marten.alex@epa.gov

From: Li, Jia
Sent: Thursday, March 12, 2015 10:10 AM
To: Marten, Alex; Sarofim, Marcus
Cc: Shouse, Kate

Subject: SBCA conference

Hi Alex and Marcus:

Just want to touch base with you re the SBCA conference next week. I hope the SCC workshop you both participate will go well. I won't be able to attend due to other work, but both Kate and I will be interested in hearing more about how it goes afterward. Would also be interested in hearing more of Arden Rowell's presentation on the use of SCC in regulations. Our guess is that nothing will be surprising, but it's good that you both are there in case any issue comes up.

FYI – I will be participating in a panel at the conference (Session E.2 @10.45-12.15 on March 19) that presents the JBCA special issue on climate impacts and adaptation. Michael Toman, Robert Lempert, Jim Neumann and Fran Sussman will also be participating. Unfortunately John Weyant bowed out the last minute so his presentation on SCC is dropped.

See each other at the conference or catch up later!

Best,

Jia

To: Marten, Alex[Marten.Alex@epa.gov]
From: Moore, Chris
Sent: Tue 2/10/2015 1:08:20 PM
Subject: RE: Question about RTI contract on climate change and location choice

Ex 5

From: Marten, Alex
Sent: Monday, February 09, 2015 3:23 PM
To: Moore, Chris
Subject: FW: Question about RTI contract on climate change and location choice

Chris, were you the WAM at the end of this project or was that the other Chris?

--

Alex L. Marten
phone: (202) 566-2301
email: marten.alex@epa.gov

From: Bierwagen, Britta
Sent: Monday, February 09, 2015 3:22 PM
To: Klemick, Heather; Newbold, Steve; Marten, Alex
Cc: Morefield, Philip
Subject: Question about RTI contract on climate change and location choice

Hi,

My colleague, Phil Morefield, and I are evaluating proposals for work to quantify relationships between climate and domestic migration. We want to make use of this information in our land use change model (http://epa.gov/ncea/global/iclus/) to further examine impacts of climate change on population movements, housing development and associated effects in the future.

Ex 4

Thank you for your help.

-Britta

Britta Bierwagen, Ph.D. | **Global Change Assessment Staff |** National Center for Environmental Assessment | U.S. EPA – ORD (MC 8601P) | 1200 Pennsylvania Ave., NW | Washington, D.C. 20460

Phone: 703-347-8613 | Fax: 703-347-8694 | bierwagen.britta@epa.gov

Physical and overnight delivery address: U.S. EPA North Potomac Yard N-7837 | 2733 S. Crystal Dr. | Arlington, VA 22202

To: Marten, Alex[Marten.Alex@epa.gov]; Kopits, Elizabeth[Kopits.Elizabeth@epa.gov]; McGartland, Al[McGartland.Al@epa.gov]; Griffiths, Charles[Griffiths.Charles@epa.gov]
From: Wheeler, William
Sent: Tue 1/13/2015 2:52:19 PM
Subject: FW: FYI only, E&E News: "Researchers say the social cost of carbon will be 6 times the Obama administration's estimate"

FYI

Will Wheeler, Economist
U.S. EPA, NCEE
202-566-2264

From: Skane, Elizabeth
Sent: Tuesday, January 13, 2015 9:38 AM
To: Wheeler, William
Subject: FYI only, E&E News: "Researchers say the social cost of carbon will be 6 times the Obama administration's estimate"

http://www.eenews.net/climatewire/2015/01/13/stories/1060011557

Researchers say the social cost of carbon will be 6 times the Obama administration's estimate

Evan Lehmann, E&E reporter
Published: Tuesday, January 13, 2015

Climate change could have much larger impacts on the economy than the U.S. government is anticipating, according to an analysis released yesterday that suggests the social cost of carbon should be six times higher.

A paper by two Stanford University researchers argues that the true cost of releasing greenhouse gases is about $220 a ton because rising temperatures could badly hinder a nation's economic growth over decades or centuries. The Obama administration estimates that the social cost of carbon is $37 a ton.

The paper, published yesterday in the journal *Nature Climate Change*, adds to a growing number of voices calling for improvements to the complicated process of establishing the cost estimate, which is used to measure the benefits of regulations. A dozen federal agencies set the price using three computer models that project emission rates, economic activity and climate damages.

The Stanford paper bases its findings on prior research showing that the economic health of a country suffers during periods of high temperatures. Heat can harm agricultural and industrial output, while increasing political instability. In that way, the Stanford analysis subscribes to emerging calls among experts to incorporate new observations into the trio of models that date back to the 1990s.

"The social cost of carbon is almost certainly larger of what's being used so far," said co-author Frances Moore, a doctoral candidate at Stanford's School of Earth Sciences.

In a key departure from the government's analysis, the **paper** uses the previous empirical research to assert that climate impacts could damage a nation's economic growth rate over time, rather than just harassing its year-to-year economic output.

That could mean that nations face permanent malfunctions, like economic declines in labor, capital and technology from severe weather and other "temperature shocks." The authors say these bigger impacts have a "compounding effect" that is more damaging to the economy than temporary strains from heat on agricultural output and more expensive air conditioning costs.

"So the economy is kind of permanently lower," Moore said. "If you have repeated shocks, in that case, they accumulate over time. That's why even very, very small reductions in growth rates have these really big effects over time."

It's an 'overestimate'

The social cost of carbon is used in the cost-benefit analysis of some federal regulations. If the impact of emissions is deemed expensive for society, it could justify more aggressive policies to reduce their release by industry. Opponents of climate action criticized the Obama administration for raising the social cost of carbon in 2013 by almost 50 percent.

William Pizer, a Duke University professor and former Obama administration official who has worked on the estimate, applauded the Stanford researchers for applying updated observations into their carbon estimates. He and several other former Obama advisers say the administration should improve its use of updated science when establishing the price.

But Pizer also questioned the methodology of the Stanford analysis. The empirical research it relied on tracked short-term temperature spikes and their impacts on nations' economies -- not long-term trends that might show permanent economic reductions.

"To me, it just seems like it has to be an overestimate," Pizer said of the Stanford result of $220.

"I think it's great they're doing this," he added. "I just think this is another data point that someone needs to weigh as they're trying to figure out what the right social cost of carbon is. But this isn't like a definitive new answer."

Moore acknowledged the uncertainties in her research. For example, she noted that there's not enough evidence to know if climate change will continue to have outsized impacts on poorer countries or if as their economies grow they'll be able to adapt and decrease their damage.

A grimmer outcome consists of "biophysical temperature thresholds" -- the idea that the heat will prevent large economic advances. Both scenarios effect the speed and aggressiveness with which emissions should be reduced -- and the price of their social cost of carbon.

Moore hopes the new research will help inform the administration that a larger spectrum of damages should be considered when establishing the monetary estimate.

Twitter: @evanlehmann | Email: elehmann@eenews.net

Elizabeth Skane 🚲 Special Assistant / Regulatory Manager 🚲 Office of Science & Technology / Office of Water / US EPA 🚲 202.564.5696

To: Evans, DavidA[Evans.DavidA@epa.gov]; Simpson, David[Simpson.David@epa.gov]
Cc: Wolverton, Ann[Wolverton.Ann@epa.gov]; Garbaccio, Richard[Garbaccio.Richard@epa.gov]
Bcc: alex.marten.work@gmail.com[alex.marten.work@gmail.com]
From: Marten, Alex
Sent: Wed 3/4/2015 8:34:10 PM
Subject: RE: A somewhat more serious inquiry regarding economy-wide modeling

Ex 5

Ex 5

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Alex L. Marten
phone: (202) 566-2301
email: marten.alex@epa.gov

From: Evans, DavidA
Sent: Wednesday, March 04, 2015 3:01 PM
To: Simpson, David
Cc: Wolverton, Ann; Garbaccio, Richard; Marten, Alex
Subject: RE: A somewhat more serious inquiry regarding economy-wide modeling

I'm going to pass on that question given that my colleagues' combined experience developing CGE models and the SCC estimates suggests a far superior answer from them.

From: Simpson, David
Sent: Wednesday, March 04, 2015 2:59 PM
To: Evans, DavidA
Cc: Wolverton, Ann; Garbaccio, Richard; Marten, Alex
Subject: A somewhat more serious inquiry regarding economy-wide modeling

Hey, economy-wide modelers,

Ex 5

Is there an answer I'd understand?

David

To: Marten, Alex[Marten.Alex@epa.gov]; Shouse, Kate[Shouse.Kate@epa.gov]
Cc: Barron, Alex[Barron.Alex@epa.gov]; Roberts, Martha[Roberts.Martha@epa.gov]; McGartland, Al[McGartland.Al@epa.gov]
From: Kopits, Elizabeth
Sent: Thur 6/11/2015 4:20:38 PM
Subject: FYI - my notes on recent filings in MN SCC case
Notes on MN case filings.docx

Hi Kate and Alex –

I figured it would be good for us to stay on top of this a bit, so here are my notes on the filings in the MN SCC case, based on a relatively quick skim of all the documents submitted by MN, Peabody, Xcel, MLIG, and MCEA so far.

Testifying on behalf of MN Dept of Commerce:

•□□□□□□□□ Michael Hanneman - directly addressed nearly every aspect of the USG SCC development and found each IWG decision to be reasonable. (only aspect he didn't seem to be asked about was global vs. domestic.) Lots of nice supportive quotes.

•□□□□□□□□ Kevin Gurney (ASU) – don't have his testimony yet.

MLIG:

•□□□□□□□□ Ted Gayer – focus is that he doesn't support use of global estimate for MN (or federal) policy making.

•□□□□□□□□ Anne Smith – Questions reasonableness of using SCC estimates from IAMs for any policy-making due to sensitivity of IAMs to various assumptions. However, given that she understands the Commission has decided to take the damage cost approach, she focuses her testimony on how to obtain relatively more appropriate estimates than the IWG did. Making changes to address 5 criticisms, she suggests SC-CO2 of $1.62 to $5.14 (2014$) for the year 2020 would be the appropriate value for MN to use.

MCEA:

•□□□□□□□□ Stephen Polasky – very supportive of IWG process and estimates and their use by MN. Also discusses at length why USG SCC is likely conservative.

Peabody:

•□□□□□□□□ Roy Spencer (meteorologist) - Focuses on how recently observed temperature trends (last 18 yrs or so) invalidate climate projections underlying SCC calculations.

•□□□□□□□□ Roger Bezdek (economist) - Doesn't think SCC estimates are credible. Focuses on environmental and economic benefits of CO2 and how higher energy prices would hurt households in MN.

Xcel:

•□□□□□□□□ Nicholas Martin (Xcel environmental policy manager) – does not endorse using any single value from USG SCC for commission decisions. However, allows that data underlying the USG SCC can be used as the basis for developing a range of values that the Commission can use. Develops and proposes a range based on 25th and 75th %tiles of IWG results, and averaging these across discount rates. Resulting range is $12.33 to $41.80 (in 2014 dollars per short ton of CO2) for emissions in 2020.

See attached notes, and full testimonies for details. (copies of everything are on NCEE share drive (G:\Kopits\SCC\MN_SCC_files submitted to contested case hearing\).

Elizabeth

From: Kopits, Elizabeth
Sent: Wednesday, June 10, 2015 3:06 PM
To: Marten, Alex
Subject: RE: Nice talking with you yesterday

P.S. I'm putting a copy of all the files in G:\Kopits\SCC\MN_SCC_files submitted to contested case hearing.

From: Kopits, Elizabeth
Sent: Wednesday, June 10, 2015 3:03 PM
To: Shouse, Kate; Marten, Alex
Subject: FW: Nice talking with you yesterday

FYI – Forgot to mention this just now.

A few of us in NCEE met with some of the new folks coming over from Stratus to Abt yesterday- - including Dave Chapman who asked us some questions about SCC a while back for the work he was doing for Minnesota. He mentioned yesterday that they had recently submitted their files for that case and he said they are all public info so I asked him to send me the link.

He kindly put them all on their ftp site for us. I guess the next step will be for all sides to submit rebuttals. I assume all of this will be public info too. I suppose we should keep up on it to some extent.

E.

From: David Chapman [mailto:DChapman@stratusconsulting.com]
Sent: Wednesday, June 10, 2015 2:47 PM
To: Kopits, Elizabeth
Subject: Nice talking with you yesterday

Elizabeth,

Thanks for taking the time to talk with us yesterday. I enjoyed meeting you in person and our discussions.

Since the files for the filed testimony in the Minnesota SCC contested case hearings are so many and large, I put them up on our FTP site:

ftp.stratusconsulting.com

User: Ex 6 - Other
PWD:

You should see two folders – one is the comments received by OMB, the other is the testimony and supporting documents filed in the MN contested case hearing. Let me know if you have any issues trying to access these files. This is all public information.

I have also asked our MN client if they are OK with me sending you our spreadsheet analysis of the comments OMB received on the SCC.

I'll let you know about that as soon as I hear back.

Regards,

David

This electronic message and any attachments hereto are the property of the sender and may contain information that is confidential or proprietary to the sender. It is intended for the exclusive use of the recipient or recipients named above. If you are not an intended recipient of the message, please be advised that you are not authorized to disclose, copy, or distribute the message or any information in the message. Please notify the sender of your receipt immediately by return electronic e-mail and delete the message and any attachments. Although this e-mail and any attachments are believed to be free of any virus or other defect that might affect any computer system into which it is received and opened, it is the responsibility of the recipient to ensure that it is virus free and no responsibility is accepted by the sender for any loss or damage arising in any way from its use.

Privileged and Confidential
Work Product Prepared Under Direction of Counsel
Protected by Federal Rule of Evidence 408

MN Dept of Commerce, Division of Energy Resources:

Michael Hanneman – directly addressed nearly every aspect of the USG SCC development and found each IWG decision to be reasonable. (Only point which he did not seem to be asked about was global vs. domestic). He expressed support for USG SCC overall and for use by MN. His assessment of IWG methodology starts on p. 64 of his testimony – contains lots of good quotes.

Note one new tidbit I found in his lengthy background overview of SCC:

> "The use of an estimate of the SCC is currently a component of numerous Integrated Resource Plans across the nation. For example, Puget Sound Energy, Portland General Electric, Tennessee Valley Authority, and NV Energy are among the many utilities incorporating the IWG's SCC estimates in their recent planning documents." (I looked up one of these so far – Puget Sound Energy IRP: http://pse.com/aboutpse/EnergySupply/Pages/Resource-Planning.aspx)

Peabody:

Prof. Roy Spencer – PhD in meteorology, principal research scientist at U. Alabama since 2001; Senior Sceintist at NASA 97-01. Focuses on how recently observed temperature trends (last 18 yrs or so) invalidate climate projections underlying SCC calculations.

Dr. Roger Bezdek – economist (seems to now have his own consulting firm, but has worked all over – in govt, private industry, academia; also submitted comments in OMB's comment period). Does not support use of USG SCC in MN or elsewhere. Doesn't think SCC estimates are credible. Goes on and on about environmental and economic benefits of CO2 and how higher energy prices would hurt households in MN. Attached his recent study "Carbon Dioxide: Social Cost or Social Benefit?".

MLIG (MN large industrial group –ad hoc group of large industrial electric utility customers):

Ted Gayer – focus of testimony is that he does not support use of global (or even national) SCC in MN policy decisions. MN policies should be evaluated based on benefits they confer to the State – not national, and certainly not global – population. (His expert report includes argument that federal policy should consider benefits to U.S. residents only.)

Anne Smith – Economist and modeler at NERA; did work supporting API and UARG comments on SCC submitted to OMB, and TCEQ comments on Clean Power Plan submitted to EPA. Says that there are 5 types of IWG assumptions that make the USG SCC inappropriate for MN's use:

1) If one is calculating the environmental cost of CO2 based on the damages caused by the emissions in MN, it would make sense to use an average damage per ton.
2) Analysis horizon of 2300 contains a degree of speculative content that is inconsistent with MN's criteria for setting its environmental cost values as discussed in the MN PUC 1997 Order Establishing Environmental Cost Values in Docket No. E-999/CI-93-583
3) the Agencies have recommended using only the IWG's SCC value based on a 3% discount rate, which is an unreasonably narrow recommendation. The IWG itself also considered a 5% discount rate, which is reasonable to include as well.
4) IWG's SCC values are based on global damages, not Minnesota damages or U.S. damages. This is inappropriate in the case of an individual state's investment decisions when there are no reciprocal agreements with major emitting nations to also adopt that same SCC.

(However, at one point she does acknowledge: "It might make sense for the Federal government to consider global damages when calculating the SCC, because the Federal government, unlike the individual states, has authority to negotiate international agreements to reduce global carbon emissions. For the Federal government, nationwide domestic policies may support its positions in those negotiations.")

5) IWG's SCC values have not accounted for the possibility of leakage, which is a particular concern for reduction actions that take place within the electricity system of a single state that is interconnected to electricity systems in other states that are not participating in the same resource planning constraints.

Questions reasonableness of using SCC estimates from IAMs for any policy-making due to sensitivity of IAMs to various assumptions. However, given that she understands the Commission has decided to take the damage cost approach, at least initially, she focuses her testimony on how to obtain relatively more appropriate estimates than the IWG did.

Making changes addressing her 5 criticisms above, she suggests a SC-CO2 of $1.62 to $5.14 (2014$) for the year 2020 would be the appropriate value for MN to use. (Specific assumptions: discount rates of 3% and 5%; marginal damage estimates based on the first ton of CO2 emitted, and also on the average of the values for the first and last tons of CO2 emitted; domestic damages rather than global damages; and model horizons of 2100 and 2140.) And if there is any leakage expected, the value would need to be adjusted downward further by the percent of emissions that would reappear elsewhere.

MCEA (MN Center for Environmental Advocacy):

Stephen Polasky – economics prof at U. of MN. Supportive of IWG process and estimates and their use by MN.

> "The IWG process for producing and updating estimates of value of the SCC employs well accepted scientific methods and a transparent approach that is likely to produce the best available and reasonable estimates of the SCC. IWG averaged estimates from the three most reputable and widely used IAMs and relied on the collective judgment of a group of experts from a range of federal agencies. It has committed to regular updates to adjust the estimates of SCC to incorporate new information as it becomes available. Minnesota can benefit from this process by adopting the federal SCC, and in the future by adjusting the SCC when future updates are produced by the IWG, thereby reducing the burden on the PUC to remain up-to-date on the latest climate change research and scientific understanding while continuing to use a reliable estimate of the damages from CO2 emissions."

Also discusses at length why USG SCC is likely conservative: doesn't give adequate weight to catastrophic damages, IWG use relatively high d.r., may not adequately account for impacts of climate change on econ growth, and omit several potentially important types of damages.

Xcel:

Nicholas Martin – environmental policy manager for Xcel.

Does not endorse using USG SCC for commission decisions if any single value is adopted. Use of any single value from the SCC TSD is inappropriate because:

- USG SCC was designed for different purpose

  > "…In the context of regulatory impact analysis, even if the models are imprecise and over- or under-estimate the benefits of reducing CO2 emissions, as long as benefits exceed costs, it makes sense to develop a regulation. In contrast, if used for Commission decisions, the imprecise SCC would help determine not whether to regulate, but rather how to make individual resource allocation decisions. These decisions – such as whether to operate or retire a power plant, what type of generation capacity to invest in, how to set solar tariffs, how to evaluate Conservation Improvement Program (CIP) benefits – are sometimes binary, difficult to reverse, and often have large and long-term implications for electricity rates, environmental impacts, and reliability."
- SCC is inherently uncertain and speculative
- No single Federal SCC value. Averaging model results inappropriate because doesn't represent the central tendency of a statistical population that is not normally distributed (median would be better).. Use of any single value constitutes false precision, etc.
- USG SCC estimates global damages to 2300 and thus is much broader than the impacts that CO2 emissions and climate change may have on U.S. or MN.

"…In the context of regulatory impact analysis, even if the models are imprecise and over- or under-estimate the benefits of reducing CO2 emissions, as long as benefits exceed costs, it makes sense to develop a regulation. In contrast, if used for Commission decisions, the imprecise SCC would help determine not whether to regulate, but rather how to make individual resource allocation decisions. These decisions – such as whether to operate or retire a power plant, what type of generation capacity to invest in, how to set solar tariffs, how to evaluate Conservation Improvement Program (CIP) benefits – are sometimes binary, difficult to reverse, and often have large and long-term implications for electricity rates, environmental impacts, and reliability."

However, allows that data underlying the SCC can be used as the basis for developing a range of values that the Commission can use. In addition to being a requirement in the statute, a range accounts for uncertainty in damages and lack of consensus on discount rates.

> "Considering the Commission's desire to identify the "best available" measure, and stipulation that the CO2 environmental cost value be based on a damage costs approach, we conclude that in the absence of 1 any clearly superior damage cost alternatives, the Federal SCC despite its flaws and uncertainties can be used as the basis for developing CO2 environmental cost values. However, no single Federal SCC value can be adopted. Instead, the Federal SCC can be used as the starting point for developing values, as long as the Commission adopts a range of values rather than any single value,.."

Proposes a range based on following approach: obtained the raw Federal SCC modeling results, then:

- Aggregated the results across climate models, socioeconomic scenarios, and discount rates,

which involved 150,000 data points for each discount rate/emission year combination – a total of 2.25 million data points,

- Analyzed summary statistics,
- Determined an initial range of CO2 environmental cost values by selecting statistical percentiles representing a significant probability of capturing the value of climate damages as predicted by the SCC models, and
- Equally weighted the SCC values for each of the three discount rates used by the IWG at the low and high ends of our initial range (ie., take average of 25th%tile of 2.5% d.r. results, 25th%tile of 3% d.r. results, and 25th%tile of 5% d.r. results; do same using 75th%tile to calculate upper end of range).

Resulting range: $12.33 to $41.80 (in 2014 dollars per short ton of CO2) for emissions in 2020. (Provide corresponding low and high values for emissions in each year through 2050.)

Section of the testimony that provides overview of USG SCC includes criticisms of IWG process – e.g., no peer review, very little public input so far (claims OMB comment period is really first time OMB took comment on SCC. There has been no response from OMB or announcement on how it plans to respond. Comments received in individual rulemakings don't count.)

To: Barron, Alex[Barron.Alex@epa.gov]
From: Marten, Alex
Sent: Sat 2/21/2015 10:42:59 PM
Subject: Re: SCC RTC w/ staff comments

I also wanted to follow up w/ you on specific requests you had on the last version which I wasn't able to address/look into in time. Below is the result of those tasks. Please let me know if you would like to discuss any of them further.

Ex 5

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Alex Marten
marten.alex@epa.gov

From: Marten, Alex
Sent: Saturday, February 21, 2015 5:41 PM
To: McGartland, Al; Barron, Alex
Cc: Shouse, Kate
Subject: SCC RTC w/ staff comments

Hi Al & Alex,

Attached is the SCC RTC that OMB distributed earlier in the month with staff comments from both NCEE and OAP.

OMB is requesting Agency comments by mid next week. Ex 5

Ex 5

If you want to comment on this version please let me know, but please feel free to wait unit we have incorporated other IWG comments.

--
Alex Marten
marten.alex@epa.gov

To: Barron, Alex[Barron.Alex@epa.gov]; McGartland, Al[McGartland.Al@epa.gov]
From: Marten, Alex
Sent: Thur 1/29/2015 9:10:00 PM
Subject: RE: draft SC work timeline_1 29 15 forOMB.docx

Ex 5

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Alex L. Marten
phone: (202) 566-2301
email: marten.alex@epa.gov

From: Barron, Alex
Sent: Thursday, January 29, 2015 9:49 AM
To: Marten, Alex; McGartland, Al
Subject: draft SC work timeline_1 29 15 forOMB.docx

Ex 5

Let's chat on this later this afternoon.

Alex

To: Barron, Alex[Barron.Alex@epa.gov]; McGartland, Al[McGartland.Al@epa.gov]
Cc: Kopits, Elizabeth[Kopits.Elizabeth@epa.gov]
From: Marten, Alex
Sent: Thur 1/22/2015 9:39:28 PM
Subject: RE: draft SCCSCM work timeline_1 22 15 ab ek.docx

Ex 5

Ex 5

Ex 5

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From: Barron, Alex
Sent: Thursday, January 22, 2015 4:23 PM
To: Marten, Alex; McGartland, Al
Cc: Kopits, Elizabeth
Subject: draft SCCSCM work timeline_1 22 15 ab ek.docx

Thanks Elizabeth, I've generated a clean version that flags the question of Ex 5 Ex 5 Alex, Al – Any additional feedback?

Alex

To: McGartland, Al[McGartland.Al@epa.gov]; Barron, Alex[Barron.Alex@epa.gov]; Wolverton, Ann[Wolverton.Ann@epa.gov]; Ferris, Ann[Ferris.Ann@epa.gov]; Kopits, Elizabeth[Kopits.Elizabeth@epa.gov]
Cc: Snyder, Brett[Snyder.Brett@epa.gov]; Bowen, Jennifer[Bowen.Jennifer@epa.gov]
From: Shadbegian, Ron
Sent: Fri 1/16/2015 2:30:25 PM
Subject: Benefits of carbon use far outweigh its costs

It turns out the article I mentioned yesterday on the benefits of CO2 was from this past September.

http://thehill.com/blogs/congress-blog/energy-environment/218795-benefits-of-carbon-use-far-outweigh-its-costs

but a more recent version **"Pro&Con: Carbon dioxide, despite the EPA's word games, is profoundly Earth-friendly"** which is quite similar, but with a more pointed attack on the Administration and EPA came out last week (copied below):

http://www.southcoasttoday.com/article/20150109/OPINION/150109373/101230/NEWS?template=printart

Benefits of carbon use far outweigh its costs

By Roger H. Bezdek

Hundreds of thousands of people paraded through New York City Sunday in a "people's climate march" designed to influence world leaders at a UN climate summit. They contend that fossil fuels and carbon dioxide (CO_2) emissions cause "global warming." But since global temperatures have been stable or declining for the past two decades, the term "global warming" has morphed into "climate change" or "climate weirding."

Whatever the term, the protesters contend that Earth's climate is highly sensitive to CO_2, and then hypothesize almost every conceivable malady, including sea level rise, increased hurricanes and tornados, worsening droughts, heavier snowfalls, and other extreme weather events impacting humanity.

Fear mongering may capture headlines, though there are several major fallacies in this approach. First, there has been no global warming for at least the past two decades, which means such warming could not have caused any weather events.

Second, the dire climate-related occurrences being cited as evidence are not happening. For example:

- Any sea level rise is modest, and there is no evidence of a cause and effect from CO_2.
- Even though weather and storm detection measures have improved markedly in recent decades, there is no indication of increased tornadoes, hurricanes, snowfall, or other extreme weather events and, in fact, such events have decreased over the past century.
- Sea ice is not melting; rather, it has increased to a new record high in the Antarctic.
- Floods are not getting worse, and there has been no particular change in the frequency or severity of floods worldwide.
- Droughts are not becoming more severe, and the fraction of the world's land under drought has been declining for 30 years.

Third, carbon dioxide (CO_2) is not a pollutant: It is the basis of life on Earth. It facilitates plant growth and enhances agricultural productivity. It is the primary raw material utilized by plants to produce the organic matter out of which they construct their tissues, which subsequently become the food source for animals and humans. The more CO_2 there is in the air, the better plants grow.

We assessed the economic value of this CO_2 benefit for 45 crops over the period 1961-2011 and estimated that it cumulatively totaled $3.2 trillion – increasing from $19 billion in 1961 to over $140 billion in 2010. We forecast that over the period 2012 - 2050, these CO_2 benefits will total $10 trillion – benefits which the protesters and their supporters ignore. Finally, and most important, they ignore the most obvious benefits of using fossil fuels. Fossil fuels facilitated the industrial revolutions, launched the modern world, and ensure the livelihoods, living standards, health, and longevity we all currently enjoy.

Over the past 200 years, largely because of hydrocarbon energy, human population increased eightfold, average incomes rose 11-fold, and global life expectancy more than doubled. Concurrently, CO_2 emissions increased 2,800-fold, to 8.4 billion tons/year -- and atmospheric concentration rose from 320 ppm CO_2 to nearly 400 ppm.

Hydrocarbons provide 81 percent of world energy, and the positive relationship between fossil fuels, economic growth, and CO_2 emissions is strong – supporting $70 trillion per year in world GDP. Seminal research has concluded that "Ours is a high energy civilization based largely on combustion of fossil fuels," and that "The theoretical and empirical evidence indicates that energy use and output are tightly coupled, with energy availability playing a key role in enabling growth."

How do the CO_2 benefits compare to potential damages? We compared the CO_2 costs and benefits per ton based on the federal government's Interagency Working Group "official" social cost of carbon estimates. We found that CO_2 benefits outweigh the costs by, literally, orders of magnitude: Anywhere from 50-to-1 to 220-to-1. Normally, B-C ratios in the range of 2-to-1 or 3-to-1 are considered very favorable. In other words, the benefits of CO_2 overwhelmingly outweigh the estimated CO_2 costs. In fact, the CO_2 costs are relatively so small as to be in the statistical noise of the CO_2 benefits.

All major forecasts, including those of the U.S. Energy Information Administration and the International Energy Agency predict that, for decades to come, there will continue to be a close link between energy and the economy and that fossil fuels will continue to provide about 80% of world energy. The benefits of fossil fuel utilization will continue to outweigh – by orders of magnitude – any conceivable costs.

If the world is serious about economic growth, poverty reduction, living standards, and affordable energy, fossil fuels are essential. Restrictions on hydrocarbon energy based on false global warming scares will only undermine progress in these areas.

Bezdek is an energy economist and president of Management Information Services, Inc., in Washington D.C. He has served as senior adviser in the U.S. Treasury Department, as U.S. energy delegate to the EU and NATO, and as a consultant to the White House, federal and state government agencies, and numerous corporations and research organizations. His most recent book is The Impending World Energy Mess.

By Roger H. Bezdek

January 09. 2015 2:01AM

Pro&Con: Carbon dioxide, despite the EPA's word games, is profoundly Earth-friendly

Activists from different countries holding signs in support of the unborn on the sidelines of the Climate Change Conference, on a beach in Lima, Peru, on Dec. 4. Low oil prices could paradoxically help the

In a thinly disguised assault on coal and hydrocarbons, the Obama administration would have us believe that carbon dioxide (CO2) is a threat to life itself.

Nothing could be further from the truth. In fact, a recent study by my company for the American Coalition for Clean Coal Electricity found that the benefits of carbon dioxide to all of us are far greater than its costs.

The government bases many of its regulatory positions on the so-called social cost of carbon, an estimate of climate change damages in a given year. However, our study showed the government positions were based on flawed science:

There is no scientific evidence for significant climate effects of rising CO2 levels and there is no evidence that global warming will produce catastrophic climate changes.

There has been no global warming for two decades, during which CO2 emissions increased significantly. The only "evidence" comes from invalidated climate models that disagree with each other and that are increasingly inaccurate.

The government is exaggerating climate sensitivity and relies on unsubstantiated claims of international reports.

The government data, we believe, are artificial constructs designed by the Obama administration to penalize fossil fuels and allow it to achieve by executive mandate what it cannot via Congress, such as a carbon tax.

In fact, we found the "social cost of carbon" to be a concept dependent on assumptions and allows its user to arrive at almost any desired result. Dire climate-related occurrences are not happening. For example:

Sea level rise is modest, and there is no cause and effect from CO2.

There is no indication of increased extreme weather events.

Sea ice is not melting; rather, it has increased to a record high in the Antarctic.

There has been no change in the frequency or severity of floods worldwide.

Nor are droughts becoming more severe.

Carbon dioxide is the basis of life on Earth. It facilitates plant growth and enhances agricultural productivity. It is the primary raw material utilized by plants, which are the food source for animals and humans. The more CO2 there is in the air, the better plants grow.

Our study found that the economic value of this carbon dioxide benefit totaled $3.2 trillion from 1961 to 2011. It also forecast that over the period 2012-2050, these CO2 benefits will total $10 trillion.

Finally, there are obvious benefits of using fossil fuels. These fuels facilitated successive industrial revolutions, launched the modern world and ensure the livelihoods, living standards, health and longevity we all currently enjoy.

Over the past 200 years, largely due to hydrocarbon energy, world population increased eight-fold, incomes rose 11-fold, and life expectancy more than doubled. At the same time, carbon dioxide emissions increased and atmospheric concentration rose from 320 parts per million to 400 parts per million.

Hydrocarbons provide 81 percent of world energy and the positive relationship between fossil fuels, economic growth and CO2 emissions is strong — supporting $70 trillion per year in world GDP. Our study verified previous research that concluded, "Ours is a high energy civilization based largely on fossil fuels."

How do carbon dioxide's benefits compare to potential damage? Our study compared CO2 costs and benefits based on the government's SCC estimates. We found that carbon dioxide's benefits outweigh costs by literally, orders of magnitude — anywhere from 50-to-1 to 220-to-1.

Normally, benefit/cost ratios of 2-to-1 or 3-to-1 are considered very favorable. In other words, our research concluded that CO2 benefits overwhelmingly outweigh estimated CO2 costs.

All major forecasts predict that, for decades to come, there will continue to be a close link between energy and the economy and that fossil fuels will continue to provide about 80 percent of world energy. Our study found that the benefits of fossil fuel utilization will continue to outweigh — by orders of magnitude — any conceivable costs.

The government estimates are wrong. If the world is serious about economic growth, poverty reduction, higher living standards and affordable energy, fossil fuels are essential. Restrictions

on hydrocarbon energy based on flawed science only undermine progress in these areas.

Roger H. Bezdek is president of Management Information Services, Inc. in Washington, D.C. and an internationally recognized energy economist with 30 years' experience in research and management in the energy, environmental and regulatory areas. He writes from Oakton, Virginia.

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From: Miles-McLean, Stuart
Sent: Mon 3/9/2015 9:10:32 PM
Subject: E&ENewsPM, 03/09: Senate Republicans demand update on cost-of-carbon public comments

CLIMATE:

Senate Republicans demand update on cost-of-carbon public comments

Jean Chemnick, E&E reporter

Published: Monday, March 9, 2015

Republicans on a key Senate panel want to know what the White House Office of Information and Regulatory Affairs has done with the thousands of public comments submitted more than a year ago on its controversial 2013 update to the social cost of carbon (SCC).

The administration bowed to pressure in late 2013 and offered a public comment period on the estimate, even though it was not required to do so legally. But GOP members of the Senate Environment and Public Works Committee noted today in a letter to OIRA Administrator Howard Shelanski that the White House has yet to announce any plans to adjust the estimate or otherwise respond to the comments submitted to it before Feb. 26 of last year (*Greenwire*, Feb. 26, 2014).

"Above all, it is only reasonable for the public to know how OIRA plans to use their comments," wrote the senators in a letter spearheaded by EPW Chairman James Inhofe (R-Okla.). "We want to encourage public participation in the regulatory process, not stifle it by ignoring those individuals who engaged in the process by submitting comments."

The SCC is not a regulation. It seeks to estimate the incremental cost of releasing a ton of man-made carbon dioxide into the atmosphere in terms of property damage, health care costs, lost agricultural output and other factors. The administration sparked a controversy nearly two years ago when it released a revision to its 2010 estimate that greatly increased its value. The new SCC sets the cost of CO2 at $38 per metric ton in 2015, whereas the 2010 estimate would have set it at $24.

But although it is not a rule itself, the SCC has figured in numerous rulemakings, including U.S. EPA's Clean Power Plan for existing power plants and the administration's draft guidance to agencies on how to incorporate climate change into their National Environmental Policy Act reviews.

EPA opponents complain that the administration uses the figure to justify the cost of its rules and charge that it is the product of a flawed and nontransparent process. Inhofe and his colleagues renewed those complaints in today's letter, demanding more information about the "secretive" interagency working group that led to the revised figure two years ago, as well as information about OIRA's public comment process.

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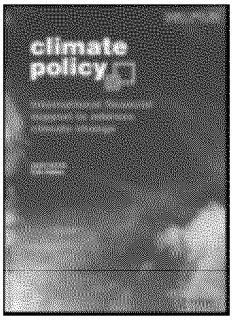

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Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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climate policy

B research article

Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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Benefit–cost analysis can serve as an informative input into the policy-making process, but only to the degree it characterizes the major impacts of the regulation under consideration. Recently, the US, amongst other nations, has begun to use estimates of the social cost of CO_2 (SC-CO_2) to develop analyses that more fully capture the climate change impacts of GHG abatement. The SC-CO_2 represents the aggregate willingness to pay to avoid the damages associated with an additional tonne of CO_2 emissions. In comparison, the social costs of non-CO_2 GHGs have received little attention from researchers and policy analysts, despite their non-negligible climate impact. This article addresses this issue by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. By extending existing integrated assessment models, it is possible to develop a set of social cost estimates for these gases that are consistent with the SC-CO_2 estimates currently in use by the US federal government.

Policy relevance

Within the benefit–cost analyses that inform the design of major regulations, all Federal agencies within the US Government (USG) use a set of agreed upon SC-CO_2 estimates to value the impact of CO_2 emissions changes. However, the value of changes in non-CO_2 GHG emissions has not been included in USG policy analysis to date. This article addresses that omission by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. These new estimates are designed to be compatible with the USG SC-CO_2 estimates currently in use and may therefore be directly applied to value emissions changes for these non-CO_2 gases within the benefit–cost analyses used to evaluate future policies.

Keywords: integrated assessment; non-CO_2 GHGs; social cost of carbon

1. Introduction

The social cost of CO_2 (SC-CO_2) is a measure of the monetary value of the damages occurring both within and outside economic markets as the result of an additional unit of CO_2 emissions. Specifically, it represents society's aggregate willingness to pay to prevent future impacts that occur when one additional unit of CO_2 is emitted into the atmosphere in a particular year. Estimates of SC-CO_2

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†The views expressed in this article are those of the authors and do not necessarily reflect the views or policies of the US Environmental Protection Agency.

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therefore provide a way to value changes in CO_2 emissions in benefit–cost analyses (BCAs) of policy alternatives. Without an estimate of the SC-CO_2, the benefits of mitigating the climate change impacts from CO_2 emissions would implicitly be valued at zero in BCAs, thereby significantly weakening the information provided by such analyses. Since 2009, the US Federal Government (USG) has used a set of agreed-upon SC-CO_2 estimates in the BCAs used to evaluate major regulations that impact CO_2 emissions (USG, 2010), including over 30 regulatory actions to date. The USG SC-CO_2 estimates are also increasingly being used in analysis and discussions outside the USG (e.g. by states, regional organizations, other nations, international organizations, NGOs, and academic researchers)[1] and have even figured in several recent public hearings and court cases (e.g. Keohane, 2010a, 2010b).

Although CO_2 is the primary anthropogenic GHG, other GHGs such as methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) are also important contributors to climate change. The combined effect of all GHGs accumulated in the atmosphere is to increase the Earth's radiative forcing, which is the amount of energy from the Sun that is trapped in the Earth's atmosphere and therefore acts to warm the planet and change the climate. In 2011, the atmospheric CO_2 concentration contributed 64% of overall radiative forcing, while CH_4 and N_2O accounted for approximately 23% (Myhre et al., 2013). Non-CO_2 GHGs, notably CH_4 and N_2O, therefore contribute significantly to the negative impacts on human well-being from climate change. Furthermore, several recent studies have shown that consideration of non-CO_2 GHGs, particularly CH_4 and N_2O, is important for the design of cost-effective climate policy (Reilly et al., 1999; Tol, Heintz, & Lammers, 2003; Weyant, De La Chesnaye, & Blenford, 2006).

The monetary value of changes in emissions of non-CO_2 GHGs has not been included in USG policy analysis to date. This shortcoming prevents the development of accurate and comprehensive assessments of potential regulatory alternatives by the USG and others that rely on the USG SC-CO_2 estimates (Kopp & Mignone 2012; Marten & Newbold, 2012). For example, fossil fuels (e.g. coal and natural gas) have different compositions of GHG emissions across gases when considering the entire process of extraction, production, transmission, and combustion. Thus, if a regulation is anticipated to cause an industry to substitute between fuels, analysts may be providing inadequate information to decision makers and the public about its benefits if only the welfare implications of direct CO_2 emissions are considered while ignoring changes in CH_4 and other GHG emissions (Alvarez, Pacala, Winebrake, Chameides, & Hamburg, 2011).

A key reason for the value of non-CO_2 GHG emissions impacts not being included in USG analyses so far is that existing estimates of the social cost of non-CO_2 GHGs presented in the literature are inconsistent with USG SC-CO_2 modelling assumptions. For example, the recent US Environmental Protection Agency BCA of new pollution standards for the oil and natural gas industry concluded that, because they are not consistent with the USG SC-CO_2, 'the methane climate benefit estimates available in the current literature are not acceptable to use to value the methane reductions finalized in this rulemaking' (USEPA, 2012). This article seeks to address that gap by developing a new set of social cost estimates for CH_4 and N_2O (SC-CH_4 and SC-N_2O, respectively) that are fully consistent with the modelling assumptions underlying the current USG SC-CO_2 estimates. This article also develops an approach to extending the models used by the USG to generate estimates of the social cost of additional GHGs that are consistent with the latest USG estimates of the SC-CO_2.

It is important to note at the outset that by restricting attention to the derivation of social cost estimates consistent with the USG SC-CO_2 estimates, any limitations that apply to inputs and modelling

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assumptions underlying the USG SC-CO_2 estimates (e.g. Arrow et al., 2013; Kopp & Mignone 2012; Marten, 2011; O'Neil, 2010; Warren, Mastrandrea, Hope, & Hof, 2010) also apply to the SC-CH_4 and SC-N_2O estimates derived here. Thus, while it is anticipated that the USG will continue to improve the models and data it uses to estimate the SC-CO_2, this article focuses on the more immediate task of developing a set of consistent estimates for the social cost of other GHG emissions so that they need not be implicitly assigned a value of zero in USG policy analyses.

The remainder of the article is organized as follows. Section 2 presents an overview of the USG SC-CO_2 estimation approach and how it compares to the existing literature on the social cost of non-CO_2 GHGs, including a discussion of some of the critiques of the approach. Section 3 presents the approach for estimating the SC-CH_4 and SC-N_2O in a manner consistent with the USG SC-CO_2 estimates. Section 4 presents the results and a comparison of the relative social costs to the previous literature and the global warming potential (GWP)-based metric that is often used as an approximation in the absence of direct estimates, and Section 5 provides concluding remarks.

2. Background

In 2009–2010 the USG formed an interagency working group to develop a set of SC-CO_2 estimates for use by all Executive Branch agencies to value marginal changes in CO_2 emissions in regulatory impact analyses (USG, 2010). The goal of this exercise was to improve the accuracy and consistency with which agencies value marginal changes in CO_2 emissions. Before the release of these estimates, CO_2 emissions changes were valued in some but not all regulatory analyses, and the SC-CO_2 estimates used by different agencies varied substantially. The USG recently updated their estimates for the SC-CO_2 by employing new versions of the three underlying integrated assessment models (IAMs), but leaving the original estimation approach and underlying assumptions unchanged (USG, 2013). This section provides a brief overview of the estimation approach and assumptions used by the USG for estimating SC-CO_2, describes some critiques of the approach by other researchers, and discusses the existing literature on the social cost of non-CO_2 GHGs.

2.1. USG SC-CO_2 estimation approach

To estimate the SC-CO_2 the USG used three IAMs that couple simplified models of atmospheric gas cycles and climate systems with highly aggregate models of the global economy and human behaviour to capture the effects that GHG emissions, through their effect on the climate, have on human welfare. Within IAMs, the modelling that guides the transition from emissions into climate impacts is based on scientific assessments, while the mapping of climate impacts into changes in human welfare is based on economic research that has studied the effect of climate on various market and non-market sectors. Nordhaus and Boyer (2000) provide a very informative and detailed description of how such models are developed.[2]

The three models used by the USG are those that feature most prominently in the published social cost of carbon literature: the Dynamic Integrated Climate and Economy (DICE) (Nordhaus, 2008; Nordhaus & Boyer, 2000), the Policy Analysis of the Greenhouse Effect (PAGE) (Hope, 2006b, 2008), and the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) (Anthoff, Hepburn, & Tol, 2009; Tol, 2002a, 2002b, 2009) models. The USG chose to use the IAMs'

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climate system submodels and the functions that map climate change into economic damages as implemented by the model developers, but adopted a common set of input assumptions for equilibrium climate sensitivity, discount rates, global population, economic output, and GHG emissions projections. The remainder of this section provides a brief description of these common assumptions and the steps used to calculate the SC-CO_2 estimates. Interested readers can find more details in the USG's 2010 technical support document (USG, 2010).

2.1.1. Reference socio-economic-emissions scenarios

The USG selected five scenarios of economic output, population, and GHG emissions projections using results from the 2009 Stanford Energy Modeling Forum exercise number 22 (EMF-22). Four of the scenarios are based on baseline runs from global economic models (MERGE, MESSAGE, MiniCAM, and IMAGE) and span a range of emissions projections and plausible outcomes for future population and economic output absent significant global action to address climate change. These scenarios allowed for internally consistent forecasts of economic output, population, and emissions for the years 2000–2100. The fifth scenario used by the USG is based on the average of the 550 ppm CO_2e stabilization runs for each of the four models from which baseline scenarios were selected to represent potential action by the rest of the world absent US action. Across the five scenarios, atmospheric CO_2 concentrations in 2100 ranged from approximately 450 to 890 ppm (550–1130 ppm in CO_2e). Over the time horizon, the forecasts of the average growth rate for global per capita economic output ranged from 1.5% to 2.0% per year, and the average global population growth rate ranged from 0.4% to 0.5% per year. To run the IAMs through the year 2300, the USG extrapolated the selected EMF scenarios using the following assumptions: starting in 2100 the population growth rate declines linearly to zero in 2200; starting in 2100 the growth rate of economic output per capita declines linearly to zero in 2300; for all years after 2100 the growth rate of the carbon intensity of the global economy (CO_2 emissions/economic output) remains constant at its 2090–2100 average; starting in 2100 net land-use CO_2 emissions decline linearly to zero in 2200; and for all years beyond 2100 non-CO_2 radiative forcing anomalies remain constant at their 2100 levels.

Several limitations of the simplifying assumptions underlying the USG approach to scenario development have been discussed by other researchers. O'Neil (2010) pointed out that the selected EMF scenarios do not reflect the full range of outcomes that appear in other studies in the literature, and Kopp and Mignone (2012) suggested that the selected scenarios may effectively over-sample the peaks of the distributions. As for the extrapolations, while running the models out for multi-century time horizons is not necessary for relatively short-lived GHGs like CH_4, it is important for understanding the impacts of long lived GHGs such as CO_2 and N_2O that will affect human welfare well beyond 2100. As emphasized by O'Neil (2010) and Kopp and Mignone (2012), the state of the world beyond 2100 is highly uncertain and the scenario extrapolation approach taken by the USG represents only one of many possibilities. Furthermore, the extrapolations for each component of the scenarios (economic output, population, emissions) are separate and nothing ensures internal consistency within the scenarios past 2100. As shown by Marten and Newbold (2012), the temporal decomposition of damages for a perturbation of CO_2 and N_2O are relatively similar in shape and therefore the general findings of studies that explore the sensitivity of the SC-CO_2 to these assumptions should also be applicable to the SC-N_2O.

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2.1.2. Equilibrium climate sensitivity

In reduced-form IAMs, the speed and magnitude of temperature change for a given emissions projection are influenced largely by the 'equilibrium climate sensitivity' (ECS) parameter. The ECS represents the long-term global average temperature response to a level of radiative forcing associated with a sustained doubling of atmospheric CO_2 concentration (around 550 ppm). To represent the uncertainty in the responsiveness of the climate system to changing atmospheric conditions, the USG used a probability distribution for the ECS parameter of the form suggested by Roe and Baker (2007). The USG calibrated the parameters of the probability distribution to have a median equal to 3 8C, two-thirds probability that the ECS lies between 2 and 4.5 8C, which was intended to be consistent with the UN Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) consensus statement about the ECS (Meehl et al., 2007). The distribution was truncated from above at 10 8C. This specification of the ECS distribution is retained to maintain consistency with the USG estimates of the SC-CO_2, but it is noted that the recently released AR5 by the IPCC has revisited the equilibrium climate sensitivity and revised the range downwards to 1.5–4.5 8C and no longer provides a most likely value (Collins et al., 2013). The ultimate effect of updating the ECS distribution to be consistent with the IPCC AR5 findings will depend heavily on the central tendency selected for the distribution.

2.1.3. Discount rates

Because the damages from an additional tonne of CO_2 emissions occur over many decades, the discount rate, which reflects the tradeoff between present and future consumption, plays a critical role in estimating the SC-CO_2. In light of disagreement in the literature regarding the appropriate discount rate to use in this context and uncertainty about future conditions that impact the discount rate, the USG used three constant discount rates intended to span a plausible range: 2.5%, 3%, and 5% per year. It is worth noting that the debate regarding not only the appropriate discount rate but also its time path is ongoing (Arrow et al., 2013; Dasgupta, 2008). While the appropriate value for the discount rate will presumably remain an area of active debate for some time to come, there appears to be agreement that the use of a constant discount rate over long time horizons with uncertain changes in the consumption per capita growth is not theoretically consistent. This article uses the same three constant discount rates as the USG estimation process, but in Appendix C results are reported from a series of sensitivity analyses using a Ramsey discounting approach. Similar to Marten and Newbold (2012), it is found that applying Ramsey discounting using plausible values for the components of the consumption discount rate gives a range of social cost estimates that is broadly consistent with the range of results obtained using the constant discount rates.

2.1.4. Calculating the SC-CO_2

The process to estimate the SC-CO_2 for emissions in year t has four steps. First, each model is used to forecast monetized impacts associated with the baseline path of emissions, economic output, and population. Second, each model is re-run with an additional unit of CO_2 emissions in year t to forecast monetized impacts for all years beyond t along this perturbed path of emissions. Third, the marginal damages in each year are calculated as the difference between the monetized impacts forecast in steps 1 and 2. Finally, the resulting path of marginal damages is discounted and summed to calculate

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the present value of the marginal damages in the year when the additional unit of emissions used to perturb the model is emitted.

The USG repeated this process with each model, discount rate, and socio-economic-emissions scenario for each decade between 2010 and 2050. Because the ECS parameter is modelled probabilistically, and because PAGE and FUND incorporate uncertainty in other model parameters, the final output from each model run represents a distribution over the SC-CO_2 in each year. These distributions were estimated using 10,000 simulations in each model run. Therefore, the exercise produced 45 separate distributions of the SC-CO_2 for a given emissions year, based on the three models, three discount rates, and five socio-economic-emissions scenarios considered. To provide a range of estimates that reflects this uncertainty but still emphasizes the central tendency, the distributions from each of the models and scenarios were equally weighted and combined to produce three separate probability distributions for the SC-CO_2 in a given year, one for each assumed discount rate. Four SC-CO_2 estimates were selected from these three probability distributions to reflect the global damages caused by one tonne of CO_2 emissions. Three estimates are based on the average SC-CO_2 across the three models and five socio-economic-emissions scenarios for the 5%, 3%, and 2.5% discount rates, respectively. The fourth value is the 95th percentile of the SC-CO_2 distribution at the 3% discount rate, and was chosen to represent potential higher-than-expected impacts from anthropogenic GHG emissions.

2.2. Existing estimates of the social cost of non-CO_2 GHG emissions

A significant limitation of the aforementioned USG interagency process is that the social costs of non-CO_2 GHG emissions were not estimated. Therefore, as an alternative to applying direct estimates for the social costs of non-CO_2 GHG emissions in the primary BCA, several recent USG regulatory analyses have approximated the benefits of non-CO_2 GHG emissions reductions in sensitivity analyses by transforming the non-CO_2 GHG emissions to 'CO_2-equivalents' using estimates of the GWP for the GHG in question and then using the USG SC-CO_2 for valuation (e.g. US EPA, 2012, 2013).

Gas comparison metrics, such as the GWP, have been designed to measure the impact of different GHGs relative to CO_2, where the point of comparison along the pathway from emissions to monetized damages (depicted in Figure 1) may differ across measures. The GWP, in particular, is designed to measure the additional radiative forcing (i.e. the amount of energy absorbed by atmospheric concentrations of GHGs) from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years). The GWP and other gas-comparison metrics are problematic as an SC-CO_2 scalar in BCA, as the remaining linkages in the pathway depicted in Figure 1 are complex and non-linear. Marten and Newbold (2012) demonstrate that using the GWP to adjust SC-CO_2 estimates to capture the impact of non-CO_2 gases provides a significant improvement over the implicit assumption that they are zero when such benefits are left unquantified, but may still underestimate mitigation benefits. Alternative gas comparison metrics that compare GHGs at different points in the chain of

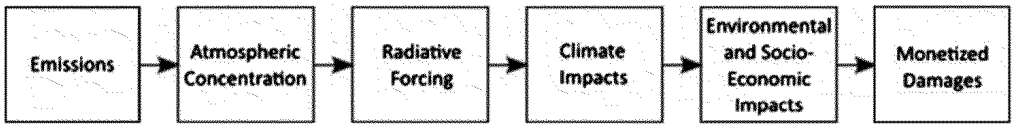

Figure 1 Path from GHG emissions to monetized damages

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causation (e.g. global temperature change potential (Shine, Fuglestvedt, Hailemariam, & Stuber, 2005), peak commitment temperature (Smith et al., 2012), temperature proxy index (Tanaka, O'Neill, Rokityanskiy, Obersteiner, & Tol, 2009)) have also been shown to be imperfect substitutes for direct estimates.

Several researchers have directly estimated the social cost of non-CO_2 GHG emissions using IAMs, although the number of such estimates is small compared to the large number of SC-CO_2 estimates available in the literature. Among these previous direct estimates there is considerable variation in the model versions and input assumptions used. See Table 1 for a summary of the 11 non-CO_2 studies published to date.

As shown in Table 1, the estimates cover emissions years from 1990 to 2050, although the specific perturbation year is not stated in all studies. The studies also cover a wide range of constant and variable discount rate specifications and consider a range of baseline socio-economic and emissions scenarios that have been developed over the last 20 years. Finally, some studies in the literature have chosen not to report the social cost estimates directly. Instead, they opt to report only the 'global damage potential', which is a ratio of the social cost of gas X to the SC-CO_2. Normalizing the SC-CH_4 or

TABLE 1 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Model	Time horizon	Discount rate	Emissions year	Scenario[a]	Climate sensitivity
Reilly and Richards (1993)	N/A	140 years	2, 5, 8%	1990	N/A	N/A
Fankhauser (1994)	N/A	230 years	Ramsey	1991–2030	IS92[b]	N/A
Kandlikar (1995)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Kandlikar (1996)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Hammitt et al. (1996)	N/A	2200	1, 3, 5%	1995–2015	IS92a,c,e	1.5, 2,5, 4.5 8C
Tol (1999)	FUND 1.6	2100	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Tol et al. (2003)	FUND 1.7	2200	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Hope (2005)	PAGE95	2200	Ramsey	2000	SRES A2	Probabilistic, mode of 3 8C
Hope (2006a)	PAGE2002	2200	Ramsey	2001	SRES A2	Probabilistic, mean of 3 8C
Waldhoff et al. (2011)	FUND 3.5	3000	Ramsey	2010–2019	FUND, SRES A1B, A2, B1, B2	2, 3, 4.5 8C
Marten and Newbold (2012)	DICE2007 w/ MAGICC	2300	Ramsey, 2.5, 3, 5%	2010–2050	EMF-22 MiniCAM Base	Probabilistic,median of 3 8C

[a]IS90 scenarios are based on the IPCC First Assessment Report (IPCC, 1990); IS92 scenarios are based on the IPCC Supplementary Report (IPCC, 1992); SRES scenarios are based on the IPCC Special Report on Emissions (IPCC, 2000); the FUND scenario is the default scenario in the FUND model; EMF-22 scenarios are based on results from Stanford's Energy Modeling Forum's 22nd exercise (Clarke et al., 2009).[b]The particular IS92 scenario used was not specified.

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SC-N_2O estimate using the SC-CO_2, in part, controls for differences in the modelling to allow for a better comparison with other estimates in the literature.

Fankhauser (1994) was one of the first to develop estimates of the average SC-CH_4 and SC-N_2O for emissions in the 2010 and 2020 decades given a 100-year time horizon for climate change damages. Kandlikar (1995) and Hammitt, Jain, Adams, and Wuebbles (1996) also developed estimates of SC-CH_4 and SC-N_2O for a single socio-economic-emissions scenario and using constant discount rates. Tol et al. (2003) and Hope (2005, 2006a) developed estimates for the SC-CH_4 in 2000 using the FUND and PAGE models, respectively. Waldhoff, Anthoff, Rose, and Tol (2011) used a newer version of the FUND model to develop estimates of the social cost of marginal CO_2, CH_4, N_2O, and SF_6 emissions for the average year in the 2010 decade. While they considered only a single emissions period, they conducted a wide range of sensitivity analyses including four socio-economic-emissions scenarios from the IPCC special report on emissions (IPCC, 2000) in addition to the default FUND scenario. In Section 4, the specific results of these previous studies are discussed with a comparison to the estimates obtained in the present study.

The above-mentioned previous studies provide a basic understanding of the relative social costs of different GHGs but do not provide sufficient information about how this relationship changes over time. Marten and Newbold (2012) used an IAM that couples the climate model MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) with economic components of the 2007 version of William Nordhaus' DICE model to directly estimate the social cost of marginal CO_2, CH_4, and N_2O emissions. They estimated the annual social costs for the years 2010–2050 along a single socio-economic-emissions pathway given uncertainty about the equilibrium climate sensitivity parameter. An advantage of their approach is that through the use of a more detailed, yet still relatively simple, climate model their results are not affected by over-simplification of temperature response or atmospheric chemistry, which have been shown to have non-negligible effects on the estimates of social costs (Marten, 2011; Warren et al., 2010).

The work of Marten and Newbold (2012) uses many of the assumptions used by the USG in its estimation of SC-CO_2, including discount rates, the equilibrium climate sensitivity distribution, and post-2100 socio-economic and emissions extrapolations. However, they focus on only one of the three models and one of the five socio-economic-emissions scenarios used by the USG. Furthermore, they use a different climate sub-model, which leads their estimate of the SC-CO_2 to be different from the USG estimate, even for the same IAM and scenario combination. Therefore, although these studies, including Marten and Newbold (2012), have increased our understanding about the relative social costs of GHG emissions, they have not provided a set of estimates that are entirely consistent with the USG SC-CO_2 estimates. In Section 4, the estimates derived in this article are compared with those of Marten and Newbold (2012) to more clearly demonstrate the similarities and differences in the two sets of estimates for SC-CH_4 and SC-N_2O.

3. Estimating the social cost of non-CO_2 GHGs consistent with USG SC-CO_2

The primary obstacle in estimating the social cost of non-CO_2 GHG emissions in a manner consistent with the USG SC-CO_2 estimates is that not all of the IAMs used include explicit representations of the non-CO_2 gases of interest. This section describes the degree to which non-CO_2 GHGs are currently

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represented in the default versions of DICE, PAGE, and FUND, and then discusses how they are amended to estimate the social cost of these gases.

3.1. Representation of non-CO_2 GHGs in DICE, PAGE, and FUND

The FUND model explicitly considers CH_4, N_2O, and SF_6 in addition to CO_2. The model uses one-box atmospheric gas cycle models for these gases, with geometric decay towards pre-industrial levels. For CH_4 and N_2O, FUND estimates the additional radiative forcing imposed by the atmospheric buildup of these gases using the simplified expressions presented in Chapter 6 of the IPCC's Third Assessment Report (TAR) (Ramaswamy et al., 2001). FUND also augments the TAR expression for the additional radiative forcing from CH_4 to account for the influences of stratospheric water vapour and tropospheric ozone changes. Because FUND uses CH_4 and N_2O emissions as inputs and internally computes their impact on the climate system, it is possible to directly estimate the social cost of those gases without modifying the model.

In the DICE model, the only GHG that is explicitly represented is CO_2; an exogenous radiative forcing projection is used to account for the impact of all other gases on the climate. To develop an exogenous radiative forcing pathway consistent with the emissions scenarios used to estimate the SC-CO_2, the USG decomposed the default DICE exogenous radiative forcing vector into CH_4, N_2O, F-gases, aerosols, and other residual forcing components. The USG then replaced the radiative forcing attributed to CH_4, N_2O, and F-gases with estimates associated with the EMF-22 scenarios. As non-CO_2 emissions are not a direct input into DICE, it is not possible to simply perturb the emissions projection and re-run the model to obtain a forecast of additional damages.

The 2002 version of the PAGE model, which was used by the USG in developing its first set of estimates (USG, 2010), includes an atmospheric model for CH_4 and SF_6, but represents the effects of other non-CO_2 GHGs in an exogenous radiative forcing projection. Presumably to simplify the process and maintain consistency with DICE, the USG did not use PAGE's internal CH_4 component. Instead, the same exogenous radiative forcing projection was used for the effect of CH_4, N_2O, and F-gas emissions as was used for DICE. Since then, a N_2O component has been added to the PAGE model, although in the recent 2013 SC-CO_2 update the USG maintained the approach of using the same single exogenous forcing projection as was applied to DICE (USG, 2013). Therefore PAGE, as implemented by the USG, faces the same limitations as DICE with respect to estimating the social costs of marginal non-CO_2 emissions that are consistent with the USG SC-CO_2 estimates. For these reasons, computing estimates for the social cost of non-CO_2 gases in DICE and PAGE requires either replacing the climate component of these models with a more complete representation, as was done with DICE by Marten and Newbold (2012), or deriving an estimate of the path of additional radiative forcing that would result from a perturbation of the gas in question. This article uses the latter approach for DICE and PAGE, as the former would represent a substantial change to the underlying IAMs and would have implications for the SC-CO_2 estimates, making this work inconsistent with the USG SC-CO_2 estimates currently used in regulatory analysis.

3.2. Estimating the social cost of non-CO_2 GHGs in DICE and PAGE

The process used in this article to estimate the social cost of non-CO_2 GHGs in DICE and PAGE as implemented by the USG requires first generating a forecast of the additional radiative forcing

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associated with a perturbation of a non-CO_2 gas's emissions in a single year, and then adding this radiative forcing perturbation to each model's exogenous radiative forcing projection. To determine the additional radiative forcing associated with the emission perturbation, there is a need to model the change in atmospheric concentration and the radiative forcing associated with the additional concentration. For both CH_4 and N_2O, a simple one-box atmospheric gas cycle model with a constant decay rate is used to estimate the atmospheric concentration of each gas based on its assumed emissions. The use of a one-box gas cycle for CH_4 and N_2O with constant decay follows the approach used by the IPCC to compute GWPs (Forster et al., 2007) and the FUND model (Anthoff & Tol, 2013). In both the baseline and the perturbed case, the contribution of the gas to the global radiative forcing anomaly is determined by the forcing relationships presented in the IPCC TAR (Ramaswamy et al., 2001), which were not updated by the IPCC in AR4. The incremental radiative forcing is defined by the difference between the baseline forcing path and the emissions path that includes a one tonne perturbation in a given year. Next, the path of additional radiative forcing is added to the stream of exogenous radiative forcing in each IAM to estimate the climate damages in the perturbed scenario. These damages are then compared to the baseline damages to determine the social cost of gas X (SC-X). Specifically, the process is as follows:

1. Run the IAM as described in the SC-CO_2 technical support document (USG, 2010) to estimate baseline damages.
2. Estimate the baseline atmospheric concentration for gas X.
3. Estimate the baseline radiative forcing contribution of gas X.
4. Perturb the stream of gas X emissions by one tonne in year t.
5. Estimate atmospheric concentration for gas X in the perturbed scenario.
6. Estimate the radiative forcing contribution of gas X in the perturbed scenario.
7. Compute the incremental radiative forcing as the difference between the results of steps 3 and 6.
8. Add the additional radiative forcing from step 7 to the exogenous radiative forcing path used in the IAM in step 1.
9. Re-run the IAM to compute the damages along the perturbed emissions path.
10. Compute the social cost of gas X for emission year t as the present value of the difference in damages estimated in steps 1 and 9.

Two practical issues associated with implementation are worth noting. First, while the SC-X estimates are associated with a one tonne perturbation, to avoid computational rounding error a 1 Mt perturbation is used and then the resulting change in damages is scaled to get the average effect per tonne. Experiments conducted by Griffiths et al. (2012) to assess the applicability of the SC-CO_2 to non-marginal emission changes show that the average per tonne SC-CO_2 estimate is relatively constant over large differences in perturbation size. Additional experiments in the context of this article found that alternative perturbation sizes do not significantly change the average one tonne social cost estimate. Second, the additional radiative forcing due to the emissions perturbation is computed based on an annual time step, but because DICE and PAGE use longer time steps the average radiative forcing over the time step is added to the model's exogenous radiative forcing vectors.

The remainder of this section describes the procedure for modelling the incremental radiative forcing of a perturbation for CH_4 and N_2O, and explores the sensitivity of these projections to

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two issues. First, it evaluates whether the simple one-box gas cycle model with a constant decay rate produces a close approximation to the forecasts of future atmospheric CH_4 and N_2O concentrations based on a more sophisticated climate model. Second, it explores the sensitivity of the results to the method used for extrapolating non-CO_2 emissions from 2100 to 2300. This is important, because the USG did not specify a particular set of emissions pathways for each constituent gas, instead assuming only that non-CO_2 radiative forcing remains constant past 2100. Such a situation could arise from a myriad of possible individual gas projections and the USG did not specify which it was assuming.

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3.3. Methane

A simple one-box atmospheric gas cycle model for methane specifies the concentration in year t, $C_t^{CH_4}$ [ppb], such that

$$C_t^{CH_4} = C_{t-1}^{CH_4} + d_{CH_4}(C_{pre}^{CH_4} - C_{t-1}^{CH_4}) + g_{CH_4}E_{t-1}^{CH_4}, \tag{1}$$

where d_{CH_4} defines the rate of decay, $C_{pre}^{CH_4}$ [ppb] is the pre-industrial atmospheric concentration, and g_{CH_4} [ppb/Mt] converts emissions, $E_{t-1}^{CH_4}$ [Mt], from mass to atmospheric volume. The mass to volume conversion factor is g_{CH_4} ¼ 0.3597 ppb/Mt and $C_{pre}^{CH_4}$ ¼ 700 ppb, following the IPCC TAR. The rate of decay is set to d_{CH_4} ¼ 1/12 following the IPCC AR4 stated CH_4 lifetime of 12 years. The iteration begins in the year 2006 using the emissions from the EMF-22 scenario (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used so that $C_{2005}^{CH_4}$ ¼ 1774 ppb.

The contribution of atmospheric methane to global radiative forcing, denoted $Q_t^{CH_4}$, is defined using the relationship in Table 6.2 of the IPCC TAR:

$$Q_t^{CH_4} = f\ 0.036\ \left[C_t^{CH_4} - C_{pre}^{CH_4} - [f(C_t^{CH_4}, C_{pre}^{N_2O}) - (C_{pre}^{CH_4}, C_{pre}^{N_2O})]\right], \tag{2}$$

where $C_{pre}^{N_2O}$ [ppb] is the pre-industrial atmospheric concentration of nitrous oxide and

$$f(C^{CH_4}, C^{N_2O}) = 0.47 \ln\left[1 + 2.01 \times 10^{-5}(C^{CH_4}C^{N_2O})\right]^{0.75} + 5.31 \times 10^{-15}C^{CH_4}(C^{CH_4}C^{N_2O})^{1.52}. \tag{3}$$

The function in expression (3) accounts for the overlapping absorption bands of CH_4 and N_2O, thereby reducing their effective absorption. Parameter f is used to proxy for indirect effects of CH_4 that include the enhancement of stratospheric water vapour and tropospheric ozone changes. Following the IPCC AR4, an enhancement effect of 40% (25% from tropospheric ozone change and 15% for stratospheric water vapour enhancement) is used, such that f ¼ 1.4. The pre-industrial concentration of N_2O is set consistent with the IPCC TAR, such that $C_{pre}^{N_2O}$ ¼ 270 ppb.

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A key simplification in this approach is the constant decay rate used in the atmospheric gas cycle model. As discussed by IPCC Working Group I in Chapter 4 of the TAR, the lifetime of methane emissions in the atmosphere depends on temperature and the concentrations of CO, NOx, and other VOCs in the atmosphere (Ehhalt et al., 2001). Sensitivity analysis is used to understand the potential implications of ignoring these interactions by comparing the incremental atmospheric concentration projected by the simple model described above to the analogous projection from the climate model MAGICC,[3] which, while still relatively simple, incorporates these interactions between the lifetime of CH_4 in the atmosphere and the other gases and climate variables. This exercise uses CH_4 emissions from the EMF-22 MiniCAM reference scenario and considers a one tonne perturbation of CH_4 in 2015. It is noted that these results are robust across alternative emissions levels.[4]

Figure 2(a) presents the projected average decadal increment to atmospheric concentrations using both the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. At the time of the perturbation (2015), the inter-annual time step of MAGICC allows for an uptake of the additional emissions into the atmosphere, whereas the strict annual time step of the simple model causes a year to pass before the change is registered. After the initial year, the models originally differ by around 15%. This difference falls to under 10% within the first decade, with the faster effective growth in the simple model causing its additional concentration to eventually fall below that of MAGICC.

The difference in the incremental radiative forcing from the perturbation between the simple model and MAGICC is also of importance. Although MAGICC relies on similar equations to derive the radiative forcing of atmospheric CH_4 concentrations, it differs in the way it handles indirect effects of CH_4 on tropospheric ozone and stratospheric water vapour, in addition to including other temperature-related feedbacks. Figure 2(b) presents the average additional radiative forcing per decade attributed to the 2015 CH_4 perturbation in both models. The average increase in radiative forcing over the decade is considered because this is the input required by DICE due to its ten-year time step and therefore a more relevant comparison (PAGE requires a similar multi-year average). When considering the average additional radiative forcing over the decade, the initial difference in concentration between MAGICC and the simple model has a minimal effect and the difference in radiative forcing between the two models is less than 2% over the first two decades. However, this difference grows to –18% over the subsequent two decades. This escalation in the difference is in part due to the use of a constant decay rate in the simple model, whereas MAGICC takes into account the growing atmospheric concentrations of other gases and increasing atmospheric temperature, which increase the lifetime of atmospheric CH_4.

To understand the effect that this difference would have on an estimate of the SC-CH_4, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of CH_4, as computed using both the simple model and MAGICC, is added to the exogenous forcing projection. As above, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 2 presents the results of this experiment. In line with the results comparing the radiative forcing perturbations above, the two approaches produce similar social cost estimates for emissions in 2015, where additional analysis has shown these results to hold with PAGE as well. The impact of assuming a constant decay rate is greater further out into the future, due to the projected increase in the atmospheric concentration of other relevant gases and atmospheric temperature that are accounted for in MAGICC, and the social cost

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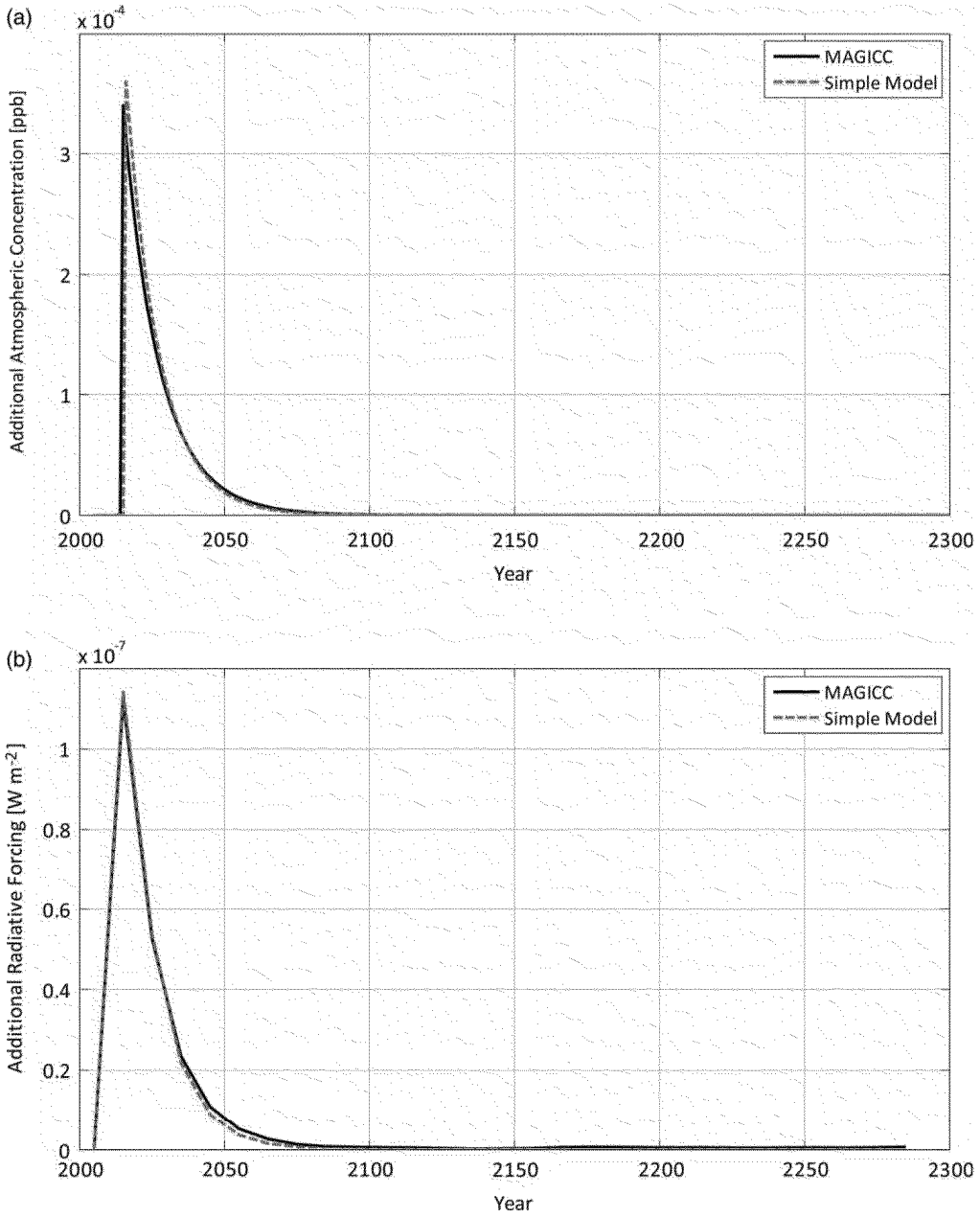

Figure 2 Effects of perturbation in 2015 CH_4 emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

estimates begin to diverge for later emissions years. For the same reason, the two approaches will show greater differences for lower discount rates that give increased weight to future time periods. While over-simplification of the climate system can, in some circumstances, have significant effects on

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TABLE 2 Effect of CH_4 gas cycle model on SC-CH_4 (2007$ per tonne CH_4): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	1135	1183	2 4%
	3.0%	822	851	2 3%
	5.0%	349	354	2 2%
2045	2.5%	2490	2707	2 8%
	3.0%	1933	2084	2 7%
	5.0%	956	1006	2 5%

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social cost estimates (e.g. Marten 2011), the near-term differences based on this simplification seem relatively small considering the precision of such social cost estimates.

3.4. Nitrous oxide

The simple one-box atmospheric gas cycle model for N_2O takes a similar form to the model used for CH_4, such that the concentration of nitrous oxide in year t, $C_t^{N_2O}$ [ppb], is specified as

$$C_t^{N_2O} = C_{t-1}^{N_2O} + d_{N_2O}(C_{pre}^{N_2O} - C_{t-1}^{N_2O}) + g_{N_2O}E_{t-1}^{N_2O}, \tag{4}$$

where d_{N_2O} is the rate of decay, and g_{N_2O} [ppb N_2O/Mt N] converts emissions, $E_{t-1}^{N_2O}$ [Mt N], from mass to atmospheric volume. Following the IPCC AR4, the mass to volume conversion factor is g_{N_2O} ¼ 0.2079 ppb N_2O/Mt N and the rate of decay is d_{N_2O} ¼ 1/114 based on a 114-year lifetime. As with CH_4, the iteration begins in the year 2006 using the emissions from the EMF-22 scenarios (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used, such that $C_{2005}^{N_2O}$ ¼ 319 ppb.

The contribution of atmospheric N_2O to global radiative forcing, denoted $Q_t^{N_2O}$, is defined using the relationship in Table 6.2 of the IPCC TAR, such that

$$Q_t^{CH_4} = 0.12 \left[C_t^{N_2O} - C_{pre}^{N_2O} - [f(C_{pre}^{CH_4}, C_t^{N_2O}) - f(C_{pre}^{CH_4}, C_{pre}^{N_2O})] \right], \tag{5}$$

where $f(C^{CH_4}, C^{N_2O})$ is defined in expression (3).

As with CH_4, a key simplifying assumption is the constant decay rate used in the simple gas cycle model (and potentially the time it takes the gas to become well mixed within the atmosphere). As discussed in the IPCC TAR, the decay rate of N_2O will depend on the atmospheric concentration of N_2O and so will not be constant in reality. To examine the extent to which this impacts the results of the simple model, an analogous set of experiments as conducted for CH_4 were performed. Given future

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N_2O emissions based on the EMF-22 MiniCAM reference scenario, a one tonne N_2O perturbation in 2015 is considered. Figure 3(a) shows the projected atmospheric concentration increase from the perturbation using the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. This comparison illustrates that the simple model tracks the output of MAGICC well for the entire 300-year time horizon. Outside the initial perturbation year, the two projections do not differ by more than 2% within the first century, with the largest difference occurring in the perturbation year, for the same reasons as with CH_4.

Figure 3(b) presents the estimates of average additional radiative forcing per decade as a result of the N_2O perturbation using both models. The additional radiative forcing from the N_2O perturbation in the one-box model is forecast to be slightly lower (7%) in the first decade compared to MAGICC. Subsequently, the difference is within 2% through to 2300.

As with CH_4, to assess the effect that this difference would have on the SC-N_2O, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of N_2O computed using both the simple model and MAGICC is added to the exogenous forcing projection. As before, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 3 presents the results of this experiment. As the comparisons of the projected radiative forcing perturbations would suggest, the difference between the social cost estimates for the two approaches is relatively small. In contrast to the case of CH_4, here an increase in the discount rate increases rather than decreases the divergence between the estimates due to the greater weight being placed on the earlier years when the radiative forcing perturbations have a slightly higher degree of divergence.

3.5. Effect of post-2100 non-CO_2 radiative forcing assumptions

The EMF-22 socio-economic-emissions scenarios used by the USG include years only up to 2100, while the USG ran the IAMs out to 2300. Therefore, additional assumptions were required to extrapolate the scenarios beyond 2100. For the purposes of this study, the most important of these assumptions is that non-CO_2 radiative forcing will remain constant at its 2100 level until 2300. Such a broad assumption was sufficient for the purposes of the USG in estimating the SC-CO_2. However, estimating the social cost of non-CO_2 GHGs requires explicit projections of baseline emissions of non-CO_2 gases in order to correctly determine the effect of the perturbation. The USG's broad assumption regarding the extrapolation of non-CO_2 gases is therefore problematic as constant non-CO_2 radiative forcing post 2100 may occur in an infinite number of ways. For instance, one way to achieve this outcome is to assume that emissions of each non-CO_2 gas falls to a level equal to its respective rate of decay in 2100. This assumption would keep atmospheric concentrations, and in turn radiative forcing, constant. Based on the simple gas cycle models laid out in the earlier sections this implies that, for gas X,

$$E_t^X = \frac{-d_X(C_{pre}^X - C_{2100}^X)}{g_X} \forall t \ . \ 2100. \tag{6}$$

To put this assumption into context, the solid lines in Figure 4(a) and (b) present the emissions paths for CH_4 and N_2O, respectively, under the MiniCAM EMF-22 reference scenario extrapolated using

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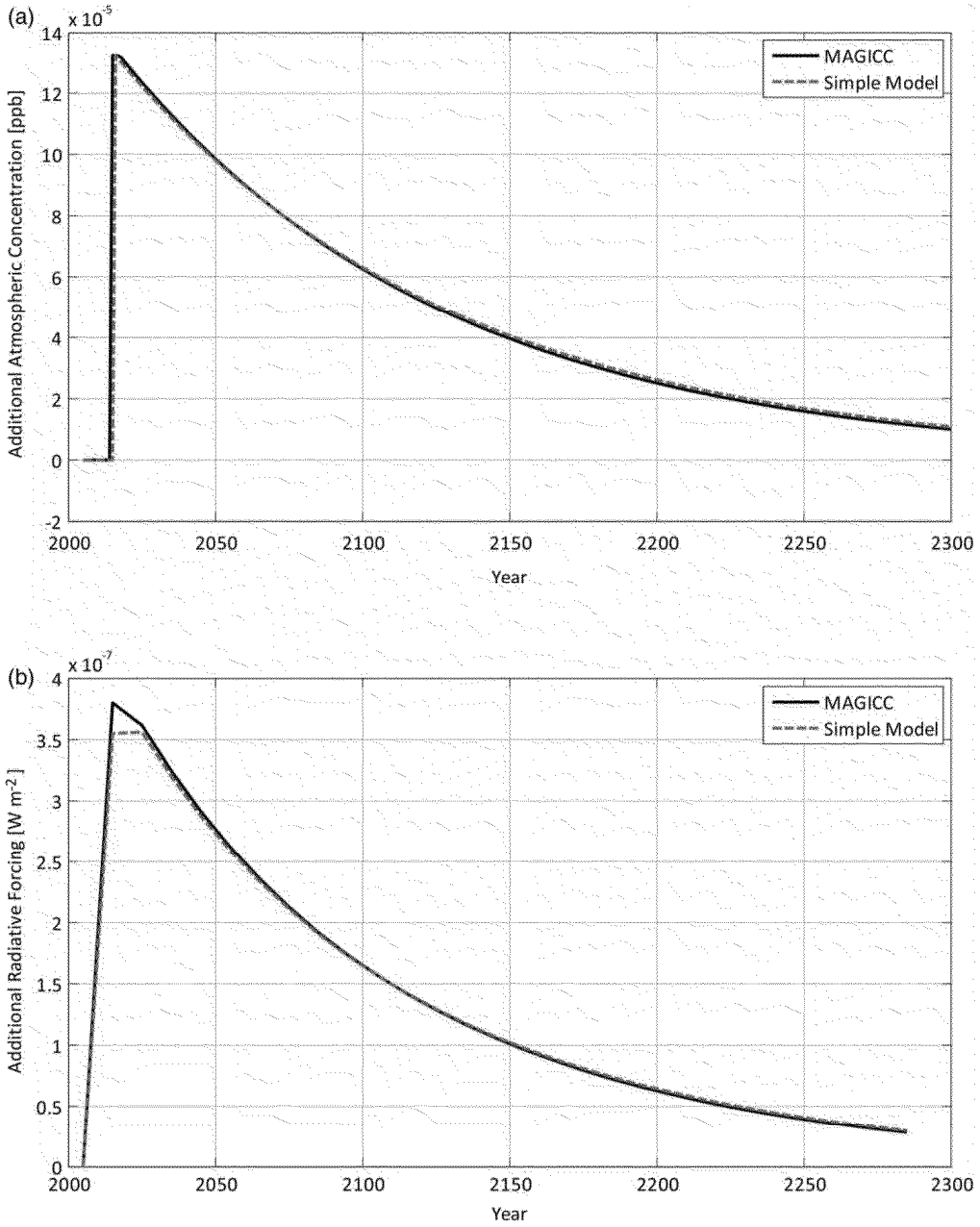

Figure 3 Effects of perturbation in 2015 N_2O emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

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TABLE 3 Effect of climate model on SC-N_2O (2007$ per tonne N_2O): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	19,689	19,819	2 1%
	3.0%	12,390	12,525	2 1%
	5.0%	3,346	3,419	2 2%
2045	2.5%	36,968	37,358	2 1%
	3.0%	25,030	25,427	2 2%
	5.0%	8,280	8,528	2 3%

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expression (6), while the dashed lines show two alternative extrapolation approaches, one where emissions are held constant at their 2100 level and one that assumes emissions intensity (emissions/economic output) continues to decline at the same rate forecast by the EMF-22 scenario in 2090–2100 (dotted line). This latter alternative is analogous to the USG assumption regarding industrial CO_2 emissions. The two alternatives will not result in the radiative forcing contribution of gas X remaining constant post-2100, but do not in themselves violate the assumption that overall non-CO_2 radiative forcing remains constant. Noteworthy is the fact that the assumption in (6) is almost analogous to keeping CH_4 emissions constant at their 2100 levels, whereas for N_2O the assumption requires a sudden decrease in emissions of over 35%.

While Figure 4 illustrates that these three extrapolation approaches can lead to vastly different projections for emissions after 2100, the relevant comparison is how these assumptions affect the additional radiative forcing from a perturbation of the gas and in turn the SC-X estimates. Figure 5(a–d) present the additional radiative forcing resulting from a one tonne perturbation based on the simple model presented in Sections 3.1 and 3.2. Figure 5(a) and (b) demonstrates the difference for a perturbation in 2015, whereas Figure 5(c) and (d) represents perturbations in 2045. For CH_4, the cumulative radiative forcing from the projection over the time horizon differs by less than 0.001%, even for a

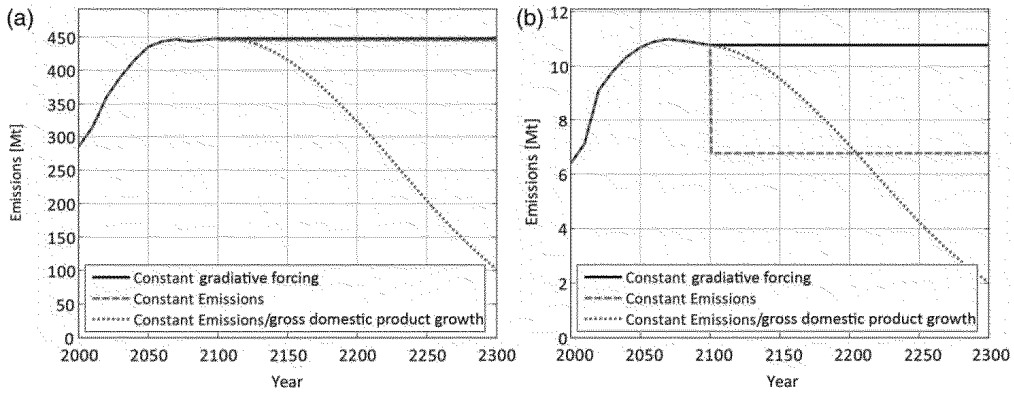

Figure 4 EMF-22 MiniCAM extended emissions scenario: (a) CH_4 emissions; (b) N_2O emissions

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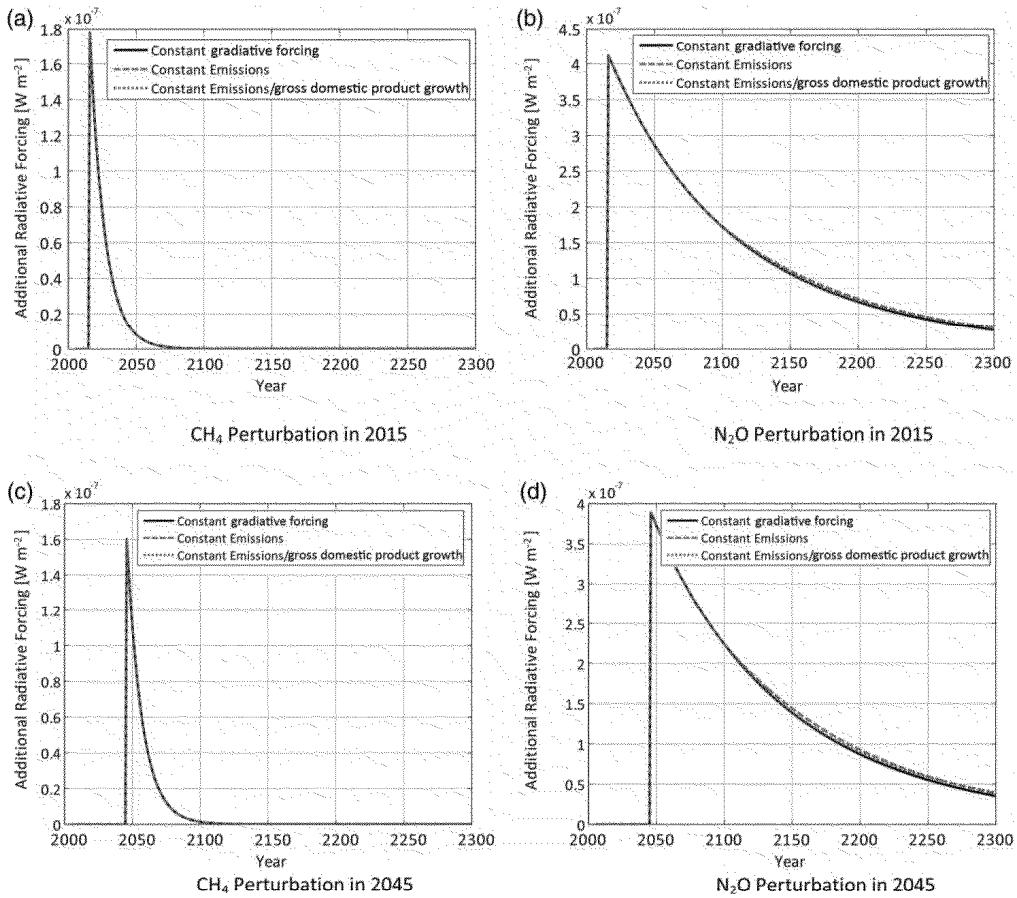

Figure 5 Effect of extrapolation approach on radiative forcing perturbation from simple model: (a) CH_4 perturbation in 2015; (b) N_2O perturbation in 2015; (c) CH_4 perturbation in 2045; (d) N_2O perturbation in 2045

perturbation in 2045. Accordingly, the relevant annual difference is smaller even than one-thousandth of a percent. This result occurs because of the short atmospheric lifetime of the gas, which renders assumptions regarding CH_4 emissions after 2100 unimportant for near-term perturbations. Post-2100 emissions will have a larger effect in the case of N_2O, which has a much longer atmospheric residence time. However, even for a perturbation in 2045, the difference in cumulative additional radiative forcing is less than 2.5% across the extrapolation assumptions.

To examine the impact of these assumptions on SC-CH_4 and SC-N_2O, an experiment was conducted using the DICE model based on the EMF-22 MiniCAM socio-economic-emissions scenario. The results of this experiment are presented in Table 4 for the perturbation year 2045 (noting that the extrapolation method will have greater impact on future emissions years). As may be seen, the relatively short atmospheric lifetime of CH_4 leads to a situation in which post-2100 assumptions do not affect SC-CH_4 estimates, even in 2045. For the longer-lived gas N_2O, in emission year 2045, where the effect of the post-2100 extrapolation approach would be largest, the difference across the three

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TABLE 4 Effect of post-2100 extrapolation on the 2045 SC-X (2007$ per tonne): DICE2010, MiniCAM

Gas	Discount rate	Constant RF	Constant emissions	Constant emissions intensity growth
CH_4	2.5%	2,490	2,490	2,490
	3.0%	1,933	1,933	1,933
	5.0%	956	956	956
N_2O	2.5%	36,968	36,588	36,662
	3.0%	25,030	24,837	24,868
	5.0%	8,280	8,261	8,263

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assumptions is less than 1% and the projections are equivalent to two significant digits. Therefore, in the remainder of this article, non-CO_2 emissions are extrapolated past 2100 using expression (6) to ensure that the gas-specific contribution to overall radiative forcing remains constant in the simple model. While additional study may lead to improvements of long-term forecasts of CH_4 and N_2O emissions and possible correlations, compared to the paths in Figure 5(a), the very minimal effect of such assumptions on the social cost estimates suggests the impact of such efforts would be minimal in this context.

4. Results

For FUND, the social cost of non-CO_2 GHGs is estimated by perturbing the paths of emissions directly, while for DICE and PAGE the approach presented in Section 3 is used. In both cases, all additional assumptions made by the USG are applied, including the five EMF-22 socio-economic-emissions scenarios, the Roe and Baker (2007) distribution for the equilibrium climate sensitivity, and constant discount rates of 2.5%, 3.0%, and 5.0%. Following the USG, the estimates for the expected social cost are averaged across scenarios and models, with each model and scenario given equal weight. Estimates are not combined across discount rates, and a fourth estimate is included representing the 95th percentile when using the 3.0% discount rate. By using the same assumptions and procedures as the USG, estimates of the SC-CO_2 derived in this article are identical to the values used in US Federal rule making. Specifically, these estimates are equivalent to the recent 2013 update of the USG SC-CO_2, which revised the original 2010 USG upwards based on new versions of the IAMs used. The non-CO_2 results, as well as the USG SC-CO_2 estimates, are presented in Table 5 for emissions years 2020 and 2050.[5] Results for additional years, and the results of sensitivity analyses using Ramsey discounting, may be found in Appendix B and C, respectively.

As expected, considering their higher radiative efficacy, the social costs associated with a tonne of CH_4 and N_2O emissions are substantially higher than for CO_2. The values are higher at lower discount rates, although the impact of the discount rate is lower for CH_4 given its relatively short lifetime. Similar to CO_2, the social cost estimates for CH_4 and N_2O increase over time as the climate and economic systems become more stressed, although the growth rate of the social cost estimate may differ between the gases, as discussed in the following.

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TABLE 5 SC-X (2007$ per tonne)

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CO_2	12	43	64	128
	CH_4	550	1,200	1,600	3,200
	N_2O	4,800	15,000	22,000	41,000
2050	CO_2	26	71	97	220
	CH_4	1,400	2,500	3,100	6,900
	N_2O	11,000	27,000	38,000	74,000

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To better understand how the social costs of CH_4 and N_2O compare to CO_2, Table 6 presents the global damage potentials corresponding to the social cost estimates from Table 5. (The disaggregated results, by model and scenario, for 2020 are provided in Appendix B.) As explained in Section 2, the global damage potential for gas X is the ratio of SC-X to SC-CO_2, and therefore by construction captures all the important linkages between emissions and monetized climate change damages (to the degree they are captured by the IAMs) directly within the gas comparison metric. As noted by Frankhauser (1994), this is preferred to the commonly used GWP gas comparison metric, which only measures the additional radiative forcing from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years) and ignores important nonlinear relationships beyond radiative forcing in the chain between emissions and damages.

The global damage potential of CH_4 decreases with the discount rate due to the relatively shorter atmospheric lifetime. This difference in atmospheric lifetime leads to a situation where lowering the discount rate has a greater impact on the SC-CO_2 than the SC-CH_4. This finding is robust across the models. The estimates in Table 6 also present the same result for N_2O in the aggregate case, although this characteristic is not consistent across the models or the previous literature. Based on the disaggregated results (presented in Appendix B), the results from the DICE model suggests the global damage potential for N_2O increases with lower discount rates due to a lower effective decay rate over the relevant time horizon for N_2O than CO_2. This result is consistent with previous findings by Marten and Newbold (2012). However, for FUND the opposite is seen to hold. Waldhoff et al. (2011) show that this result is primarily due to the inclusion of increased production in the agriculture and forestry sectors from CO_2 fertilization effects. At lower discount rates these benefits place a greater downward

TABLE 6 Global damage potential

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CH_4	46	29	25	25
	N_2O	397	359	353	317
2050	CH_4	52	36	32	31
	N_2O	414	388	387	338

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impact on the SC-CO_2, thereby lowering the global damage potential. If one were to remove those impacts from the FUND model the global damage potential for N_2O becomes relatively insensitive to the discount rate. One would expect the role of the discount rate in determining the global damage potential in PAGE to be the same as in DICE, but the results suggest that this is not the case. It seems most likely that this is because the PAGE model has only ten time steps to cover the entire time horizon, which results in very large, up to 100-year, time steps further out in time. As noted in Section 3, the additional radiative forcing from the N_2O perturbation is implemented as the average across the model's time steps. It seems that PAGE does not average radiative forcing over the time step for CO_2, which causes the global damage potential for N_2O to decrease with the discount rate. It is not clear if this result would hold if the size of the time steps in the model were reduced.

A comparison across models further highlights the importance of CO_2 fertilization impacts on the global damage potential. CO_2 emissions, and the resulting increase in atmospheric concentration, have the potential to increase yields in the agriculture and forestry sector. This characteristic is not shared by other GHG emissions. Accordingly, the FUND model, which explicitly captures this effect, exerts downward pressure on the SC-CO_2 that is not present for the SC-CH_4 and SC-N_2O, allowing for the possibility of substantially higher global damage potential estimates. The results based on the FUND model presented in this article exhibit this effect; however, the CO_2 fertilization effect is not explicitly modelled in DICE and PAGE and therefore they are found to produce lower estimates of the global damage potential. For example, using the 3% discount rate, the global damage potential for CH_4 as estimated by FUND ranges between 58 and 88 depending on the scenario, whereas it ranges from 19 to 28 for DICE and PAGE. As the DICE and PAGE models only consider two natural system impacts, temperature and sea level, if they do implicitly include potential CO_2 fertilization benefits, they are included by using the temperature anomaly as a proxy for the increasing atmospheric CO_2 concentration. Fertilization benefits would therefore be allowed to falsely accrue to perturbations of other GHG emissions besides CO_2. It is not clear the degree to which these models try to incorporate CO_2 fertilization effects and therefore the degree to which this issue is of concern.

Finally, the results in this article show that the 100-year GWP (25 for CH_4 and 298 for N_2O; Forster et al., 2007) probably provides an underestimate of the global damage potential of each gas, a finding consistent with previous studies by Marten and Newbold (2012) and Waldhoff et al. (2011). Unlike the GWP as calculated by the IPCC, the global damage potential will be dependent upon the year of the emissions perturbations, so the degree of underestimation varies by year. For CH_4, the global damage potential in Table 6 is 0–84% higher than the GWP in 2020, increasing to 24–108% in 2050. For N_2O, the global damage potential is 6–33% higher than the GWP in 2020, increasing to 13–39% in 2050. While inaccurate, using the GWP to convert emissions reductions into CO_2 equivalents that can be valued with the SC-CO_2 would probably provide a conservative estimate for the abatement benefits.

For the comparison above, the GWP estimates presented in the AR4 by the IPCC (Forster et al., 2007) were used to maintain consistency with the assumptions regarding the direct and indirect effect of CH_4 and N_2O concentrations within the modelling. The recent AR5 by the IPCC (Myhre et al., 2013) has increased the estimate of the indirect effects of CH_4, which gives a higher 100-year GWP for CH_4 of 28. A reduction in their estimate of the radiative efficacy of N_2O has decreased its 100-year GWP to 265. It is likely that updated modelling of the social cost estimates based on similar assumptions would maintain the finding that the GWP is an underestimate of the global damage potential.

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4.1. Comparison with previous estimates

For comparison, Table 7 presents the social cost estimates, when available, and the global damage potential estimates for CH_4 and N_2O from three recent studies in the literature whose features are more up to date and therefore more directly comparable with this study: Hope (2006a), Waldhoff et al. (2011), and Marten and Newbold (2012). A direct comparison to the longer list of studies presented in Table 1 is more difficult as they are based on models and socio-economic and emissions scenarios that were developed up to 20 years ago in a rapidly evolving field.

The social cost estimates presented in Table 5 are higher than the estimates in Hope (2006a) and Waldhoff et al. (2011) for CH_4, and in the range of Waldhoff et al. (2011) for N_2O. This result holds whether the comparison is made with the aggregate results in Table 5 or the disaggregated model-specific results. One reason for the significant difference in the SC-CH_4 estimates is that the earlier studies rely on older model versions (PAGE2002 and FUND3.5), neither of which include the indirect effects of CH_4 emissions on radiative forcing, but are included within this analysis. As noted in Section 3.3 the indirect effects of CH_4 are modelled as a 40% increase in its effective radiative forcing. The result of this change alone would likely be a greater than 40% increase in the SC-CH_4 due to the nonlinear damage functions. Furthermore, the assumptions regarding preference parameters in the main cases of Hope (2006a) and Waldhoff et al. (2011) lead to effective discount rates that are significantly higher than 3%. Other differences in input assumptions (e.g. equilibrium climate sensitivity, socio-economic emissions scenario) will also lead to differences, although these are likely to be of second-order importance given the relative similarity in the assumptions.

However, the results in Table 5 averaged across the combinations of the three models and five scenarios are relatively similar to those of Marten and Newbold (2012), which focused on a single scenario

TABLE 7 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Discount Rate	Emissions Year	Social cost (2007$/tonne X)[a]		Global damage potential (SC-X/SC-CO_2)	
			SC-CH_4	SC-N_2O	CH_4	N_2O
Hope (2006a)	Ramsey	2001	125	–	20	–
Waldhoff et al. (2011)[b]	Ramsey	2010–2019	265	7,616	26	738
			–	–	8–221	383–3,503
Marten and Newbold (2012)	2.5%	2020	1,500	26,000	23	403
		2050	3,500	50,000	32	444
	3%	2020	1,100	17,000	27	400
		2050	2,900	34,000	36	439
	5%	2020	550	4,900	42	380
		2050	1,500	12,000	53	415

[a]All values are discounted to the year of the emissions perturbation.
[b]The first row presents the base case and the second row presents the range found from sensitivity analysis (over socio-economic scenario, climate sensitivity, pure rate of time preference, climate sensitivity and CO_2 fertilization).

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and model. This result is in part based on the fact that both sets of results include the indirect effects of CH_4, use the same discount rates and equilibrium climate sensitivity distribution, and relatively similar scenarios. The estimates in this study are slightly higher for the SC-CH_4 and slightly lower for the SC-N_2O compared to Marten and Newbold (2012). Of particular interest is the specific comparison of this article's estimates based on DICE 2010 and the MiniCAM scenario to those of Marten and Newbold (2012) using the same scenario, discount rates, and equilibrium climate sensitivity but an the older 2007 version of the DICE model and a more complete climate sub-model. In this case, estimates for both the SC-CH_4 and SC-N_2O (presented in Appendix B) are notably lower. The myriad of differences between the model vintages and climate sub-models make it difficult to assess which differences are most important for explaining this relationship.

As previously noted, the global damage potential may provide a better value with which to compare across studies that estimate the social cost of non-CO_2 GHG emissions, as it helps to control for some of the underlying differences in assumptions across studies. For example, the global damage potential is far less sensitive to the discount rate used than the SC-X values themselves. However, the global damage potential does not address the lack of indirect CH_4 effects, as may be seen in the lower estimates of Hope (2006a) and Waldhoff et al. (2011). In these cases the exclusion of the 40% additional increase in radiative forcing from the indirect effects of the CH_4 perturbation explains the majority of the difference. In comparison to Marten and Newbold (2012), the results presented in Table 6 are relatively similar for CH_4 in both the aggregate and disaggregated results. For N_2O, similar results are found in the DICE estimates, but notable differences are found in how the aggregate results respond to the discount rate, due to the differences in this relationship between the models as noted above.

5. Concluding remarks

This article presents a simple and transparent approach to estimating the social cost of CH_4 (SC-CH_4) and N_2O (SC-N_2O) in a manner that is consistent with estimates of the social cost of CO_2 (SC-CO_2) already in use in benefit–cost analysis (BCA) for US Federal regulations. This approach is used to estimate the SC-CH_4 and SC-N_2O for the period 2010–2050. These directly modelled estimates are found to be larger than approximations of the social costs of these gases based on the application of common physical gas comparison metrics, such as global warming potentials (GWPs), to the SC-CO_2. This result generalizes the empirical findings of Marten and Newbold (2012) that using a GWP-based approximation approach will likely offer a conservative estimate of the social cost of non-CO_2 GHGs.

The social costs associated with emissions of non-CO_2 GHGs are substantial and should be included within the BCAs used to assess the overall welfare implications of policy alternatives. For example, by not including monetized values of the benefits from reducing CH_4 and N_2O emissions, the BCA for recent standards regulating the fuel efficiency and GHG emissions of light duty vehicles implicitly assigned them a value of zero (US EPA, 2010). However, the results of this article suggest that those reductions have benefits of US$85–493 million (2007$) for CH_4 and $1.5–12 million (2007$) for N_2O in the year 2020 alone. Failing to account for such impacts could limit the ability of the analysis to serve as a transparent and informative input into the decision-making process about the relative benefits and costs of regulatory alternatives. That said, by restricting the article to a derivation of social cost estimates consistent with the USG SC-CO_2 estimates, the myriad issues related to

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whether those estimates can themselves be improved are set aside.[6] Any limitations that apply to the USG SC-CO_2 estimates therefore also apply to the SC-CH_4 and SC-N_2O estimates derived here.

Supplemental data

Supplemental data for this article can be accessed 10.1080/14693062.2014.912981.

Notes

1. Examples include Minnesota's draft methodology for setting the value of a tariff to compensate solar panel owners for the surplus power they deliver to utilities (http://www.eenews.net/stories/1059992297, http://mn.gov/commerce/energy/images/DRAFT-MN-VOS-Methodology-111913.pdf), the Northwest Power and Conservation Council's symposium supporting the development of the 7th Power Plan (http://www.nwcouncil.org/energy/powerplan/7/symposiums/greenhouse/agenda), BCA of Canada's Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations (http://canadagazette.gc.ca/rp-pr/p2/2013/2013-03-13/html/sor-dors24-eng.html), analysis of climate change projects at the Inter-American Development Bank (correspondence with Patrick Doyle, Senior Climate and Energy Officer, Structured and Corporate Finance Department), the International Monetary Fund's recent Energy Subsidy Reform report (http://www.imf.org/external/np/pp/eng/2013/012813.pdf), and Parry and Strand (2012).
2. An alternative approach for estimating the social cost of GHG emissions could be based on stated preference (SP) surveys designed to elicit respondents' maximum willingness-to-pay for various levels of GHG emission reductions (e.g. Longo, Markandya, & Petrucci, 2008; Soliño, 2010). This approach would not suffer from the difficulties associated with creating and parameterizing a numerical integrated assessment model. However, it would suffer from its own set of difficulties, including well-known general limitations that affect all SP studies including the potential for 'hypothetical bias' (e.g. Carson, 2012; Hausman, 2012; Kling, Phaneuf, & Zhao, 2012), plus difficulties that may be specific to this application stemming from the generally limited knowledge base regarding the potential climatic, biophysical, and especially economic impacts of GHG emissions on current and far future generations that most respondents will bring to the survey.
3. The fork of MAGICC version 5.3 included in Pacific Northwest National Laboratory's open source model GCAM version 2 (Calvin et al., 2009) is used without carbon cycle feedbacks and, unless otherwise specified, an equilibrium climate sensitivity of 3 8C. We note that sensitivity analysis found the general results of this side analysis to be robust to other values of the equilibrium climate sensitivity.
4. The EMF-22 scenario is extended past 2100 assuming that emissions stay constant at the 2100 level. This assumption is revisited later in this article.
5. The PAGE 2009 model restricts the user to representing the entire time horizon, in this case out to 2300, with only ten time steps. This leads to the unrealistic situation in a small number of simulations where the marginal unit of emissions can cause 'catastrophic' climate impacts to occur one period earlier, which could be 100 years earlier in some cases. We consider these occurrences to be a limitation of the model and drop them from the overall distribution of estimates. Appendix A contains further details about this issue.
6. In addition to the critiques previously cited, we point the interested reader to the work of Marten et al. (2013) and Oppenheimer (2013) for a review of literature that considers potential improvements in the assessment and valuation of climate change impacts.

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ED_442-000860742

To: Marten, Alex[Marten.Alex@epa.gov]
From: Kime, Robin
Sent: Fri 6/12/2015 11:08:57 AM
Subject: RE: onboarding material

Hi

Thank you. Ex 5

Ex 5 Ex 5 Thanks again for sending this so quickly.

Have a good day.

From: Marten, Alex
Sent: Thursday, June 11, 2015 6:28 PM
To: Snyder, Brett; Levitt, Shelley; Kime, Robin
Cc: Wolverton, Ann
Subject: RE: onboarding material

Attached please find the Marten et al. journal article in question.

Non-Responsive

--

Alex L. Marten
phone: (202) 566-2301
email: marten.alex@epa.gov

From: Snyder, Brett
Sent: Thursday, June 11, 2015 6:18 PM
To: Levitt, Shelley; Kime, Robin

Cc: Marten, Alex; Wolverton, Ann
Subject: RE: onboarding material

Hi – here are links to the materials I think you are looking for – if you were hoping to receive something other than these, please let me know.

SCC 2013 TSD:
https://www.whitehouse.gov/sites/default/files/omb/inforeg/social_cost_of_carbon_for_ria_2013_update.pdf

Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866, Interagency Working Group on Social Cost of Carbon, United States Government (May 2013)

SCC Marten document: (note: I believe there are several papers on the topic, and some are available in journals that require subscription to access. This is a working paper on our website that is readily accessible, so providing it to start with)
http://yosemite.epa.gov/ee/epa/eed.nsf/ec2c5e0aaed27ec385256b330056025c/f7c9fc6133698cc38525782b0055
01v2.pdf **Estimating the Social Cost of Non-CO2 GHG Emissions: Methane and Nitrous Oxide**

Alex L. Marten and Stephen C. Newbold (NCEE Working Paper, January 2011)

This is a journal article link:
http://www.tandfonline.com/doi/full/10.1080/14693062.2014.912981#.VXoIAZgw9Mw

Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

Alex L. Marten, Elizabeth A. Kopits, Charles W. Griffiths, Stephen C. Newbold & Ann Wolverton (2015)

Economy-wide modeling charge:
http://yosemite.epa.gov/sab/sabproduct.nsf/0/07E67CF77B54734285257BB0004F87ED/$File/Charge%20Quest
26-15.pdf

"Transmittal of Charge to the Science Advisory Board Advisory Panel on Economy-Wide

Modeling of the Benefits and Costs of Environmental Regulation" (February 2015)

From: Levitt, Shelley
Sent: Thursday, June 11, 2015 5:04 PM
To: Snyder, Brett
Subject: FW: onboarding material

Shelley

From: Kime, Robin
Sent: Thursday, June 11, 2015 4:30 PM
To: Levitt, Shelley
Subject: onboarding material

Hi

Is there any way you could send me links to the following materials or the copies themselves?

1. SCC 2013 TSD
2. SCC "Marten et al." doc
3. Economy-wide modeling charge

Thanks either way!

Great to see you today ☺

To: Snyder, Brett[Snyder.Brett@epa.gov]
Cc: Levitt, Shelley[Levitt.Shelley@epa.gov]; Marten, Alex[Marten.Alex@epa.gov]; Wolverton, Ann[Wolverton.Ann@epa.gov]
From: Kime, Robin
Sent: Thur 6/11/2015 11:24:31 PM
Subject: Re: onboarding material

Thank you!

Sent from my iPhone

On Jun 11, 2015, at 6:18 PM, Snyder, Brett <Snyder.Brett@epa.gov> wrote:

Hi – here are links to the materials I think you are looking for – if you were hoping to receive something other than these, please let me know.

SCC 2013 TSD:
https://www.whitehouse.gov/sites/default/files/omb/inforeg/social_cost_of_carbon_for_ria_2013_update.pdf

Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866, Interagency Working Group on Social Cost of Carbon, United States Government (May 2013)

SCC Marten document: (note: I believe there are several papers on the topic, and some are available in journals that require subscription to access. This is a working paper on our website that is readily accessible, so providing it to start with)
http://yosemite.epa.gov/ee/epa/eed.nsf/ec2c5e0aaed27ec385256b330056025c/f7c9fc6133698cc38525782b00: 01v2.pdf **Estimating the Social Cost of Non-CO2 GHG Emissions: Methane and Nitrous Oxide**

Alex L. Marten and Stephen C. Newbold (NCEE Working Paper, January 2011)

This is a journal article link:
http://www.tandfonline.com/doi/full/10.1080/14693062.2014.912981#.VXoIAZgw9Mw

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Alex L. Marten, Elizabeth A. Kopits, Charles W. Griffiths, Stephen C. Newbold & Ann

Wolverton (2015)

Economy-wide modeling charge:
http://yosemite.epa.gov/sab/sabproduct.nsf/0/07E67CF77B54734285257BB0004F87ED/$File/Charge%20Qu26-15.pdf

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Is there any way you could send me links to the following materials or the copies themselves?

1. SCC 2013 TSD

2. SCC “Marten et al.” doc

3. Economy-wide modeling charge

Thanks either way!

Great to see you today ☺

To: Marten, Alex[Marten.Alex@epa.gov]
From: Kime, Robin
Sent: Tue 1/27/2015 7:35:44 PM
Subject: RE: meeting times

Hi

On 2/5 he will be a Non-Responsive so 11:30-3:00 is fine.

O 2/6, he can do 11:00-12:30 or 2:30 – 4:00.

Thx

From: Marten, Alex
Sent: Tuesday, January 27, 2015 2:18 PM
To: Kime, Robin
Subject: meeting times

Sorry Robin, I got distracted and forgot to stop by.

Are there any times on 2/5 or 2/6 that look like they might work for an SCC IWG meeting?

Thanks.

--

Alex L. Marten
phone: (202) 566-2301
email: marten.alex@epa.gov

To: Kopits, Elizabeth[Kopits.Elizabeth@epa.gov]; Beauvais, Joel[Beauvais.Joel@epa.gov]
Cc: Fawcett, Allen[Fawcett.Allen@epa.gov]; McGartland, Al[McGartland.Al@epa.gov]
From: Shouse, Kate
Sent: Fri 7/10/2015 8:29:42 PM
Subject: RE: OP Weekly Shout-Out

Thanks, everyone, for the kind words and recognition!

From: Kopits, Elizabeth
Sent: Friday, July 10, 2015 11:40 AM
To: Shouse, Kate; Beauvais, Joel
Cc: Fawcett, Allen; McGartland, Al
Subject: Fw: OP Weekly Shout-Out

Thanks, Joel. Looping in Kate too.

From: Beauvais, Joel
Sent: Friday, July 10, 2015 11:33 AM
To: OP-Everyone
Subject: OP Weekly Shout-Out

Hi Folks,

This week's "Shout-Out" goes to EPA's Social Cost of Carbon Team of **Elizabeth Kopits, Alex Marten, Steve Newbold, Charles Griffiths, and Ann Wolverton** (NCEE) and **Kate Shouse** (OAR) for their continued work to improve the estimates of social cost of carbon (SCC) that are used in regulatory analysis by EPA and other federal agencies. The SCC is an estimate of the benefits of reducing emissions of CO2, which allows those benefits to be considered in benefit-cost analysis. Through the leadership of Elizabeth and Alex, with important contributions from the team, last week, the Administration's SCC Interagency Working Group issued a response to the public comments on the estimates and the methodology used to develop them https://www.whitehouse.gov/blog/2015/07/02/estimating-benefits-carbon-dioxide-emissions-reductions. OMB also announced plans to obtain expert, independent advice from the National Academy of Sciences, Engineering, and Medicine on how to approach future updates to the SCC estimates.

OMB received about 150 substantive comments and 39,000 form letters that expressed support for the Administration's efforts to establish a harmonized SCC. Commenters offered a wide range of perspectives on the process, methodology, and results, and also provided recommendations for opportunities to improve particular aspects of the SCC methodology in future updates. OMB and the Council for Economic Advisers convened the SCC IWG to review the comments and develop the consensus-based response. EPA's SCC team did much of the heavy lifting in reviewing the comments received, providing briefings for the IWG, organizing and drafting the response document, and developing the charge for the forthcoming National Academies' process. Elizabeth was instrumental in coordinating and helping to get this multi-agency funded project underway. The Academies' input will help to ensure that the SCC estimates used by the federal government continue to reflect the best available science and methodologies.

Congratulation team, on this important contribution to the science and technical underpinnings of federal regulations.

Non-Responsive

Have a great weekend everyone.

Joel

To: Kime, Robin[Kime.Robin@epa.gov]; Kopits, Elizabeth[Kopits.Elizabeth@epa.gov]; Bowen, Jennifer[Bowen.Jennifer@epa.gov]
Cc: Marten, Alex[Marten.Alex@epa.gov]
From: Shouse, Kate
Sent: Fri 7/10/2015 12:05:24 PM
Subject: RE: question from Robin K for website for SCC info

And thanks for including me in the Shout Out, what a nice gesture!

From: Kime, Robin
Sent: Thursday, July 09, 2015 4:33 PM
To: Kopits, Elizabeth; Shouse, Kate; Bowen, Jennifer
Cc: Marten, Alex
Subject: RE: question from Robin K for website for SCC info

Will do-I really appreciate the quick review.

From: Kopits, Elizabeth
Sent: Thursday, July 09, 2015 4:31 PM
To: Kime, Robin; Shouse, Kate; Bowen, Jennifer
Cc: Marten, Alex
Subject: RE: question from Robin K for website for SCC info

You might want to replace "benefit costs estimates" with "benefit-cost analysis", but otherwise it looks fine to me. Thanks!

From: Kime, Robin
Sent: Thursday, July 09, 2015 4:21 PM
To: Kopits, Elizabeth; Shouse, Kate; Bowen, Jennifer
Cc: Marten, Alex
Subject: RE: question from Robin K for website for SCC info

Hi

Mind taking a look at this? The last sentence will be reworked but I added one at the beginning to try to summarize plainly, how SCC is used… edit away…thank you!

This week's "Shout-Out" goes to EPA's Social Cost of Carbon Team of **Elizabeth Kopits, Alex Marten, Steve Newbold, Charles Griffiths, and Ann Wolverton** (NCEE) and **Kate Shouse** (OAR) for improving the estimates of social cost of carbon (SCC) that are used in regulatory analysis by EPA and other Federal agencies. The SCC is an estimate of the benefits of reducing emissions of CO2, which allows those benefits to be considered in benefit costs estimates. Through the leadership of Elizabeth and Alex with important contributions from the team, last week, the Administration's SCC Interagency Working Group (IWG) issued a response to the public comments on the estimates and the methodology used to develop them https://www.whitehouse.gov/blog/2015/07/02/estimating-benefits-carbon-dioxide-emissions-reductions. OMB also announced plans to obtain expert, independent advice from the National Academy of Sciences, Engineering, and Medicine on how to approach future updates to the SCC estimates.

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From: Kopits, Elizabeth
Sent: Thursday, July 09, 2015 4:14 PM
To: Shouse, Kate; Bowen, Jennifer; Kime, Robin
Cc: Marten, Alex
Subject: RE: question from Robin K for website for SCC info

Thanks, Kate! I didn't know about the new scc specific OMB webpage.

Elizabeth

From: Shouse, Kate
Sent: Thursday, July 09, 2015 4:12 PM
To: Kopits, Elizabeth; Bowen, Jennifer; Kime, Robin
Cc: Marten, Alex
Subject: RE: question from Robin K for website for SCC info

Thanks, Elizabeth. We are working to update the EPA website and hope it goes live by end of this week or early next week. I can email everyone on this message once it's finished. The contractor is making changes now; we'll proofread it offline, then press go.

Also, I may be the last one to find this but OMB created an SCC page that consolidates the TSDs, RTC, and all of the relevant blog posts at https://www.whitehouse.gov/omb/oira/social-cost-of-carbon . I think the links Elizabeth listed below are the best (pending the update to EPA's site) but wanted to flag this in case others missed it.

Thanks,
Kate

From: Kopits, Elizabeth
Sent: Thursday, July 09, 2015 4:05 PM
To: Bowen, Jennifer; Kime, Robin
Cc: Marten, Alex; Shouse, Kate
Subject: RE: question from Robin K for website for SCC info

Hi Jenny and Robin,

If you are looking for an EPA website on SCC, it is: http://www.epa.gov/climatechange/EPAactivities/economics/scc.html . However, I don't think this has been updated yet to reflect the recent revision, etc. Kate Shouse (ccd above) might be able to tell you when we are likely to update it.

However, the 7/2 OMB blog post (https://www.whitehouse.gov/blog/2015/07/02/estimating-benefits-carbon-dioxide-emissions-reductions) provides the most recent info and includes links to the current TSD and response to public comments received through the recent OMB comment solicitation.

Hope this helps.

Thanks,

Elizabeth

From: Bowen, Jennifer
Sent: Thursday, July 09, 2015 3:57 PM
To: Kopits, Elizabeth; Marten, Alex
Cc: Kime, Robin
Subject: question from Robin K for website for SCC info

What is the best website to point folks to for more info re: SCC?

Thank you.

Jenny

To: Kopits, Elizabeth[Kopits.Elizabeth@epa.gov]
From: Bowen, Jennifer
Sent: Thur 7/9/2015 8:34:20 PM
Subject: RE: question from Robin K for website for SCC info

Thanks – I'm not sure if Robin meant to send it to all of you, but in any case, thanks for reviewing!

From: Kopits, Elizabeth
Sent: Thursday, July 09, 2015 4:31 PM
To: Kime, Robin; Shouse, Kate; Bowen, Jennifer
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From: Kopits, Elizabeth
Sent: Thursday, July 09, 2015 4:14 PM
To: Shouse, Kate; Bowen, Jennifer; Kime, Robin
Cc: Marten, Alex
Subject: RE: question from Robin K for website for SCC info

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Elizabeth

From: Shouse, Kate
Sent: Thursday, July 09, 2015 4:12 PM
To: Kopits, Elizabeth; Bowen, Jennifer; Kime, Robin
Cc: Marten, Alex

Subject: RE: question from Robin K for website for SCC info

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Thanks,
Kate

From: Kopits, Elizabeth
Sent: Thursday, July 09, 2015 4:05 PM
To: Bowen, Jennifer; Kime, Robin
Cc: Marten, Alex; Shouse, Kate
Subject: RE: question from Robin K for website for SCC info

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Elizabeth

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Sent: Thursday, July 09, 2015 3:57 PM
To: Kopits, Elizabeth; Marten, Alex
Cc: Kime, Robin
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Thank you.

Jenny

To: Kopits, Elizabeth[Kopits.Elizabeth@epa.gov]
From: Marten, Alex
Sent: Thur 5/7/2015 1:43:24 PM
Subject: RE: Any objections??
2015 05 07 IAG justification.docx

Ex. 5

--

Alex L. Marten
phone: (202) 566-2301
email: marten.alex@epa.gov

From: Kopits, Elizabeth
Sent: Thursday, May 07, 2015 9:32 AM
To: Marten, Alex
Subject: Any objections??

Ex. 5

Ex. 5

From: Harvey, Alecia
Sent: Wednesday, May 06, 2015 3:31 PM
To: Kopits, Elizabeth; Marten, Alex
Subject: Can you ...
Importance: High

Give me the below information as soon as you get it even if I get a million emails from you:

Project title:

Project description:

Describe the proposed project's objectives and how the IA will accomplish them. The objectives must be consistent with the statutory authority for the agreement. If the funded work is part of a larger project, the description of the project should be clear as to which parts of the work will be funded by the IA and which will not:

Brief description of why this IA alternative was selected:

Description of why the particular agency was selected:

I may have more questions later. Thanks

To: Kopits, Elizabeth[Kopits.Elizabeth@epa.gov]; Marten, Alex[Marten.Alex@epa.gov]
Cc: Sarofim, Marcus[Sarofim.Marcus@epa.gov]
From: Shouse, Kate
Sent: Wed 6/10/2015 4:58:13 PM
Subject: comments re: unquantified climate effects

Hi: If we have time at the end of our 2 pm call this afternoon, I'd like to touch base on an unrelated issue. I am drafting responses to the CPP SCC comments and would like your input on the following (see below). Sending this now so you have the pieces; will elaborate when we get a chance to talk.

Comment on CPP: Commenter 23418 stated that EPA does not fully detail all of the qualitative climate benefits from carbon dioxide reductions that are not currently included in the monetized estimate of the social cost of carbon. The commenter said that in the final CPP and the final regulatory impact analysis, EPA should detail all significant, unquantified climate effects, as consistent with administration-wide policy, the Interagency Working Group's instructions, EPA's past practices, and best economic practices.

Ex. 5

March 2014 report,
http://costofcarbon.org/files/Omitted_Damages_Whats_Missing_From_the_Social_Cost_of_Carbon.pdf,
"This paper represents the fi rst attempt to systematically examine and document these omissions for the latest versions of the three IAMs used by the IWG, as well as earlier versions when they

are used in calibrating the updated models."

To: Kopits, Elizabeth[Kopits.Elizabeth@epa.gov]
From: David Chapman
Sent: Tue 6/23/2015 7:27:49 PM
Subject: RE: Is it possible to get some materials from you?

Thanks will do.

David

From: Kopits, Elizabeth [mailto:Kopits.Elizabeth@epa.gov]
Sent: Tuesday, June 23, 2015 12:58 PM
To: David Chapman
Subject: RE: Is it possible to get some materials from you?

Tomorrow at 11:30 should be fine. Feel free to reach me at 202-566-2299.

Thanks!

Elizabeth

From: David Chapman [mailto:DChapman@stratusconsulting.com]
Sent: Tuesday, June 23, 2015 2:55 PM
To: Kopits, Elizabeth
Subject: Re: Is it possible to get some materials from you?

Let's plan for tomorrow morning, I'm tied up for the next hour or so. How about 11:30 your time tomorrow?

David

On Jun 23, 2015, at 12:53, Kopits, Elizabeth <Kopits.Elizabeth@epa.gov> wrote:

> Thanks! And yes, I have time for a brief call – either within the next half hour, or tomorrow morning. Just let me know what works best for you.

Regards,

Elizabeth

From: David Chapman [mailto:DChapman@stratusconsulting.com]
Sent: Tuesday, June 23, 2015 1:57 PM
To: Kopits, Elizabeth
Subject: RE: Is it possible to get some materials from you?

Elizabeth,

Thanks, sorry I was out of town for a bit and just catching up.

Yes, we would like the raw SCC results – the Nov 2013 results would be best to start.

I wonder if we might discuss what we are trying to do, and make sure that the output you have would help with that

before you go through the trouble of sending us the output.

Would you have any time for a call this afternoon or tomorrow am?

Also, I heard back from our MN clients and they are fine with me providing the summaries of our review of the comments provided to OMB on the SCC. Consider these sort of notes – they aren't in any final form, but rather a way for us to organize and review the materials.

I've attached those files.

Thanks,

David

From: Kopits, Elizabeth [mailto:Kopits.Elizabeth@epa.gov]
Sent: Tuesday, June 23, 2015 11:02 AM
To: David Chapman
Subject: RE: Is it possible to get some materials from you?

Hi David,

If it is still useful, I am happy to send you the raw SCC results. Just let me know which set you would like – 2010 or 2013.

Thanks,

Elizabeth

From: Kopits, Elizabeth
Sent: Thursday, June 18, 2015 3:13 PM
To: 'David Chapman'
Subject: RE: Is it possible to get some materials from you?

Hi David,

I'm so sorry this email slipped through the cracks earlier this week. I am happy to send you the raw output that we have sent to others. Are you interested in the 2010 or 2013 results, or both? I am running to a meeting soon and off tomorrow but can send them along on Monday if that is OK.

Thanks,

Elizabeth

From: David Chapman [mailto:DChapman@stratusconsulting.com]

Sent: Tuesday, June 16, 2015 1:06 PM
To: Kopits, Elizabeth
Subject: Is it possible to get some materials from you?

Elizabeth,

As you may have seen in some of the comments provided by industry in the Minnesota SCC case – specifically the Minnesota Large Industrial Group's expert Anne Smith and the The Brattle group apparently requested and received the raw data outputs from the IWG for their analysis.

Is it possible for us to get the raw data output from the IWG – SCC calculation also?

Thanks so much,

David

This electronic message and any attachments hereto are the property of the sender and may contain information that is confidential or proprietary to the sender. It is intended for the exclusive use of the recipient or recipients named above. If you are not an intended recipient of the message, please be advised that you are not authorized to disclose, copy, or distribute the message or any information in the message. Please notify the sender of your receipt immediately by return electronic e-mail and delete the message and any attachments. Although this e-mail and any attachments are believed to be free of any virus or other defect that might affect any computer system into which it is received and opened, it is the responsibility of the recipient to ensure that it is virus free and no responsibility is accepted by the sender for any loss or damage arising in any way from its use.

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Protected by Federal Rule of Evidence 408

To: Dayaratna, Kevin[kevin.Dayaratna@heritage.org]; Marten, Alex[Marten.Alex@epa.gov]; Kopits, Elizabeth[Kopits.Elizabeth@epa.gov]
Cc: Kreutzer, David[David.Kreutzer@heritage.org]
From: Newbold, Steve
Sent: Mon 2/9/2015 9:23:32 PM
Subject: RE: Files to replication May 2013 SCCO2 estimates based on DICE

Hi Kevin,

Yes, you should find that the results are exactly the same either way.

****
Steve Newbold
U.S. EPA
National Center for Environmental Economics (NCEE)
EPA West, 4316T, MC 1809T
1200 Pennsylvania Ave NW
Washington, DC 20004
(202) 566-2293
****

-----Original Message-----
From: Dayaratna, Kevin [mailto:kevin.Dayaratna@heritage.org]
Sent: Monday, February 09, 2015 4:12 PM
To: Marten, Alex; Kopits, Elizabeth
Cc: Newbold, Steve; Kreutzer, David
Subject: RE: Files to replication May 2013 SCCO2 estimates based on DICE

Alex:

I actually just looked this over myself, and I think the answer is now; the numbers should be the same (at least statistically).

So, no need for you to look into it further.

Thanks,
Kevin

Kevin Dayaratna, Ph.D.
Senior Statistician and Research Programmer Institute for Economic Freedom and Opportunity The Heritage Foundation
214 Massachusetts Avenue, NE
Washington, DC 20002
202-608-1540
heritage.org

-----Original Message-----
From: Dayaratna, Kevin
Sent: Monday, February 09, 2015 3:39 PM
To: 'Marten, Alex'; Kopits, Elizabeth
Cc: Newbold, Steve; Kreutzer, David
Subject: RE: Files to replication May 2013 SCCO2 estimates based on DICE

To: Dayaratna, Kevin[kevin.Dayaratna@heritage.org]; Marten, Alex[Marten.Alex@epa.gov]; Kopits, Elizabeth[Kopits.Elizabeth@epa.gov]
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Alex:

Thanks for your email.

I understand that the SCC calculation on lines 202-206 only include changes in consumption up to year H-1 in that for loop, and that you do not include in the simulation years beyond 2300 in your report. However, are the results the same (line 49) if you tweak that line to have an end year closer to 2300? Suppose for example, it were tweaked as follows:

years = [2005:10:2305]';

Would this impact the SCC estimates and be more in line with the idea of having the simulations run up to 2300?

Kevin

-----Original Message-----
From: Marten, Alex [mailto:Marten.Alex@epa.gov]
Sent: Monday, February 09, 2015 3:30 PM
To: Dayaratna, Kevin; Kopits, Elizabeth
Cc: Newbold, Steve; Kreutzer, David
Subject: RE: Files to replication May 2013 SCCO2 estimates based on DICE

Hi Kevin,

We ran the DICE calculations out to 2045 to facilitate comparison with Bill Nordhaus' original results, since this is the time horizon he uses. However, when we calculate the SCC we do not include any of the simulation years beyond 2300. The SCC calculation on lines 202-206 only includes changes in consumption up to year H, which is defined on line 36 to be 2300. (So if you wish, you may be able to speed up the code by not including the extra years that are not used in the SCC calculation.)

Also, you might have noticed that the loop beginning on line 202 should read "for tau = years(t):H" rather than "for tau = years(t):H-1", as in the version we sent you previously. The original version went "up to 2300" and not "through 2300" and so it did not include the marginal damages in the year 2300. This does not affect any of the numbers in the TSD. Even for a 2050 emissions year at a 2.5% discount rate (where this would matter the most) the inclusion of marginal damages in 2300 would increase the DICE estimates by less than $0.06, with an effect of less than $0.02 in most simulations.

I hope this is helpful, and we appreciate that you are reviewing the code. Please let us know if you have any further questions.

--
Alex L. Marten
phone: (202) 566-2301
email: marten.alex@epa.gov

-----Original Message-----
From: Dayaratna, Kevin [mailto:kevin.Dayaratna@heritage.org]
Sent: Wednesday, February 04, 2015 11:56 AM
To: Kopits, Elizabeth
Cc: Marten, Alex; Newbold, Steve; Kreutzer, David
Subject: RE: Files to replication May 2013 SCCO2 estimates based on DICE

Elizabeth:

Alex:

Thanks for your email.

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years = [2005:10:2305]';

Would this impact the SCC estimates and be more in line with the idea of having the simulations run up to 2300?

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Alex L. Marten
phone: (202) 566-2301
email: marten.alex@epa.gov

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Sent: Wednesday, February 04, 2015 11:56 AM
To: Kopits, Elizabeth
Cc: Marten, Alex; Newbold, Steve; Kreutzer, David
Subject: RE: Files to replication May 2013 SCCO2 estimates based on DICE

Elizabeth:

Hope all is well with you.

I have a question about the DICE model codes you guys sent us during the summer of 2013. In your report, you mention that 2300 is the end of the interagency analysis time horizon (page 7) - http://www.whitehouse.gov/sites/default/files/omb/assets/inforeg/technical-update-social-cost-of-carbon-for-regulator-impact-analysis.pdf

However, I noticed in the codes (lines 48-49 of SCC_EPA_DICE2010_May2013.m) you specify that the vector of years for the DICE calculations to be up to 2405:

% Specify vector of years for DICE calculations:
years = [2005:10:2405]';

So my question is, why are calculations carried out to 2405 if the 2300 is the end of the interagency analysis time horizon?

Kevin

Kevin Dayaratna, Ph.D.
Senior Statistician and Research Programmer Institute for Economic Freedom and Opportunity The Heritage Foundation
214 Massachusetts Avenue, NE
Washington, DC 20002
202-608-1540
heritage.org<http://heritage.org/>

From: Kopits, Elizabeth [Kopits.Elizabeth@epa.gov]
Sent: Wednesday, July 24, 2013 9:02 AM
To: Kreutzer, David
Cc: Marten, Alex; Newbold, Steve; Dayaratna, Kevin
Subject: FW: Files to replication May 2013 SCCO2 estimates based on DICE

Dear David,

I apologize for my delay in sending the DICE code. Other assignments required my immediate attention, and we wanted to clean up the code before sending it out.

As noted below, attached are three Matlab files and two Excel files that together can be used to replicate the DICE-based SCCO2 estimates published in the May 2013 Technical Support Document by the Interagency Working Group on the Social Cost of Carbon. Please let me know if you have any questions, or feel free to contact Steve Newbold (copied above) directly as well.

Regards,
Elizabeth

From: newbold.steve@gmail.com [mailto:newbold.steve@gmail.com] On Behalf Of Steve Newbold
Sent: Wednesday, July 24, 2013 8:44 AM
To: Kopits, Elizabeth
Cc: Marten, Alex
Subject: Files to replication May 2013 SCCO2 estimates based on DICE

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Please feel free to provide these files to anyone who requests them and to give them my contact information in case any questions arise.

Thanks,

****
Steve Newbold
U.S. EPA
National Center for Environmental Economics (NCEE) EPA West 4316T (MC1809T)
1200 Pennsylvania Ave NW
Washington, DC 20460
(202)566-2293
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Thanks,

****
Steve Newbold
U.S. EPA
National Center for Environmental Economics (NCEE) EPA West 4316T (MC1809T)
1200 Pennsylvania Ave NW
Washington, DC 20460
(202)566-2293
****

```
%==========================================================================
% SCC_EPA_DICE2010_May2013.m
%==========================================================================


% This Matlab script will reproduce the DICE-based SCC estimates published
% by the U.S. Government Interagency Working Group on the Social Cost of
% Carbon in February 2013.  The FUND- and PAGE-based estimates must be
% combined with these DICE-based estimates to fully replicate the final SCC
% estimates.
% Also required are two associated Matlab functions:
%    SCC_DICE2010_Tdynamics.m
%    SCC_DICE2010_SLRdynamics.m
% and two input files:
%    SCC_input_EMFscenarios.xls
%    2009 11 23 Calibrated R&B distribution.xls.


%% PRELIMINARIES:
clear all; close all; clc;
set(0,'DefaultAxesFontName','Calibri','DefaultAxesFontSize',18);
figsize = [500 200 800 750];
rand('seed',4000);
infile  = [pwd '\SCC_input_EMFscenarios.xls'];
outfile = ...
     [pwd ['\SCC_DICE2010_EPA_' datestr(now,'yyyy_mm_dd_HH_MM') '.xlsx']];


%% INPUT PARAMETERS:
a0    = 0.00008162; % Damage coefficient on temperature
a1    = 0.00204626; % Damage coefficient on temperature squared
a2    = 2;          % Exponent on temperature damages
b0    = 0.00518162; % Damage coefficient on SLR
b1    = 0.00305776; % Damage coefficient on SLR squared
b2    = 2;          % Exponent on SLR damages
H     = 2300;       % Time horizon for calculating SCC [year]
A0    = 0.0303220;  % First period total factor productivity, from DICE2010
gamma = 0.3;        % Labor factor productivity, from DICE2010
delta = 0.1;        % Capital depreciation rate [yr^-1], from DICE2010
s     = 0.23;       % Approximate optimal savings in DICE2010
MC    = 10000;      % Number of Monte Carlo iterations


% Calculate total number of iterations for reporting progress to screen:
iterations = 5*3*MC; count = 0; starttime = cputime;


% Specify vector of years for DICE calculations:
years = [2005:10:2405]';


% Import data:
% Notes: GDP input data should be in trillions of US$2005
% Population input data should be in millions of individuals
% CO2 emissions input data should be in GtC/decade
% nonCO2 forcings input data should be in W/m^2
```

```
% CH4 and N20 emissions are in MtCH4 and MtN20 respectively
Y_data    = xlsread(infile,'GDP'); EMFyears = Y_data(:,1);
N_data    = xlsread(infile,'Population');
E_data    = xlsread(infile,'IndustrialCO2');
El_data   = xlsread(infile,'LandCO2');
Fex1_data = xlsread(infile,'EMFnonCO2forcings');
Fex2_data = xlsread(infile,'OthernonCO2forcings');
inflate   = 122.58/114.52; % World GDP inflator 2007/2005


% Import climate sensitivity pdf:
p = xlsread([pwd '\2009 11 23 Calibrated R&B distribution.xls'],'sheet1');
CSdomain = p(:,1);
pCS      = p(:,2);


% Initialize output tables (Tables A2, A3, and A4 in May 2013 Technical
% Support Document), select percentiles of SCC in 2020 at each discount
% rate:
TableA2 = zeros(5,10);
TableA3 = zeros(5,10);
TableA4 = zeros(5,10);


%% SCENARIO LOOP:
for scenario = 1:5;


   % Name scenario:
   if     scenario == 1; scenarioname = 'IMAGE';
   elseif scenario == 2; scenarioname = 'MERGEoptimistic';
   elseif scenario == 3; scenarioname = 'MESSAGE';
   elseif scenario == 4; scenarioname = 'MiniCAMbase';
   elseif scenario == 5; scenarioname = '5thScenario';
   end


   % Extract data for this scenario:
   Y   = Y_data(:,scenario+1)*inflate;
   N   = N_data(:,scenario+1);
   E   = E_data(:,scenario+1) + El_data(:,scenario+1);
   Fex = Fex1_data(:,scenario+1) + Fex2_data(:,2);


   % Switch EMF paths to DICE2010 time periods, using 2010 EMF value for
   % 2005-2015 DICE value, etc.
   Y   = [Y(2:end);zeros(length(years)-(length(Y)-1),1)];
   N   = [N(2:end);zeros(length(years)-(length(N)-1),1)];
   E   = [E(2:end);zeros(length(years)-(length(E)-1),1)];
   Fex = [Fex(2:end);zeros(length(years)-(length(Fex)-1),1)];


   % Calculate per-capita income:
   y = Y./(N+eps);
```

```
%% DISCOUNT RATE LOOP:
for rate = [.025 .03 .05];


   % Solve for implied path of exogenous technical change
   A    = zeros(length(years),1);
   A(1) = A0;
   K(1) = (Y(1)/A(1)/(N(1)^(1-gamma)))^(1/gamma);
   for t = 2:length(years);
      K(t) = K(t-1)*(1-delta)^10 + s*Y(t-1)*10;
      A(t) = Y(t)/(N(t)+eps)^(1-gamma)/(K(t)+eps)^gamma;
   end


   % Initialize matrix to hold SCC Monte Carlo calculations:
   SCC_MC = zeros(MC,length(years));


   %% MONTE CARLO LOOP:
   for mc = 1:MC;


      % Print status to screen:
      count = count + 1;
      if fix(mc/100)-mc/100==0;
         clc;
         fprintf(['Working on ' scenarioname '\n']);
         fprintf(['rate = ' num2str(rate) '; ']);
         fprintf(' %-.0f of %-.0f minor iterations.\n',mc,MC);
         fprintf('    [Est time to completion = %-.1f min]\n',...
                 (cputime-starttime)/count*(iterations-count)/60);
      end


      % Take random draw of CS from pdf:
      temp = find(cumsum(pCS)<=rand);
      CS   = CSdomain(temp(end));
      if MC == 1; CS = 3; end


      % Reference temperature path and economic losses:
      E0   = E;
      T0   = SCC_EPA_DICE2010_Tdynamics(CS,years,E0,Fex);
      SLR0 = SCC_EPA_DICE2010_SLRdynamics(T0,years);
      L0   = 1-1./(1 + a0*T0 + a1*T0.^a2 + b0*SLR0 + b1*SLR0.^b2);


      % Reference GDP and consumption paths:
      Y0 = zeros(length(years),1);
      K0 = zeros(length(years),1); K0(1) = K(1);
      C0 = zeros(length(years),1);
      for tau = 1:length(years(find(years<=EMFyears(end))));
         Y0(tau)   = A(tau)*K0(tau)^gamma*...
                     N(tau)^(1-gamma)*(1-L0(tau));
         C0(tau)   = (1-s)*Y0(tau);
         K0(tau+1) = K0(tau)*(1-delta)^10 + s*10*Y0(tau);
```

```
    end

    % Calculate SCC as change in consumption discounted at
    % a fixed rate:
    SCC = zeros(length(years),1);
    t = 0;
    for year = years(find(years<=EMFyears(end)))'; t = t + 1;

        % Perturbed temperature path and economic losses:
        dE  = 1;
        E1  = E; E1(t) = E1(t)+dE;
        T1  = SCC_EPA_DICE2010_Tdynamics(CS,years,E1,Fex);
        SLR1= SCC_EPA_DICE2010_SLRdynamics(T1,years);
        L1  = 1-1./(1 + a0*T1 + a1*T1.^a2 + b0*SLR1 + b1*SLR1.^b2);

        % Perturbed GDP and consumption paths:
        Y1 = Y0; K1 = K0; C1 = C0;
        for tau = t:length(years(find(years<=EMFyears(end))));
            Y1(tau)   = A(tau)*K1(tau)^gamma*...
                      N(tau)^(1-gamma)*(1-L1(tau));
            C1(tau)   = (1-s)*Y1(tau);
            K1(tau+1) = K1(tau)*(1-delta)^10 + s*Y1(tau)*10;
        end

        % Calculate SCC based on annually interpolated values:
        G   = length(years);
        C0i = interp1(years(t:G),C0(t:end),years(t):years(G),[])';
        C1i = interp1(years(t:G),C1(t:end),years(t):years(G),[])';

        tt = 0;
        for tau = years(t):H-1; tt = tt + 1;
          SCC(t) = SCC(t) + (C0i(tt)-C1i(tt))/((1+rate)^(tt-1));
        end
        SCC(t) = SCC(t)/dE;

    end

    % Convert SCC path from trillion$/GtC/yr to $/tCO2/yr:
    SCC = SCC / (10^-3) * 12/44;

    % Save results of this iteration in SCC_MC matrix:
    SCC_MC(mc,:) = SCC';

end % Monte Carlo loop

% Save results for this scenario to Excel file:
sheet = [scenarioname '_' num2str(rate)];
```

```
        xlswrite(outfile,[years';SCC_MC],sheet);


        % Interpolate results to 5 year time steps 2010-2050:
        years2 = [2010:5:2050]';
        SCC_MC2 = zeros(MC,length(years2));
        for mc=1:MC; SCC_MC2(mc,:)=interp1(years,SCC_MC(mc,:)',years2)';end
        sheet2 = [scenarioname '_' num2str(rate) '_2010-2050'];
        xlswrite(outfile,[years2';SCC_MC2],sheet2);


        % Save percentiles and means for Tables A2, A3, and A4:
        col = 0;
        for pct = [1 5 10 25 50 50 75 90 95 99]; col = col + 1;
           if rate == 0.025;
              TableA2(scenario,col) = prctile(SCC_MC2(:,3),pct);
              if col == 6; TableA2(scenario,col) = mean(SCC_MC2(:,3));end
           elseif rate == 0.03;
              TableA3(scenario,col) = prctile(SCC_MC2(:,3),pct);
              if col == 6; TableA3(scenario,col) = mean(SCC_MC2(:,3));end
           elseif rate == 0.05;
              TableA4(scenario,col) = prctile(SCC_MC2(:,3),pct);
              if col == 6; TableA4(scenario,col) = mean(SCC_MC2(:,3));end
           end
        end


     end % Discount rate loop


  end % Scenario loop


  % Save Tables A2, A3, and A4 to output file:
  xlswrite(outfile,TableA2,'Table A2');
  xlswrite(outfile,TableA3,'Table A3');
  xlswrite(outfile,TableA4,'Table A4');
```

To: Kopits, Elizabeth[Kopits.Elizabeth@epa.gov]
From: Krupnick, Alan
Sent: Wed 1/21/2015 5:02:17 PM
Subject: RE: Follow-up query

Ex 6 - Other

Non-Responsive

-----Original Message-----
From: Kopits, Elizabeth [mailto:Kopits.Elizabeth@epa.gov]
Sent: Wednesday, January 21, 2015 10:00 AM
To: Darmstadter, Joel
Cc: Ross, Heather; Krupnick, Alan; McLaughlin, Katrina; Marten, Alex
Subject: RE: Follow-up query

Hi Joel,

Thanks for offering to share your draft report. We look forward to reading it!

Non-Responsive

Ex 6 - Other

Best,
Elizabeth

-----Original Message-----
From: Darmstadter, Joel [mailto:Darmstad@rff.org]
Sent: Tuesday, January 20, 2015 3:06 PM
To: Kopits, Elizabeth
Cc: Ross, Heather; Krupnick, Alan; McLaughlin, Katrina
Subject: RE: Follow-up query

Thanks, Elizabeth, for the IWG-->EPA clarification. Only in the 2050 figure (EPA Fact Sheet $76; your attached excel tabulation $75) is there any remaining difference, but I don't think there's any reason to belabor the numbers any further for the purpose of our draft report. Which, by the way, we'll be glad to share with you and your colleagues. We should be able to get it to you within the next few days.

I've been asked to assure my own colleagues that, in the matter of CO2-vs.-CO2e, there's nothing new to report beyond what is said at 2010 IWG, p. 12, ("Valuing Non-CO2 Emissions") and your Harvard-JFK presentation of last March ("A Note on Non-CO2 GHGs"). But if there's reportable progress on the issue -- even if apart from being embodied in policy scenarios -- it would be good to learn of it.

Thanks again for your help.

Joel

-----Original Message-----
From: Kopits, Elizabeth [mailto:Kopits.Elizabeth@epa.gov]
Sent: Tuesday, January 20, 2015 8:23 AM
To: Darmstadter, Joel
Cc: Marten, Alex
Subject: RE: Follow-up query

Hi Joel,

Sorry to be so slow in getting back to you. This email got a little buried over the past few days.

The SCC numbers EPA uses for monetizing CO2 impacts in any rulemaking are taken directly from the 2013 SCC Update (Nov 2013 revision). The only difference between the numbers in the factsheet and the estimates in the TSD should be an adjustment for inflation using the GDP implicit price deflator. I am not sure who calculated the 2011 numbers in the factsheet, but using the deflator from BEA NIPA Table 1.1.9, I do find a slight difference in a few years depending on whether I round the 2007 estimates before adjusting for inflation or not (see attached). So that may be a contributing factor. Perhaps it is also possible that the factsheet calculations were done with non-final deflator estimates??
I will see if I can hunt down who made the table for the webpage, but hopefully this helps a bit for now.

I look forward to hearing more about your project on federal coal leasing and the SCC when it is available.

Best,
Elizabeth

-----Original Message-----
From: Darmstadter, Joel [mailto:Darmstad@rff.org]
Sent: Thursday, January 15, 2015 5:59 PM
To: Kopits, Elizabeth
Subject: Follow-up query

Hi, Elizabeth

It's been nearly a couple of months since our exchange relating to SCC issues. But not so long ago that I've forgotten your willingness to indulge an additional question. So here goes. (Actually, I think it may turn out to be a pretty straightforward matter.)

In an about-to-be-completed draft of our project on federal coal leasing and the SCC, we include a table citing the EPA's SCC estimates from its 2013 "Fact Sheet." The numbers are in 2011 dollars and, for the years 2015, 2020, 2030, 2040, and 2050, the respective SCC numbers are $39, 46, 55, 65, and 76.

We presumed -- but now wonder whether presumption was warranted -- that these numbers, except for a change from 2007 dollars to 2011 dollars, are taken directly from the second IWG document of 2013 (rev. November). For the five years above, the IWG numbers are $37, 43, 52, 61, and 71.

Now, the implicit GDP deflator increased by exactly 6% between 2007 and 2011. For each of the 5 comparison years above, the percent by which EPA's exceed the IWG numbers is more or less within the ballpark, with rounding probably explaining some of the discrepancy. Here are the percents by which EPA exceeds IWG for the five years in question:

2015 - 5.4%
2020 - 7.0
2030 - 5.8
2040 - 6.6

2050 - 7.0

As I say, these varying differences, while not alarming, do make us wonder whether EPA's adoption of the IWG numbers involved some further refinements or revisions rather than being more or less (that term again) mechanical reliance on the IWG.

I don't want this to impose a burdensome forensic task. But it would be good to be able to assure our readers that the IWG serves as the basic point of departure for all or most ensuing SCC citations.

With many thanks for any help you, or one of your staff, can provide.

Joel
Email: darmstad@rff.org
Phone: 202/328-5050

To: Kopits, Elizabeth[Kopits.Elizabeth@epa.gov]
From: Darmstadter, Joel
Sent: Wed 1/21/2015 4:39:56 PM
Subject: "Incidentally?"

Non-Responsive

Non-Responsive Thanks for the Alex contact. And all the best. Joel

-----Original Message-----
From: Kopits, Elizabeth [mailto:Kopits.Elizabeth@epa.gov]
Sent: Wednesday, January 21, 2015 10:00 AM
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Cc: Ross, Heather; Krupnick, Alan; McLaughlin, Katrina; Marten, Alex
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Hi Joel,

Thanks for offering to share your draft report. We look forward to reading it!

On non-CO2 GHG impacts, to date, the only approach that has been used to quantify these impacts in RIAs -- in sensitivity analysis only -- is the GWP based approximation approach (i.e., convert emission impacts to CO2e and apply the SCC estimates). But there is some literature on directly modeled estimates of the social cost of nonCO2 GHGs, and a few of us have done some in house research on what USG SCC consistent CH4 and N2O values would be - see attached.
I hope that helps for now.

Ex 6 - Other

Best,
Elizabeth

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With many thanks for any help you, or one of your staff, can provide.

Joel
Email: darmstad@rff.org
Phone: 202/328-5050

To: McGartland, Al[McGartland.Al@epa.gov]; Marten, Alex[Marten.Alex@epa.gov]; Shouse, Kate[Shouse.Kate@epa.gov]; Beauvais, Joel[Beauvais.Joel@epa.gov]
Cc: Roberts, Martha[Roberts.Martha@epa.gov]
From: Kopits, Elizabeth
Sent: Mon 7/6/2015 5:34:55 PM
Subject: Greenwire: White House quietly revises social cost of carbon

CLIMATE:

White House quietly revises social cost of carbon

Jean Chemnick, E&E reporter

Published: Monday, July 6, 2015

The White House has slightly reduced its estimate for the social cost of carbon (SCC) in response to public comments that officials collected more than a year ago.

The Office of Management and Budget posted its revision of the controversial estimate Thursday, immediately before the Fourth of July weekend. Office of Information and Regulatory Affairs Administrator Howard Shelanski and Maurice Obstfeld, a member of the Council of Economic Advisers, said in their **post** that lowering the SCC from $37 to $36 per metric ton of CO2 for 2015 was the result of minor technical revisions in the modeling used to arrive at the estimate.

Shelanski and Obstfeld said in their post that the SCC, which has appeared in 34 rulemakings, "is a tool that helps Federal agencies decide which carbon-reducing regulatory approaches make the most sense -- to know which come at too great a cost and which are a good deal for society."

The SCC was last revised in 2013 and gives a range of estimates of the long-term economic damage done by each incremental ton of carbon released into the atmosphere.

While the estimate is not in itself a regulation, Republicans on Capitol Hill have frequently targeted it and the administration process that produced it as an executive branch bid to justify costly rules, including U.S. EPA's Clean Power Plan. They launched numerous hearings and messaging bills following the 2013 revision aimed at driving home the point that the interagency working group responsible for the SCC did not pursue a public process and questioning the group's findings about the health, agricultural, infrastructural and other costs of greenhouse gas emissions. The White House noted that it relied on three publicly available peer-reviewed models to arrive at its estimate, but in late 2013 it responded to congressional pressure by offering a public commenting period on the SCC, which closed in February 2014.

Shelanski and Obstfeld said it took the administration 15 months to process the responses, including about 150 substantive comments, "some quite lengthy and technical."

Comments ran the gamut from protests that the administration underplayed the benefits of CO2 emissions to some that said it underestimated the SCC, especially by embracing a 3 percent discount rate that some say underplays the future costs of warming.

The 44-page technical **document** that accompanies the OMB post notes that "any effort to quantify and monetize the harms associated with climate change will raise serious questions of science, economics, and ethics and should be viewed as provisional."

The post pledges that the executive branch would seek independent expert advice from the National Academies of Sciences, Engineering and Medicine to inform yet another revision of the estimate, though federal agencies would continue to use the current SCC figure in their rulemakings until that revision could be made. It did not give a timeline for the next revision.

While EPA, the Energy Department and other agencies use the SCC in their rulemakings, the estimate has also made its way into some legislation. Sens. Sheldon Whitehouse (D-R.I.) and Brian Schatz (D-Hawaii) released a carbon tax bill last month that tracked with the SCC. Their staffs did not immediately respond to questions about whether they might revise the figures in their bill to accommodate the administration's revision.