Integrated Assessment Models and the Social Cost of Carbon: A Review and Assessment of U.S. Experience

Gilbert E. Metcalf* and James H. Stock†

Introduction

Greenhouse gas (GHG) emissions are a global externality. The classic prescription for addressing an externality of this type is to set a price on emissions that is equal to the social marginal damages, i.e., the net damages arising from one additional ton of emissions in any given year. This can be done by using a Pigouvian tax (Pigou 1932)—a tax on pollution that is set equal to its social marginal damages—or by establishing property rights to pollution through a cap and trade system (see the seminal treatment by Dales 1968) in which the equilibrium trading price of emissions is determined by the intersection of the demand for emissions and the fixed supply of emission allowances set by policy. Whether a price on emissions is set through a tax or a cap and trade system, the optimal policy design requires knowing the monetized social marginal damages from GHG emissions. In the case of carbon dioxide (CO_2) emissions, this monetized marginal externality value is known as the social cost of carbon (SCC).[1]

Estimating the value of the SCC is challenging. To date, academic researchers have relied heavily on integrated assessment models (IAMs), both to quantify the pathways through which GHG emissions accumulate in the atmosphere and oceans and to assess the environmental and economic impacts. Using three well-known IAMs, the U.S. Interagency Working Group (IWG) on Social Cost of Carbon generated the current U.S. government estimate of the SCC (more precisely its central SCC value and three

*Department of Economics, Tufts University, Medford, MA 02155 and NBER.; e-mail: gmetcalf@tufts.edu; fax: (617) 627-3917

†Department of Economics, Harvard University, Cambridge, MA 02138 and NBER.; e-mail: james_stock@harvard.edu; fax: (617) 495-7730

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[1]There is a vast literature, going back to Weitzman (1974), on the pros and cons of using taxes versus cap and trade systems to reduce GHG emissions. This literature generally assumes that the monetized externality of a ton of carbon emissions, i.e., the social cost of carbon, is known.

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alternative estimates), initially in 2010 and most recently in August 2016 using updated versions of those IAMs.[2]

The three articles in this symposium on the use of IAMs for climate policy examine the challenge of using IAMs to estimate the SCC in light of the very large amount of uncertainty underlying many aspects of IAM-based calculations. Weyant (2017) argues that the uncertainty in IAMs is due more to the fundamental uncertainty in scientific and economic knowledge about key model features and inputs than to flaws in the models themselves. Weyant also emphasizes the need for the research community to improve how it reports and handles the wide range of uncertainty from IAM-based calculations. Pindyck (2017) also examines the uncertainty in IAMs but reaches a quite different conclusion, echoing the earlier criticism in Pindyck (2013)—that IAMs 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" (p. 870). Pindyck proposes replacing an IAM-based SCC with an SCC that reflects the combined opinion of a panel of experts.

This article examines the role of IAMs in estimating the SCC for U.S. regulatory purposes. In particular, we examine 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 when estimating the SCC, and whether an IAM-based SCC should be abandoned and replaced by expert judgment or some other approach. Our perspective in addressing these questions is rooted in the needs of the 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).

To provide an overview of our thinking and our approach, we will argue first that for policy evaluation and implementation, policymakers need a numerical value for the SCC, along with some measure(s) of the uncertainty associated with the estimated value. Second, whatever the true value of the SCC, it is not zero. Finally, 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 will argue that some important aspects of this uncertainty are unlikely to be fully resolved within the time frame necessary for making important and costly decisions on climate policy. Given the evolving nature of the science and the ultimate goal of informing first-best policy, 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. The ultimate goal of the process is scientific credibility, public acceptance, and political and legal viability.

While it is clearly desirable to enhance the precision in the estimate of the SCC, we should expect the uncertainty about the SCC to persist for an extended period of time. Policymaking under uncertainty is the norm and, in this sense, climate policy and the SCC are no different. Because of the especially long time horizon for climate policy, both policies and estimates of the SCC must be able to evolve as new scientific information becomes available.[3]

[2]See Interagency Working Group on Social Cost of Carbon (2010) Technical Support Document and the technical updates released in 2013 and 2016, all available at https://www.whitehouse.gov/omb/oira/social-cost-of-carbon. Also see Greenstone, Kopits, and Woolverton (2013) for an overview of the process.

[3]Most models of optimal climate policy do not incorporate the stochastic nature of knowledge acquisition or climate outcomes, a simplification that is understandable given the computational challenges posed by optimal updating. See Cai, Judd, and Lontzek (2013) for 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).

We have organized our discussion as follows. We first provide a brief history of the use of IAMs and the SCC in U.S. climate policy. This is followed by a description of the current official SCC and its uses. We then turn to a discussion of whether IAMs are fundamentally flawed or a good starting point for improving SCC estimates. Then we examine alternative approaches for developing the SCC and discuss whether the U.S. government should stick with IAMs and the IWG process for estimating the SCC. We argue that while the IWG process (including its use of IAMs) has been sound thus far and is better than the alternatives, it is important to institutionalize a process to ensure ongoing improvement of the SCC. In the final section we present a summary and conclusions.

History of the Use of IAMS and the SCC In U.S. Climate Policy

Nordhaus (2013b) defines IAMs as "approaches that integrate knowledge from two or more domains into a single framework" (p. 1070). Nordhaus's definition includes models that, by themselves, do not generate estimates of the SCC (e.g., the Energy Information Administration's National Energy Modeling System [NEMS]). IAMs 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) in order to allow the researcher to track geophysical and economic variables of interest. An IAM that is constructed to analyze climate change must be able to track emissions, the concentration of GHGs in the atmosphere as well as other carbon sinks (e.g., the ocean or forests), temperature and other climate impacts arising from increased concentrations of GHGs in the atmosphere, and the damages resulting from those climate impacts. For emissions resulting from human activity, policy scenarios can be proposed to affect behavior, and thus emissions, along a number of dimensions. To illustrate, figure 1 (adapted from Nordhaus 2013b) presents the model elements (rectangles) and the model inputs/outputs (parallelograms) of a generic IAM.

Not all IAMs contain all of the elements in figure 1. For example, we are not aware of any IAM that actually contains an explicit political response module that models how policymakers react to climate change damages through policy actions that lead to emission reductions.

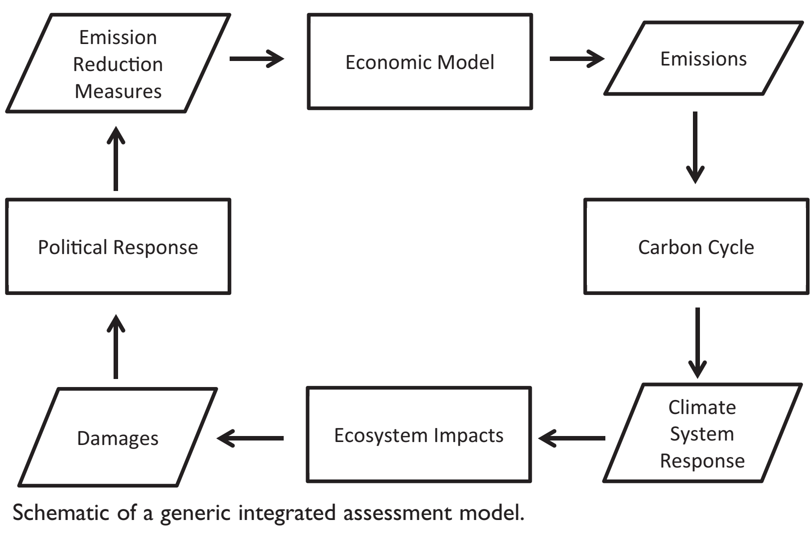

Figure 1 Schematic of a generic integrated assessment model.

Instead, IAM modeling exercises typically incorporate the political response into a given scenario. Reference case scenarios in which there is no action taken to address climate change assumes one implicit political response (i.e., no action), while optimal policy scenarios posit a different political response that sets an implicit or explicit price on GHG emissions at the optimal rate.

In the remainder of this section we describe early regulatory applications of the SCC in the absence of an official U.S. SCC and the process for constructing an official SCC.

Early Regulatory Applications of the SCC

Prior to the IWG's effort to estimate the SCC, estimates of damages from GHG emissions were incorporated into regulatory analyses in an ad hoc way that varied across agencies and rules. We present some examples of these early ad hoc efforts, to illustrate both the evolution of thinking about the SCC and the variation in agency views on SCC estimates.

National Highway Transportation Safety Administration

The March 2006 Final Regulatory Impact Analysis by the National Highway Transportation Safety Administration (NHTSA), which established fuel economy standards for model year 2008–2011 light trucks, stated 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 ... As a consequence, the agency has elected to include no economic value for reducing greenhouse gas emissions ... U.S. Department of Transportation (2006, pp. VIII-64–65).

However, in 2008, the U.S. Ninth Circuit Court of Appeals ruled that by failing to monetize the benefits of GHG emissions reductions, the NHTSA had acted "arbitrarily and capriciously," and for this and other reasons sent the rule back to the NHTSA with an order 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*" [emphasis added].[4]

Thus, in May 2008, the NHTSA issued a proposed rule for model year 2011–2015 passenger cars and light trucks that reflected an SCC value of $7 per ton CO_2-equivalent (CO_2e) in 2006 dollars. To arrive at this result, the NHTSA averaged a high value of $14 per ton (based on estimates for global benefits of reducing emissions from the IPCC's Fourth Assessment Report and adjusted forward to 2011) with a low value of zero (based on estimated damages to the U.S. economy only).

The NHTSA's final environmental impact statement for the model year 2011–2015 fuel economy standards, which was released in October 2008, recommended SCC estimates of

[4]*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).

\$2 per ton CO_2e (based on domestic benefits only) and \$33 per ton (based on global benefits) (U.S. Department of Transportation 2008). The increase in global benefits from \$14 to \$33 per ton was based on new and updated estimates of the SCC by Tol (2008). The positive value for U.S.-only benefits was based on an assessment of the ratio of U.S. to global benefits of emission reductions.

Environmental Protection Agency (EPA)

In its proposed rule regulating GHG emissions under the Clean Air Act, the U.S. EPA (2008) used four values of the SCC to estimate the benefits of reducing emissions based on a meta-analysis that builds on Tol (2008): 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 (for discount rates of 3 and 2 percent, respectively).[5] In all cases, these estimates are for emission reductions in 2007 and are measured in year 2006 dollars. Despite reporting benefit estimates that include an SCC estimate, the EPA made clear that it was not endorsing a particular SCC value.

Department of Treasury and National Academy of Sciences

In another effort related to estimating the SCC, in 2005 the U.S. Congress directed the Department of Treasury to commission a study by the National Academy of Sciences to investigate the externalities associated with energy production and consumption. The committee formed to undertake this study included the following activity in its task statement: "[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). After an extensive survey of the literature, the committee concluded that the SCC could range by two orders of magnitude—from \$1 to \$100 per ton CO_2e—depending on the choice of discount rate for discounting future damages from climate change and the extent of damages from climate change (see table 1). The report states that "at this point only order-of-magnitude estimates appear warranted" (National Research Council 2009, p. 218).

Although the National Academy of Sciences study (National Research Council 2009) was unsatisfactory because it did not provide an SCC number for use in regulatory impact analysis, it highlighted two of the key modeling choices (discount rate and damage function) that drive estimates of the SCC, issues we discuss in more detail later.

The Interagency Working Group and the Current Official SCC

Beginning in 2009, an IWG was convened by the Council of Economic Advisors and the Office of Management and Budget to develop an official SCC for use in U.S. regulatory analyses.[6] The IWG comprised representatives from EPA as well as the Departments of Agriculture, Commerce, Energy, Transportation, and Treasury. The IWG used three widely known and

[5]The EPA's global SCC estimates of \$40 and \$68 (depending on the discount rate) differ from the NHTSA's estimate of \$33 despite the fact that in both cases the underlying data are from Tol (2008). The NHTSA averaged the 125 estimates in the Tol meta-analysis, while the EPA focused on studies that were concluded since 1995 and separated out estimates of the SCC according to the underlying discount rate.

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

Table 1 Indicative damages from greenhouse gas emissions: National Research Council 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: National Research Council (2009). Table reports estimates of the social cost of carbon in dollars per metric ton of carbon dioxide.

respected IAMs to carry out its task. The first model—the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) model—has been used extensively by the IPCC. As noted earlier, its developer, Richard Tol, has carried out several meta-analyses on the SCC that have relied on his and other modelers' work. The second model is the Policy Analysis of the Greenhouse Effect (PAGE) model, developed by Chris Hope. The PAGE model was most prominently used in the *Stern Review* (Stern 2007). The third model—the Dynamic Integrated Climate and Economy (DICE) model—was developed by William Nordhaus and is especially transparent since Nordhaus has posted the model on his website and written several books that document and use the DICE model (Nordhaus and Boyer 2000; Nordhaus 2008, 2013a).

After reviewing the literature, the IWG ran each of the three models for five scenarios (i.e., sets of assumptions about emissions, economic growth, population growth and other socioeconomic assumptions), using 10,000 draws for each scenario from a distribution of equilibrium climate sensitivity (ECS).[7] The ECS, which measures the long-term equilibrium increase in global average surface temperature due to a doubling of GHG concentrations in the atmosphere relative to pre-industrial era levels, is a critical parameter in climate models. Then, for each of three assumed discount rates (2.5, 3 and 5 percent), 150,000 model runs were generated (i.e., 3 models $\times$ 5 economic scenarios $\times$ 10,000 runs) and the results were pooled, with equal weight given to each model and scenario. One should not interpret the use of the five scenarios as an attempt to model uncertainty over the time path of key socioeconomic drivers. The variation in modeling assumptions about future population, for example, simply reflects different beliefs about the central estimate of future population rather than any effort to model the distribution of possible future population outcomes.[8]

For each run, marginal damages were calculated as the present discounted value of the change in consumption from the reference case that arises from a shock to emissions in a given year. Mean values of marginal damages were reported for each year for the 150,000 runs associated with each discount rate. The IWG also reported the 95th percentile value from the

[7]The ECS was drawn from four different probability distributions based on the literature and calibrated to assumptions in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (2007).
[8]The IWG process computed the SCC based on a range of scenarios, some of which are baseline scenarios in the sense of including only policies that are currently in place, and others that include potential future policies. This complicates the interpretation of the SCC to some extent because it does not use a consistent set of assumptions about future policies.

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	$42	$62	$123
2050	$16	$45	$65	$136
2050 (rev)	$26	$69	$95	$212

Source: Interagency Working Group (2010, 2016). Table reports estimates of the SCC measured in 2007 dollars per metric ton. Rev indicates revised estimates from the 2016 technical update.

model runs that used the 3 percent discount rate as one way to take into account potentially extreme impacts of climate change.

In 2013 and again in 2016, the IWG updated the SCC estimates using the methodology in the 2010 report but updated versions of the FUND, PAGE, and DICE models. Table 2 presents the SCC estimates for 2020 and 2050 from the 2010 and 2016 reports. Focusing on the 2020 estimates from the 2016 technical update, the SCC nearly quadruples if we move from a discount rate of 5 percent to 3 percent, and more than quintuples if we move to a 2.5 percent discount 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 for which the SCC was calculated. The central estimate of the SCC in 2020 is 65 percent higher in the 2016 report than in the 2010 report, reflecting, among other things, updates to the damage functions and explicit representation of sea level rise in the DICE and PAGE models.

All three models used in the 2016 calculations exhibit mean SCC estimates that are greater than the median SCC for all of 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).[9] While the variation in the estimates depends on the scenario under consideration, variation in the estimates is driven primarily by variations in equilibrium climate sensitivity, discount rates, and model choice.

The variation in the SCC estimates across models is particularly striking. The estimates from the FUND model in the 2010 analysis are considerably lower on average, reflecting lower damages at all temperature levels (see figures 1A and 1B in the 2010 report). Although 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. The IWG does not comment on the sources of either the differences among models or the difference in damage estimates. By taking simple averages across models and economic scenarios, the IWG took no position on the relative merits of competing models or the likelihood of different economic scenarios. We will return to this issue in more detail later.

[9]Long right tails (or rightward skew) reflect the view that climate change can cause low probability, very high damage events.

Current Uses of the SCC

The IWG's SCC is currently used as an input into the official benefit–cost analyses of proposed U.S. regulations, as a component of legal challenges to government actions, and as a measure of the costs of climate change in the public discussion about climate policy. This section presents and discusses examples of each of these three uses of the SCC.

Input into Benefit–Cost Analyses of Proposed Regulations

Subsequent to its 2010 release, the IWG's estimate was adopted by the Office of Management and Budget (OMB) as the official value of the SCC for use in official benefit–cost analyses of regulations with a substantial climate impact. The most significant such regulation to date is the EPA's Clean Power Plan, which regulates CO_2 emissions from power plants. In June 2014, the EPA released its draft regulatory impact analysis for the Clean Power Plan (U.S. EPA 2014), and the final regulatory impact analysis was released in August 2015. EPA's summary of the estimated monetized benefits of the proposed rule includes four estimates of the benefits of reduced CO_2 emissions that are based on the four SCC estimates from the IWG's 2013 update (i.e., mean SCC averages at 2.5, 3.0, and 5.0 percent discount rates and the 95th percentile value from the distribution of estimated SCCs from the 3 percent discount rate run). Unlike previous NHTSA or EPA analyses, but consistent with earlier uses of the IWG's estimates,[10] the 2014 EPA analysis did not 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. (U.S. EPA 2014, p. ES-14)

Consistent with numerous other benefit–cost analyses of energy/environmental regulations undertaken since the OMB adopted the 2010 IWG report, the EPA's 2014 Regulatory Impact Assessment (RIA) explicitly defers to the IWG's estimate of the SCC, using the IWG's central value (i.e., the mean of the distribution of SCC estimates from runs that assume a 3 percent discount rate (see tables ES-8–ES-10 of the RIA).

Legal Challenges

The SCC has played a role in legal challenges to U.S. government actions. 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 (U.S. District Court for the District of Colorado 2014). In its quantification of the benefits and costs of the lease expansion, BLM had

[10]For example, prior regulatory uses of the SCC for benefit–cost 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).

excluded any costs associated with the release of methane and other GHGs, 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 rejected this claim, finding that "a tool is and was available: the social cost of carbon protocol" (p. 17). The judge went on to describe the IWG Technical Support Document and concluded that the BLM's decision to set the SCC to zero was "arbitrary and capricious" (p. 19). By overturning a federal agency decision because it did not use the IWG's SCC estimates in the benefit–cost analysis, this decision marked a significant milestone in legitimizing the IWG's SCC.

Public Discussion of Climate Policy

The SCC also plays a role in the public discussion of the costs of climate change and the monetized benefits of emissions reductions. For example, the American Opportunity Carbon Fee Act, introduced 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."[11] Introduced in the lame duck session of the 113th Congress, the bill did not generate widespread public debate. It is important to note that at least some conservative commentators accepted linking the fee to the SCC. However, these commentators emphasized that because of interactions with the rest of the tax system, leakage, and the lack of international coordination, the optimal tax would be less than the SCC (Murphy 2014). In this respect at least, the public discussion echoes the academic literature, which points out that in practice the optimal carbon tax depends not only on the external cost of marginal carbon emissions, but also on its implementation and how it interacts with the rest of the tax code. Regardless of this point, the public discussion makes clear that the SCC has played and will likely continue to play a role in legislative efforts to put limits on GHG emissions.

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

We next address the central question of this symposium: Are IAMs an acceptable basis for estimating the SCC or do we need an alternative approach? We divide this question into two parts. First, in this section we examine the shortcomings of existing IAMs and whether there is reason to believe that these shortcomings will be addressed in a time frame consistent with the formulation of climate policy. Second, in the next section we consider whether there is an alternative to IAMs that is better for estimating the SCC in the context of the existing institutional and legal structure for climate policy formulation and implementation.

Criticisms of IAMs often focus on the uncertainties in key model components that drive the results in model runs (see, e.g., Pindyck 2013). Four are especially important: equilibrium climate sensitivity parameter, damage functions, treatment of catastrophic events, and the

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

discount rate. Because equilibrium climate sensitivity is in the realm of geophysical climate science, we focus our attention here on the last three sources of uncertainty, which are more in the economics realm. We note, 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).

Damage Functions

Damage functions in early IAMs were derived from a top-down cross-sectional analysis of the relationship between the level of gross domestic product (GDP) and temperature; thus warming was associated with a shift in the level of future GDP, i.e., a downward parallel shift in the path of GDP. In part because of the public importance of the SCC, the current literature has undertaken a critical reexamination of these damage functions. However, there are significant statistical challenges to disentangling long-run climate impacts identified through cross-sectional variation from other time invariant cross-sectional variation. As a result, this literature has focused on the use of different identification strategies. One strategy uses short-run variation in the weather to examine effects on GDP growth (see, e.g., Dell, Jones, and Olken 2012 and Deryugina and Hsiang 2014). Because weather variations are plausibly exogenous, this approach produces estimates with greater internal validity than cross-sectional GDP regressions. However, the short-run nature of weather makes it difficult to analyze the effects of adaptation or to estimate with much confidence whether weather or climate shocks have long-term effects on economic growth rates rather than just levels. An alternative identification strategy is to construct bottom-up estimates of damages. While it is a much larger undertaking than a top-down approach, a bottom-up approach may provide a more believable identification of causal climate impacts. For example, Koop et al. (2014) used a combination of 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 that track more over land. Other recent bottom-up research has focused 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). Because the planet is already 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. Although most of the work in this area is quite new, the literature is growing quickly and we are optimistic that this literature will lead to substantially better-identified estimates of damage functions in IAMs.

Climate Catastrophes

As discussed by the National Research Council (2013), the Earth's climate history suggests the existence of "tipping points," 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; rapid retreat and instability of West Antarctic ice sheets have also been detected (Joughin, Smith, and Medley 2014 and Rignot et al. 2014). Other changes, such as the release of methane from thawing Arctic permafrost, could reinforce GHG warming, but are considered unlikely to occur in this century (National Research Council 2013).

Weitzman's (2009) dismal theorem focused the attention of the climate economics community on the potentially critical role of large-scale events that are abrupt on a geologic scale—so-called climate catastrophes—in formulating climate policy. The main thrust of the dismal theorem is that with risk averse preferences, society should be willing to pay substantial sums now to avoid worst-case outcomes.[12] Pindyck (2011) and Weitzman (2011) have called this "climate insurance."[13]

This climate catastrophe literature raises the issue that the possibility of worst-case outcomes is an important element of GHG emissions externalities. The challenge for economists and modelers is turning this into a monetary value. However, the channels through which a climate catastrophe leads to damages is largely distinct from the "local" damage function estimates that are statistically identified from the range of warming experienced to date. Thus it is reasonable to ask whether the climate catastrophe cost should be computed separately for the SCC or whether IAMs can measure that cost. This is essentially a technical issue on which we do not have strong views. In any event, Weyant (2017) emphasizes that much research remains to be done before IAMs can credibly address the issue of catastrophic risk. Nevertheless, given the likelihood of climate change causing disruption to particularly vulnerable communities over the next few decades, we believe it would be a mistake to simply focus on low probability catastrophic events (so-called tail events). The "normal warming" costs are still highly likely to be economically important and are particularly salient for many developing countries.

Discount Rates

The choice of the discount rate strongly affects the value of the SCC. Broadly speaking, there are two approaches to choosing the discount rate, a positive approach based on market rates and a normative approach based on valuing consumption across generations. Recent research on both approaches suggests that there could be some narrowing of the range of discount rates relative to the IWG's choices of 2.5 to 5 percent. Unlike equity, climate mitigation and adaptation projects are a hedge against worst-case outcomes. Thus the appropriate market rate should be lower than returns on equity, and in fact could be lower than risk-free long-term government debt. Giglio, Maggiori, and Stroebel (2015) provide empirical evidence that private very long-term discount rates might be quite low. This being said, there is likely to continue to be substantial uncertainty about the appropriate discount rate, because of both philosophical differences between the positive and normative approaches and measurement challenges for each approach. For example, implementing the Ramsey approach (the discount rate that emerges in an equilibrium growth model with endogenous savings) requires adopting a utility function, estimating the intertemporal elasticity of substitution, and estimating the uncertainty about future consumption growth over distant horizons. Despite the possible narrowing of the IWG range for the discount rate, the fundamental difference in perspective of the two

[12]More precisely, Weitzman's results hold for utility functions defined over consumption, with positive relative risk aversion over all positive consumption levels.

[13]Although the details of Weitzman's theorem are sensitive to functional form assumptions, 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), Nordhaus (2011, 2012), Pindyck (2011, 2013), Litterman (2013), Millner (2013), and Weitzman (2011, 2014).

approaches, combined with the scientific uncertainty concerning each approach, makes it difficult to imagine that the debate over the discount rate will be resolved anytime soon.[14]

Summing Up

These observations suggest that the uncertainty concerning damage functions, climate catastrophes, and discounting in climate change models is likely to persist, which means that there will continue to be considerable variation in estimates of the SCC for the foreseeable future. Although some might argue that this means that IAMs should be abandoned and replaced by some other method for estimating the SCC, we do not agree. Economic and scientific research is rife with uncertainty; after all, that is why new research is undertaken. Thus, for example, while the current vigorous research in these areas is unlikely to result in a lasting consensus on what is the true damage function, it is reasonable to expect that this research will help to characterize and, in some cases, substantially tighten the range of technical uncertainty associated with these and other issues concerning IAMs. As ongoing research leads to a more precise quantification of uncertainty, IAMs will be better able to quantify and, we believe, narrow the range of uncertainty of the SCC as well as provide an increasingly solid scientific basis for the various steps in the calculation of the SCC. Thus the idea of simply abandoning the use of IAMs as the basis for the SCC, just as a burgeoning body of research promises to improve these models and their measures of uncertainty, appears to us to be misguided.

What Are the Alternatives to Using an IAM-Based Official U.S. SCC?

Given the scientific uncertainty concerning damage functions, climate catastrophes, and the discount rate that is inherent in the current generation of IAMs, should the IAM-based SCC be replaced with another approach, as suggested by Pindyck (2013)? We can think of at least five alternatives to the IWG approach: ignore the SCC, allow agencies to compute agency-specific SCCs, use existing carbon prices as an estimate of the SCC, develop an official IAM to construct an official SCC, and rely on expert judgment to develop an official SCC.

We assess these alternatives using the following five criteria:[15]

1) The estimate of the SCC should use the best available science and be accompanied by quantified measures reflecting the uncertainty in the existing science.
2) The method by which the SCC is computed should be transparent, replicable, and broadly explainable and understandable to nonexperts.
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 aimed at improving estimates of the SCC would be the most productive.

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

[15]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) The process should not risk being viewed by the courts as arbitrary and capricious, and it should be isolated as much as possible from political influences.

Ignore the SCC?

The first alternative to an IAM-based SCC would be to say that because the scientific work is so incomplete and the uncertainty is so vast, the government should simply not use an SCC until more research has been completed. We view this as an indefensible approach: while there continues to be debate about the size of the SCC, there is overwhelming evidence that the costs of climate change are substantial and that whatever the true value of the SCC, it is clearly not zero. Ignoring the SCC—i.e., using a value of zero in benefit–cost analysis—would restrict climate regulations to those that can be justified solely by their cobenefits (e.g., reductions in local pollution such as particulate matter or mercury) and is inconsistent with the best available science. In fact, as we discussed earlier, abandoning the SCC because of uncertainty has already been rejected by the courts as arbitrary and capricious.

A more nuanced argument that has been made for this approach is that uncertainty about a model, or about key policy parameters (such as the SCC), may warrant taking a conservative approach to implementing such a model. Brainard (1967) provided an early version of this argument in the context of monetary policy, suggesting that uncertainty should lead to caution when the policy has costs. However, Brainard's (1967) result is sensitive to modeling assumptions. Giannoni (2002), for example, considers a monetary model in which optimal policy guards against particularly bad models by responding more (not less) aggressively to shocks than in situations where there is no model uncertainty (see also Hansen and Sargent 2007 and Cai, Judd, and Lentza 2013). In any event, this more nuanced argument does not suggest 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.

Allow Agencies to Compute Agency-Specific Social Costs of Carbon?

A second alternative would be to drop the idea of an official SCC and instead allow agencies to use their own SCCs, thus complying with the court requirement for an SCC. This approach is also a step backwards and fails to meet the criteria in numerous ways, including transparency and being explainable. The inherent redundancy of this approach also makes it administratively complex, less likely to use the best available science, and a poor use of limited government resources.

Use Existing Carbon Prices as an Estimate of the SCC?

A third alternative to constructing an official IAM-based SCC for policy purposes takes a "revealed preferences" approach. In a number of political jurisdictions, climate policy design has led to a cost of carbon being implicitly or explicitly mandated. Examples include carbon taxes in Sweden and in British Columbia, California's cap and trade system, the European Union's emissions trading system, and South Korea's recently enacted cap and trade system. Under the revealed preferences approach, the official SCC would be some average of a selected set of these existing programs, based on the assumption that the policy process has chosen the socially appropriate SCC. Although this approach has the virtue of being explainable—the United States would just be following suit—and could be updated when other jurisdictions change their SCC, it fails on most of the other criteria, including 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 unrealistic assumption that the political process manages to absorb the relevant scientific evidence while ignoring all the costs of mitigation, especially those falling on politically important interest groups. Thus a political revealed preferences approach seems quite unlikely to approximate the true SCC.

Develop an Official IAM to Construct an Official SCC?

A fourth alternative would be for the U.S. government to construct and maintain its own official IAM for U.S. policy purposes instead of using leading peer-reviewed models (as was the case for the IWG). 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 U.S. Energy Information Administration's annual integrated energy market model (the National Energy Modeling System [NEMS]), enhancing the NEMS international energy activity module, and incorporating damage functions. The advantage of this approach is that the federal government would have "in-house" modeling capabilities and expertise to build and maintain the model and to improve it in response to new research and insights about climate change. If properly implemented and funded, this approach would meet 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 the necessary expertise to build the model would have to be developed within the federal workforce, and there is no guarantee that such capacity would be maintained to carry out this ambitious undertaking and to keep up with scientific developments. Perhaps more importantly, it is not clear that a federal IAM would be sufficiently transparent and explainable for the public to have confidence in policymaking based solely on that model, because ultimately this approach has the federal government making myriads of modeling judgments, many of which will inevitably be viewed as being subject to political pressure. Moreover, although the current NEMS model is highly credible, new and controversial modeling judgments would need to be made. In the end, even if the model were housed at an independent agency or a national laboratory, it could still be (or appear to be) subject to political pressure through the budget process, which necessarily reflects the political positions of the executive branch and Congress.[16]

Rely on Expert Judgment to Arrive at an Official SCC?

A fifth approach, which is proposed in Pindyck (2013, 2017), would be to base the SCC on expert judgment. For example, the U.S. government could contract with the National Research Council to appoint a standing panel of experts that would deliberate on the SCC, agree on an initial estimate, and then convene every 5 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 approach could be based on the best available science as interpreted by the

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

experts, would entail regular updating, could convey the experts' judgment concerning both the SCC and its quantified uncertainty, and could convey the experts' views to researchers about what additional research is needed. However, we believe that this proposal falls short on the other criteria, especially if (as it appears that Pindyck's proposal would have it) the experts are prohibited from using IAMs. If the experts were not allowed to use IAMs, then presumably this would disqualify many experts who have devoted much of their careers to developing IAMs, because 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 prohibited from using IAMs, which would close one approach for quantifying insurance value. In any case, it is hard to see how a panel of experts that is prevented from using an entire class of models would produce an estimate that is transparent, replicable, and uses the best available scientific information. Moreover, as a practical matter, it is hard to imagine how the judgments of an expert panel would not be subject to political influences, because a standard institutional practice is to balance the membership of panels of experts, not based on the experts' scientific credibility, but by ensuring the representation of a wide range of views. It is also hard for us to see how a panel-of-experts approach that includes the side constraint of not using a class of scientific tools would be viewed by the courts as anything other than arbitrary and capricious.[17]

Should We Stick with the Current Interagency Process?

In the end, none of the alternative approaches discussed in the previous section meets all of our criteria for choosing an official U.S. SCC. In fact, as emphasized in our discussion of the panel-of-experts approach, it is 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. Thus we believe that integrated modeling must play some role in any climate policy analysis.

In contrast to the alternative approaches described in the previous section, the IWG process does reasonably well on the five criteria for choosing an official U.S. SCC. But that is not to say that the process can't be improved. We turn next to a brief assessment of the IWG process and our thoughts about ways in which it could be improved.

Assessing the IWG Process

Conditional on which models are used, the IWG's computational approach is straightforward and is based on economic and statistical principles. One can always question specific modeling choices the working group has made. For example, the choice to weight the three models (FUND, PAGE, DICE) and different economic scenarios equally in its averaging suggests that all models and scenarios have equal credibility. However, the differences across the

[17]The argument in Pindyck (2013, 2017) is based in part on his view that the panel should focus only on catastrophic risks. We have argued here that the research on noncatastrophic damages is steadily improving and that damage functions are increasingly calibrated to real-world data. In addition, it is important in international climate negotiations to demonstrate credibility concerning near-term damages to the most vulnerable developing countries. An SCC process that ignores noncatastrophic damages would undermine that credibility.

models are striking, which raises the question of how to appropriately weight whichever models are included in the analysis. Understanding how and why the model results differ would also be useful for both interpreting the results and determining how best to weight different models and scenarios.[18]

Setting aside issues of weighting model runs, we find the process itself to be scientifically sound and, given the care with which the 2010 Technical Support Document was written, the process is also transparent and readily understandable. Moreover, the GAO (2014), which is rarely satisfied, found the IWG process to be consistent with federal standards for internal control. The results of the IWG's analysis have also made clear the importance of key parameters, most notably the discount rate, the distribution of ECS, and the damage function choices, which provides useful feedback to the research community.

Improving the SCC Process

Nevertheless, we believe there is room for improvement in the IWG process 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 either the review or the production of new estimates. Second, although there have been numerous 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 IWG made several decisions that protected it from political influence (including, e.g., the decision to use several leading peer-reviewed models instead of just one model or an internally developed model), 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 continue to be perceived as being politically influenced. These issues are addressed by Pizer et al. (2014), which recommends a regular SCC revision schedule (e.g., every 5 years), that the process should be similar to the interagency process used for the 2010 analysis, that the estimates should be regularly reviewed by the National Academy of Sciences, and that the process should be codified through an OMB memo or circular. We agree with these recommendations, which would transform the SCC from a single number, or snapshot of the research, into a stable process. In fact, OMB initiated a National Academy of Sciences review that will inform the updating process, and we hope that such review will become part of a regular process for updating the SCC. In addition to enhancing transparency, providing expert review, and providing guidance for further research, regular oversight by the National Academy of Sciences provides additional protection from political influence since attempts at political influence would presumably be flagged by the review panel. Still, an issue that remains to be explored is whether additional steps are warranted to further protect the process from political influence by, for example, housing the technical work associated with the models at a national laboratory or an independent agency such as the Energy Information Administration.

[18]Rose et al. (2014) carried out such an exercise for the models used by the IWG.

Summary and Conclusions

This article has reviewed the various approaches to developing an SCC and criticisms of the use of IAMs in the construction of an official U.S. SCC. Given its importance in regulatory implementation and the public debate, an official SCC must be as credible as possible; we have proposed criteria aimed at ensuring that credibility. We believe that the SCC must have a numerical value and be associated with numerical measures of uncertainty and we do not see how that can be done credibly without sophisticated computer models that incorporate climate and economic considerations (i.e., without IAMs). Complicating all this, the horizon over which the uncertainty surrounding the costs of climate change is likely to be resolved extends beyond the horizon over which climate policy decisions must be made. Moreover, estimates of the SCC will change as new science becomes available. Given these complications, climate policy must be sufficiently sophisticated so that it can adapt to evolving science and evolving estimates of the SCC.

These observations lead us to three conclusions. First, in our view, the process followed by the IWG to estimate the SCC in 2010 (with technical updates in 2013 and 2016), including its use of IAMs, satisfies many of the criteria. The IWG process is more consistent with these criteria than alternatives such as different agencies using different values, failure to adopt any value (thereby implicitly adopting the clearly incorrect value of zero), or relying on an expert panel charged with reaching a numerical judgment without reference to numerical models. That being said, there is clearly room for improving the current process of estimating the SCC. One such improvement would be to provide a schedule for regular updating, as recommended by Pizer et al. (2014). Another improvement would be to incorporate formal external expert review into the SCC process. In a positive step in this direction, the OMB commissioned the National Academy of Sciences to conduct such a review (Chemnick 2015).

Second, an ongoing challenge of the SCC process is how best to communicate the uncertainty surrounding SCC estimates 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 the usual benefit–cost analysis. In our view, a key challenge for the SCC process is balancing that, on the one hand, the SCC is subject to considerable uncertainty, while on the other hand, the range of uncertainty does not plausibly include zero and the policy process needs an SCC value and range that is both useful and can be acted on. We would argue that a process that meets the five criteria we have discussed here has the best chance of tackling this problem of communicating the uncertainty of SCC estimates.

Third, the value of the SCC—whether calculated using IAMs or some other approach 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 highlighted aspects of IAMs that have considerable scientific uncertainty, such as the damage functions and the largely unmodeled consequences of large-scale abrupt changes. We have noted some 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 both the public debate and climate policies that is not normally required in other policy arenas.[19]

[19]We have focused only on the social cost of CO_2. The Interagency Working Group on Social Cost of Carbon (2016) has recently extended its methodology to estimate the social cost of nitrous oxide and methane and the methodology could be extended to other GHGs as well.

To date, the SCC has been used in a variety of settings but, to the best of our knowledge, has never been the deciding factor in the promulgation of major regulations. However, as the proposed American Opportunity Carbon Fee Act makes clear, in order for market-based policies aimed at reducing GHG emissions to be credible, the SCC must be able to stand on its own. It is hard to see how that can happen without sophisticated integrated frameworks for computing marginal climate damages (i.e., without IAMs). Thus the challenge for the research community is to continue to work to improve our understanding and modeling of climate damages, large-scale abrupt geophysical changes and their economic consequences, and long-term discount rates.

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