Estimates of the Social Cost of Carbon: Concepts and Results from the DICE-2013R Model and Alternative Approaches

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Estimates of the Social Cost of Carbon: Concepts and Results from the DICE-2013R Model and Alternative Approaches

William Nordhaus

Abstract: The social cost of carbon (SCC) is an important concept for understanding and implementing climate change policies. This term represents the economic cost caused by an additional ton of carbon dioxide emissions (or more succinctly carbon) or its equivalent. The present study describes the development of the concept, provides examples of its use in current US regulator policies, examines its analytical background, and estimates the SCC using an updated integrated assessment model, the DICE-2013R model. The study estimates that the SCC is $18.6 per ton of CO_2 in 2005 US dollars and international prices for the current period (2015). For the central case, the real SCC grows at 3% per year over the period to 2050. The major open issues concerning the SCC continue to be the appropriate discount rate, the potential for catastrophic damages, the impact of incomplete harmonization of abatement policies, and the effects of distortionary taxes.

JEL Codes: Q5, H23, Q54, H4, Q58

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A NEW AND IMPORTANT concept that has taken center stage in economic and policy discussions about global warming is the "social cost of carbon," or SCC. This term designates the economic cost caused by an additional ton of carbon dioxide emissions (or more succinctly carbon) or its equivalent. In a more precise definition, it is the change in the discounted value of the utility of consumption per unit of additional emissions, denominated in terms of current consumption. In the language of

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mathematical programming, the SCC is the shadow price of carbon emissions along a reference path of output, emissions, and climate change.

We can illustrate the concept in figure 1. This shows a base path of greenhouse gas (GHG) emissions along with a base path of a comprehensive measure of economic welfare, such as generalized consumption. We show an increment of emissions in the second period, along with an alternative path of consumption. If we take the difference in the value of consumption between the two paths, discount it appropriately back to period 2, and then divide it by the increment in emissions, that is the SCC in period 2.

With an optimized climate policy (abstracting away from complications due to tax or regulatory distortions or inconsistent treatment in different sectors), the SCC will equal the carbon price; this in turn is equal to the marginal cost of emissions reduction and to the present value of the damages from a unit of emissions. In the more realistic case where climate policy is not optimized, it is conventional to measure the SCC as the marginal damage of emissions along the actual path. There is some inconsistency in the literature on the definition of the path along which the

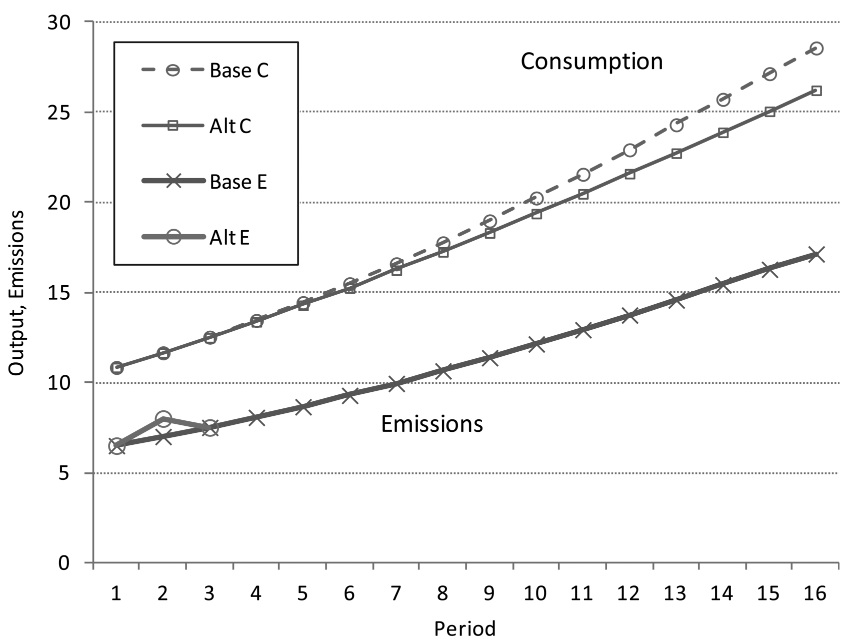

Figure 1. Illustration of calculation of social cost of carbon. The figure illustrates an original ("Base") path of emissions and consumption along with an alternative ("Alt") path in which emissions are increased by 1 unit in period 2. This leads to an alternative and lower path of economic welfare ("consumption"), shown as "Alt C." The SCC is calculated as the present value of the difference in the consumption paths divided by the increment in emissions. A color version of this figure is available online.

SCC should be calculated. This paper will generally define the SCC as the marginal damages along the baseline path of emissions and output and not along the optimized emissions path. Comparisons are made between the two where that is useful.

I begin by providing a detailed analysis of a global integrated assessment climate-economy model. For this purpose, I use an updated version, the DICE model (DICE is an acronym for Dynamic Integrated model of Climate and the Economy). While the DICE model is only a single model, the basic structure of the analysis is similar in other integrated assessment models. The section also describes the major difference between the new and previous versions. The section presents the major results of the model and compares them with other integrated assessment models (IAMs).

Section 2 then defines the SCC and describes several alternative scenarios for calculating it. The major scenarios are uncontrolled and optimized abatement, a model calibrated to the 2°C temperature target that governments and scientists have suggested, a run that uses the discounting assumed in the *Stern Review* (*Stern Review* 2007), and a high-discount-rate scenario. We show that the "growth-corrected discount rate" is crucial for understanding the way that discounting enters the analysis. The section also calculates SCCs for major countries and regions. The central estimate of the SCC in the baseline path is \$18.6 per ton of CO_2 in 2015 in 2005 US dollars.

Section 3 presents major alternative approaches to estimating the SCC. It finds that virtually all estimates of the SCC have come from one of three major IAMs. It describes the other IAMs briefly. This section reviews the analysis of the US Interagency Working Group (IWG) that performed a harmonized comparison of the three models. This section compares the IWG's output-based methodology with the DICE model's utility-based methodology. Finally, it shows the sensitivity of the analyses to alternative discount rate assumptions.

Section 4 examines several critiques of the concept of the SCC. One criticism holds that the SCC is vastly understated because of the omission of catastrophic and fat-tailed risks, while a second holds that the conceptual and empirical shortcomings of IAMs are so great that the SCC concept is useless.

Section 5 examines major applications of the SCC. It focuses particularly on the use in US regulatory policies and cost-benefit analyses. While the SCC of around \$18.6 per ton of CO_2 for 2015 would be an appropriate target for a harmonized carbon tax in a first-best world, it is likely to be higher than the appropriate number when realistic factors are included. Appropriate adjustments are necessary to reflect national rather than global benefits, tax distortions, the use of non-revenue-raising regulations, and leakage. The analysis suggests that these adjustments would lead to a lower implicit price than the standard SCC.

1. ANALYSIS OF THE SOCIAL COST OF CARBON IN THE DICE-2013R MODEL

Analyses of the SCC rely on IAMs for empirical estimates. All IAMs used for estimating the SCC have a similar structure, although they have varying emphases (different IAMs are reviewed in a later section). The discussion begins with the description of the model used to calculate the SCC in the present paper. Once the modeling details are developed, the precise definition of the SCC can be easily shown. I then present numerical estimates of the SCC.

1.1. Background on the DICE and RICE Models: The "Standard DICE-2013R Model"

The present discussion begins with a description of the DICE-2013R model. It will be denoted the "standard DICE-2013R model" because we will also take variants of the standard model to test for sensitivities. It is the latest version of a series of models of the economics of global warming. The first version of the global model was Nordhaus (1992, 1994). The first regional model was Nordhaus and Yang (1996), with the most recent updated version Nordhaus (2010). This discussion will present the major elements, and a more complete treatment is contained in Nordhaus (2008, 2010) and Nordhaus and Sztorc (2013).

The current version of the DICE-2013R is available at dicemodel.net and http://www.econ.yale/~nordhaus/homepage.Web-DICE-2013-April.htm. An extensive description of the 2013R model is available in the *User's Manual* online (Nordhaus and Sztorc 2013).

The DICE model views climate change in 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 (Ramsey 1928; Koopmans 1965). The DICE model modifies the Ramsey model to include climate investments, which are analogous to capital investments in the standard model. The model contains all elements from economics through climate change to damages. The geophysical equations are simplified versions derived from large models or model experiments.

1.2. Equations of the DICE-2013R Model

I will list the major equations; for details readers are referred to Nordhaus and Sztorc (2013). The model optimizes a social welfare function, W, which is the discounted sum of the population-weighted utility of per capita consumption. The notation here is that $c(t)$ is per capita consumption, $L(t)$ is population, and $R(t) = (1+\rho)^{-t}$ is the discount factor on utility or welfare, where ρ is the pure rate of social time preference or generational discount rate.

$$W = \sum_{t=1}^{T\max} U[c(t), L(t)]R(t). \tag{1}$$

The utility function is a constant elasticity with respect to consumption of the form $U(c) = c^{1-\alpha}/(1-\alpha)$. The parameter α is interpreted as generational inequality aversion in this context. Net output, $Q(t)$, is a function of gross output, $Y(t)$. Net output is gross output reduced by damages and mitigation costs:

$$Q(t) = \Omega(t)[1 - \Lambda(t)]Y(t) = C(t) + I(t). \tag{2}$$

In this specification, $Q(t)$ is output net of damages and abatement; $Y(t)$ is gross output, which is a Cobb-Douglas function of capital, labor, and technology; $C(t)$ is consumption; and $I(t)$ is gross investment. Labor is proportional to population, while capital accumulates according to an optimized savings rate. The additional variables in the production function are $\Omega(t)$ and $\Lambda(t)$, which represent the damage function and the abatement-cost function, respectively. The damage function is defined as $\Omega(t) = D(t)/[1 + D(t)]$, where

$$D(t) = \psi_1 T_{\mathrm{AT}}(t) + \psi_2[T_{\mathrm{AT}}(t)]^2. \tag{3}$$

Equation (3) describes the economic impacts or damages of climate change, which is a key component in calculating the SCC. The DICE-2013R model takes globally averaged temperature change (T_{AT}) as a sufficient statistic for damages. Equation (3) assumes that damages can be reasonably well approximated by a quadratic function of temperature change.

Uncontrolled industrial CO_2 emissions are given by a level of carbon intensity, $\sigma(t)$, times gross output. Total CO_2 emissions, $E(t)$, are equal to uncontrolled emissions reduced by the emissions-reduction rate, $\mu(t)$ plus exogenous land use emissions.

$$E(t) = \sigma(t)[1 - \mu(t)]Y(t) + E_{\mathrm{Land}}(t). \tag{4}$$

The geophysical equations link greenhouse gas emissions to the carbon cycle, radiative forcings, and climate change. Equation (5) represents the equations of the carbon cycle for three reservoirs.

$$M_j(t) = \varphi_{0j}E(t) + \sum_{i=1}^{3} \varphi_{ij}M_i(t-1). \tag{5}$$

The three reservoirs are j = AT, UP, and LO, which are the atmosphere, the upper oceans and biosphere, and the lower oceans, respectively. The parameters φ_{ij} represent the flow parameters between reservoirs per period. All emissions flow into the atmosphere. As with many other components of the DICE model, the simplified carbon cycle is a compromise between scientific accuracy and transparency.

The relationship between GHG accumulations and increased radiative forcing is shown in equation (6).

$$F(t) = \eta\{\log_2[M_{AT}(t)/M_{AT}(1750)]\} + F_{EX}(t), \tag{6}$$

where $F(t)$ is the change in total radiative forcings of greenhouse gases from anthropogenic sources such as CO_2, $F_{EX}(t)$ is exogenous forcings, and the first term is the forcings due to atmospheric concentrations of CO_2.

Forcings lead to warming according to a simplified two-level global climate model:

$$T_{AT}(t) = T_{AT}(t-1) + \xi_1\{F(t) - \xi_2 T_{AT}(t-1) - \xi_3[T_{AT}(t-1) - T_{LO}(t-1)]\}. \tag{7}$$

$$T_{LO}(t) = T_{LO}(t-1) + \xi_4[T_{AT}(t-1) - T_{LO}(t-1)]. \tag{8}$$

In these equations, $T_{AT}(t)$ is the global mean surface temperature and $T_{LO}(t)$ is the mean temperature of the lower oceans. Major revisions to the model are described below.

1.3. Revisions from Earlier Versions of the DICE and RICE Models

There are several large and small changes in the DICE-2013R model compared to earlier versions. The prior complete documented version of the DICE model is Nordhaus (2008), while the last complete version of the regional (RICE, signifying the Regional Integrated model of Climate and the Economy) model is in Nordhaus (2010).

The first revision is that the time step has been changed from 10 years to 5 years. This change is taken because improvements in computational capacities allow the model to be easily solved with a finer time resolution.

A second change is the projection of future output growth. Earlier versions of the DICE and other IAMs tended to have a stagnationist bias, with the growth rate of total factor productivity declining rapidly in the coming decades. The current version assumes continued rapid total factor productivity growth over the next century, particularly for developing countries.

A third revision incorporates a less rapid decline in the CO_2-output ratio in several regions and for the world, which reflects the last decade's observations. Earlier trends (through 2004) showed rapid global decarbonization, at a rate between 1.5% and 2% per year. Data through 2010 indicate that decarbonization has been closer to 1% per year. The new version assumes that, conditional on output growth, uncontrolled CO_2 emissions will grow at 0.5% per year faster than earlier model assumptions.

A fourth assumption involves the damage function. The most recent versions of both DICE and RICE used the impact estimates from the 2000 RICE model (Nordhaus and Boyer 2000). There has been significant further work on damages since that time. The new model uses estimates of monetized damages from the Tol (2009) survey as the starting point. Tol's central estimate is that damages are about 3% of global output at a temperature increase of 3°C. However, current studies generally omit several important factors (biodiversity, ocean acidification, and political reactions), extreme events (sea-level rise, changes in ocean circulation, and accelerated climate change), impacts that are inherently difficult to model (catastrophic events and very long-term warming), and uncertainty (of virtually all components from economic growth to damages). I have added an adjustment of 25% of the monetized damages to reflect these nonmonetized impacts. While this is consistent with the estimates from other studies (see Anthoff and Tol 2010; Hope 2011; FUND 2013), it is recognized that this is largely a judgmental adjustment. The current version assumes that damages are a quadratic function of temperature change and does not include sharp thresholds or tipping points, but we return to this question in section 4.

A fifth revision recalibrates the carbon cycle and climate models to recent earth system models. The equilibrium and transient temperature impacts of CO_2 accumulation have been revised to include a wider range of estimates. Earlier versions relied entirely on the estimates from general circulation models (e.g., the ensemble of models used in the IPCC (Intergovernmental Panel on Climate Change) Fourth Assessment, Science 2007). The present version uses estimates from sources such as the instrumental record and estimates based on the paleoclimatic reconstructions. The carbon cycle has been adjusted to reflect the saturation of ocean absorption with higher temperatures and carbon content. See the *User's Manual* for details.

A sixth set of changes are updates to incorporate the latest output, population, and emissions data and projections. Output histories and projections come from the International Monetary Fund's World Economic Outlook database. Population projections through 2100 are from the United Nations. CO_2 emissions are from the Carbon Dioxide Information Analysis Center (CDIAC). Non-CO_2 radiative forcings for 2010 and projections to 2100 are also from projections prepared for the IPCC Fifth Assessment. The definitions of regions (particularly the European Union and developing countries) have changed to reflect changing compositions and reflect the structure as of 2012.

A seventh question concerns the calibration of the model for rates of return on capital. The philosophy behind the DICE model is that the capital structure and rate of return should reflect actual economic outcomes. This implies that the parameters should generate savings rates and rates of return on capital that are consistent with observations (this is sometimes called the "descriptive approach" to discounting after Arrow et al. [1996]). The data on rates of return used in the calibration are as follows: (*a*) the risk-free real return, generally taken to be US or other prime sovereign debt, is in the range of 0%–1% per year depending upon period, concept, and tax status; (*b*) the rate of return on risky capital of large corporations in mature markets, after company taxes but before individual taxes, is in the range of 5%–8% per year depending on period, concept, and tax status; (*c*) the rate of return on risky investments in illiquid or immature markets, as well as for poorly capitalized individuals, is generally much higher than for corporations and ranges from 0% to 100% per year depending on the circumstances; (*d*) it is unclear how much of the difference between the return on risky capital and the risk-free return is compensation for nondiversifiable risk (see Mehra 2008), but for the present study I assume that the equity premium reflects nondiversifiable risks; (*e*) the extent to which climate investments are correlated with systematic consumption risk is an open question, although preliminary work from Nordhaus (2008) and Gollier (2013) suggest a relatively high consumption beta. For the present study, I assume that the consumption beta on climate investments is close to one.

Based on these considerations, I assume that the rate of return relevant for discounting the costs and benefits of climate-sensitive investments and damages is 5% per year in the near term and 4.5% per year over the period to 2100. This is the global average of a lower figure for the United States and a higher figure for other countries, and it is therefore consistent with estimates in other studies that use US data, such as the US Interagency Working Group discussed later. With this calibration, we choose the pure rate of social time preference (ρ) to be 1.5% per year and the consumption elasticity (α) to be 1.45.

An eighth revision is to change the units of measurement from tons of carbon to tons of CO_2 or CO_2-equivalent, this being to reflect the current conventions in most price and economic data.

A ninth change is a redefinition of the concept of the "baseline" for modeling purposes. In earlier vintages, baseline meant "no policies." In the current model, baseline assumes that current policies as of 2013 are extended indefinitely. This approach is standard for forecasting, say of government budgets, and is more appropriate for a world of evolving climate policies. Estimates from Nordhaus (2010) indicate that 2010 policies were the equivalent of \$1 per ton of CO_2 global emissions reductions. Note that this approach requires calculating baseline emissions intensities as reflecting the current level of emissions reductions.

The major net effect of these revisions is to increase modestly the growth rate of world output, the emissions and concentrations of CO_2, the temperature trajectory, climate damages, and the calculated social cost of carbon. Most of the revisions in the data have been "bad news" for climate change.

1.4. Major Results for DICE-2013R

It will be useful to show some representative results from the revised model. We also compare the results with a recent model comparison exercise, the EMF-22 study, surveyed under the aegis of the Energy Modeling Forum (EMF) at Stanford University. This study compared the results of several IAMs from modeling teams from around the world.

Figure 2 shows the industrial emissions of CO_2 over the coming century. It compares the present version of the model with the EMF projections. The figure

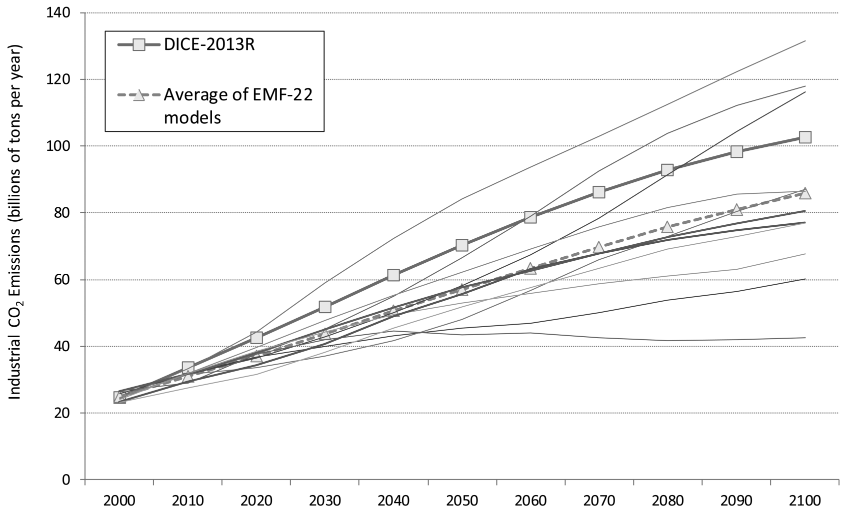

Figure 2. Projected industrial CO_2 emissions in baseline scenario. The heavy dashed line with triangles is the average of the 11 models surveyed in the EMF-22 project. The heavy line with squares is the DICE-2013R version. The light lines are the individual EMF-22 models. The EMF results are described in Clarke et al. (2009); detailed modeling results were made available by Leon Clarke. A color version of this figure is available online.

shows both the average of the models in bold and 11 individual models as light lines. The DICE-2013R version is near the top of the range, with the changes explained in the last section.

Figure 3 shows a comparison of projected temperatures of different models and scenarios. For the temperature projections for 10 EMF-22 models, I have used the CO_2 concentrations for the different models and the DICE climate model and non-CO_2 forcings; this was necessary because most of the models did not calculate temperature trends, and they used inconsistent non-CO_2 forcings. The heavy lines are the average of the EMF-22 models and the DICE-2013R model. Also shown are four scenarios from the IPCC Fourth Assessment Reports that have been commonly cited. The DICE-2013R results are at the upper end primarily because of the higher projected CO_2 emissions, as just discussed.[1] (Note that the Fifth Assessment Report uses a different methodology in its climate projections, and these cannot be easily compared with economic models or with earlier estimates.)

1. Although some of the EMF-22 integrated assessment models provide temperature trajectories, they exclude short-lived greenhouse gases and aerosols and therefore do not provide a comparable temperature projection. The runs shown in fig. 3 take the industrial CO_2 concentrations from the EMF-22 models. These are then combined with estimates of land-use CO_2 emissions and the radiative forcings for other GHGs from the RICE-2010 model. We then

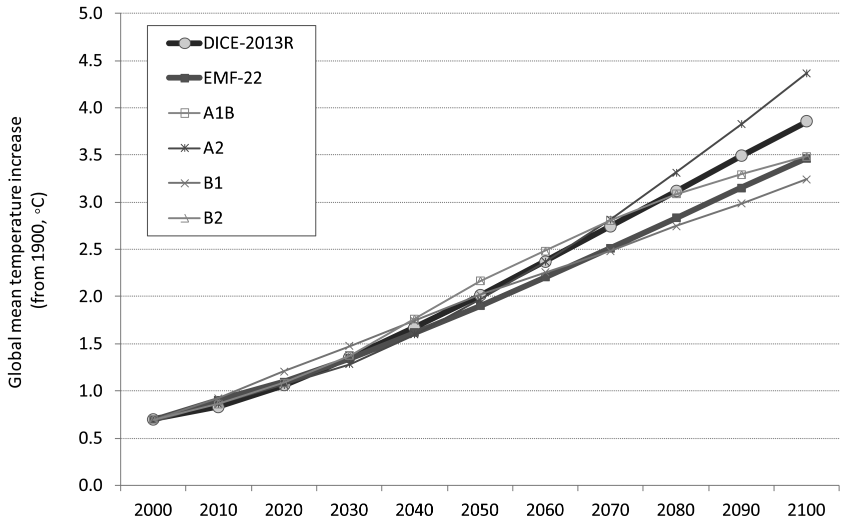

Figure 3. Global mean temperature increase as projected by IPCC scenarios and integrated assessment economic models. The figure compares the projections of four scenarios using IPCC scenarios with those of the DICE-2013R model and the average of 10 EMF-22 integrated economic models. The letters A1B, A2, B1, and B2 represent the results of four IPCC standardized emissions and the ensemble of climate model projections from the IPCC Fourth Assessment Report. A color version of this figure is available online.

These results provide the context for how the DICE-2013R model fits into other model projections. They present a cautionary warning about both the difficulties of projections as well as the differences that can arise from alternative model assumptions, algorithms, output projections, and energy sectors. The spaghetti diagram of different forecasts has been a feature of emissions and other projections since early surveys, such as Nordhaus and Yohe (1983), and it is a good indication that forecast errors increase as we go further into future.

2. ESTIMATES OF THE SOCIAL COST OF CARBON

2.1. Definition of SCC

We now provide a precise definition of the social cost of carbon. Using equations (1)–(8), we can solve for the social welfare function, W, in terms of the various exogenous and policy variables. We then define the social cost of carbon at time t as SCC(t).

put all these into the climate module of the RICE-2010 model. The 10 models were ETSAP-TIAM, FUND, GTEM, MERGE Optimistic, MERGE Pessimistic, MESSAGE, MiniCAM-BASE, POLES, SGM, and WITCH. A full description of the models is contained in the source at Clarke et al. (2009).

$$\mathrm{SCC}(t) \equiv -\frac{\partial W}{\partial E(t)} \bigg/ \frac{\partial W}{\partial C(t)}. \tag{9}$$

The numerator is the marginal impact of emissions at time t on welfare, while the denominator is the marginal welfare value of a unit of aggregate consumption in period t. The ratio calculates the economic impact of a unit of emissions in terms of t-period consumption as a numéraire. In actual calculations, we take a discrete approximation to (9). Note that the SCC is time-indexed. This indicates that the marginal cost of emissions at time t (in terms of consumption at time t as a numéraire) changes over time.

2.2. Estimates of the SCC in the DICE-2013R Model

We have estimated the SCC in the DICE-2013R model for several alternative scenarios. These reflect differing assumptions about policy, damages, and discounting. We list the scenarios briefly and describe them in more detail below.

1. The first is the "baseline" scenario, which uses the standard DICE-2013R model and assumes no changes in climate change policy from 2010 levels.
2. The second is the "optimal" climate policy scenario, which uses the standard DICE-2013R model and optimizes the time path of emissions reductions and investment.
3. A third run modifies the damage function in the standard DICE model so that the optimal path leads to a limit on temperature increase to 2°C above the 1900 level.
4. The fourth run is a variant of run 3 and assumes that the 2°C limit is an average rather than an annual or decadal maximum.
5. The fifth run examines the impact of a near-zero discount rate on the SCC.
6. The sixth run is a variant on the fifth that calibrates other parameters to keep real returns on capital in the lower-time-preference scenario equal to the rate of return in the baseline scenario.
7. A final run is a high-discount-rate sensitivity analysis that raises the pure rate of social time preference to 3.5% per year.

More details on the assumptions in the different runs are provided as the analysis proceeds.

The methodology for estimating the SCC is straightforward using the GAMS (General Algebraic Modeling System). We calculate the shadow price on CO_2 emissions in each run and then divide that by the shadow price of consumption. This provides exactly the formula shown in equation (9) above. The units are 2005 US international dollars per metric ton of CO_2 and are expressed in terms of consumption in the given year. The results are shown in table 1, and the different scenarios are dis-

Table 1. Global Social Cost of Carbon under Different Assumptions

Scenario	2015	2020	2025	2030	2050
Base parameters:					
Baseline*	18.6	22.1	26.2	30.6	53.1
Optimal controls†	17.7	21.2	25.0	29.3	51.5
2°C limit damage function:					
Maximum†	47.6	60.1	75.5	94.4	216.4
Max of average†	25.0	30.6	37.1	44.7	87.9
Stern Review discounting:					
Uncalibrated*	89.8	103.7	117.4	131.3	190.0
Calibrated*	20.7	25.0	30.1	35.9	66.9
Alternative high discount*	6.4	7.7	9.2	10.9	19.6

Note.—The social cost of carbon is measured in 2005 international US dollars. The years at the top refer to the date at which emissions take place. Therefore, $18.6 is the cost of emissions in 2015 in terms of consumption in 2015.

* Calculation along the reference path with current policy.

† Calculation along the optimized emissions path.

cussed in turn. (An alternative approach is needed when the EXCEL version of the DICE model is used. For that, we perturb emissions by 1 million tons in a given year. We calculate the change in the present value of utility scaled by consumption in the given year to get the SCC. This gives the identical results, subject to computational precision.)

2.2.1. SCC for Standard DICE Model Parameters

The central cases for the SCC are shown in the first two rows of table 1. The first row shows the estimate for the standard DICE model with baseline or current climate policy. The SCC figure here is $18.6 per ton of CO_2 for emissions in 2015, $22.1 for emissions in 2020, and so forth. Recall that these are time-dated SCCs since the cost of emissions depend upon the year in which emissions take place. (Sometimes estimates are given in dollars per ton of carbon. The carbon weight is 1/3.667 times the CO_2 weight, so the carbon price is 3.667 times the CO_2 price, in this case $18.6 per ton of CO_2 is $68 per ton of carbon.) This SCC rises at a real rate of 3% per year over the period to 2050. The rate of change of the SCC depends upon several factors, particularly the rate of growth of world output, the removal rate of atmospheric carbon, and the discount rate.

The SCC along an optimized path, shown in row 2, is about 5% less than along the baseline path. It is a moderate surprise that the SCC does not differ markedly between the optimized case and the baseline case. The reason for this result is that the damage function is close to linear in the range between the two cases. In other words, the marginal damage in early periods is only slightly affected by optimizing emissions.

2.2.2. The Social Cost of Carbon in the Context of the 2°C Target

The first set of estimates is based on the standard parameters from the DICE model. The optimized path yields temperatures that are above the limit that has been agreed upon in international meetings and has been recommended by several scientific groups. The current consensus is known as the "Copenhagen Accord" (see United Nations 2009). The accord adopts a target of limiting the increase in global mean temperature, "recognizing the scientific view that the increase . . . should be below 2 degrees Celsius." There was no specific scientific document to support this statement, although the European Union has developed such a target in the context of a cost-benefit analysis. This target has been referenced in further International Conferences of the Parties.

It will be useful to put the Copenhagen target in the context of the current study. The approach taken here assumes that policy makers who negotiated the Copenhagen temperature target implicitly have a different damage function from that used in the DICE (and most other) economic models.

How can we rationalize the 2°C target? In other words, (i) what change in the economic parameters would lead to an optimized temperature that corresponds to that adopted in the Copenhagen Accord? And (ii) what is the SCC that would be associated with this alternative set of parameters? One possibility is a lower discount rate, which I investigate in the next section. The other possibility is a damage function that assumes much higher damages than standard models. No other change in parameters that was tested would come close to producing the result. (I note as an aside that the higher-damage interpretation appears more consistent with the expressed gravity of concerns about climate change as well as high discount rates that are implicit in other decisions.)

I then proceeded to recalibrate the DICE-model damage function so that an optimal abatement plan would lead to the 2°C target. More precisely, I assume that the 2°C target reflects a cost-benefit optimum with a different damage function, which is denoted the "2-degree-consistent damage function." This is implemented by increasing the first-order damage coefficient (the coefficients in the damage function in eq. [3]). I did this for two different cost-benefit solutions. In the first, the cost-benefit optimum produces a maximum temperature increase for the 2050–2250 period that is 2°C above the 1900 level. In the second, the cost-benefit optimum produces average temperature increases for the 2050–2250 period that are 2°C above the 1900 level. The rationale of the second approach is that many of the damages (such as ice-sheet melting and sea-level rise) are better approximated by a function of the average than the maximum temperature.

With this procedure, the damage coefficients would need to be increased by a factor 2.0 times larger than the DICE base estimates to produce a 2°C average target and by a factor of 4.4 times larger to be consistent with a 2°C maximum temperature. These functions assume that damages are 2.4% (DICE standard), 4.9% (2 °C average), and 10.6% (2% maximum) of output at 3°C warming. As an interpretive note, while the implicit damage coefficient associated with the Copenhagen maximum target is not impossibly high, no credible estimates in the literature exist to justify such high damage rates. However, the coefficient associated with the 2°C average is not outside the range of hypothesized damages estimates.

Table 1 shows estimates of the SCC for the two 2°C cases, which are $47.6 and $25.0 per ton of CO_2 in 2015 for the two cases of maximum and average. These are approximately 2.6 and 1.3 times the SCC with the standard parameters, respectively. Note that a policy that looks at the temperature average rather than the temperature maximum has a substantially lower SCC.

The conclusion here is as follows: economic models may not incorporate all the concerns of scientists and policy makers about the damages of climate change. The current damage estimates may significantly underestimate the damages because of impacts that are difficult to monetize (such as ecosystem effects) or concerns about catastrophic outcomes. If we increase the damage function so that the economic optimum coincides with the 2°C target, we find that the SCC rises sharply. The implicit damage function in the 2°C maximum target is much larger than any estimate from the damage literature.

2.2.3. *The Role of Discounting: A Simplified Example*

Estimates of the SCC differ greatly across different approaches. The wild card in calculations of the SCC is the discount rate. This point is intuitively obvious in a simple example. Assume that we linearize all the equations of the DICE model. Assume that all environmental variables have reached a stationary state where emissions, concentrations, population, temperature, and other physical variables are constant. Output, consumption, and damages are growing at constant rate g, and the goods discount rate is r. If we perturb emissions by 1 unit, this will cause a path of damages that is distributed over the distant future. For simplicity, assume that the damages start immediately but that the damage-output ratio declines at a decay rate of δ per year.

We can use the Ramsey equation to evaluate the SCC as a function of the key variables. The Ramsey equation provides the equilibrium rate of return in an optimal growth model with constant growth in population and per capita consumption without risk or taxes. In this equilibrium, the real interest rate (r) equals the pure rate of social time preference (ρ) plus the rate of growth of per capita consumption (g) times the consumption elasticity of the utility function (α). In long-run equilibrium, we have the Ramsey equation $r = \rho + \alpha g$. The key variable will be the "growth-corrected discount rate," $r - g$. Under our assumptions, $r - g = \rho + (\alpha - 1)g$. To simplify, assume that $\alpha = 1$, or that the utility function is logarithmic, which implies that $r - g = \rho$. (These long-run growth and discounting are used in the *Stern Review* and are approximately the case for the DICE model.)

Under these assumptions, the SCC is proportional to $1/(\rho + \delta)$. Assume that $\delta = 0.005$ per year, which is an approximate value for the decay rate of damages. Then, for alternative values of $\rho = 0.001$ (*Stern Review*), 0.015 (DICE), or 0.035 (the high discounting alternative examined here), and normalizing so that the SCC with DICE is \$20, we get values of the SCC at \$67, \$20, and \$10 per ton of emissions for the three discount rates. There is no mystery here. With long lags in the physical system and with damages far in the future, differences in discounting will lead to large differences in the SCC.

2.2.4. SCC with Alternative Discount Rates

We next present estimates of the SCC in the DICE-2013R model with alternative discounting assumptions. Row 5 in table 1 takes the parameters of the model and only changes the pure rate of social time preference (ρ) from 0.015 to 0.001 per year, the latter being the rate assumed in the *Stern Review*. The Stern uncalibrated run has a SCC of \$89.8 per ton of CO_2—almost five times the SCC with baseline discounting. (We do not show the SCC along the optimal path, but it is about one-third smaller because of the larger damages and lower discounting.)

Calculating the impact of alternative discount rates using the calibration approach of the DICE model is slightly more complicated than the case just given. If we just change the rate of time preference, then we will get rates of return on capital projections that do not match observed baseline market values. The sixth line in table 1 (*Stern Review*, recalibrated) shows the results of recalibrating the model to match market discount rates. To recalibrate with a rate of time preference using the *Stern Review* value ($\rho = 0.001$), we need to raise the rate of inequality aversion (from $\alpha = 1.45$ to $\alpha = 2.1$). The calibration keeps the rate of return at the baseline average for the first 30 years. Figure 4 shows the real return on capital in the four discounting cases, where the differences induced by the uncalibrated *Stern Review* run are evident.

The results of the recalibration are dramatic. If we maintain the super-low rate of time preference (at $\rho = 0.001$) but adjust inequality aversion to maintain baseline interest rates, the SCC is virtually indistinguishable from the baseline SCC. The reason is that the upward adjustment of the elasticity of inequality aversion offsets most of the downward adjustment in the pure rate of time preference.

A final case is row 7 in table 1 uses a high alternative discount rate. This scenario raises the pure rate of time preference to 3.5% per year. The rate of return is approximately 2 percentage points higher than the baseline, and the SCC is approximately one-third the baseline case. The SCC is also much lower.

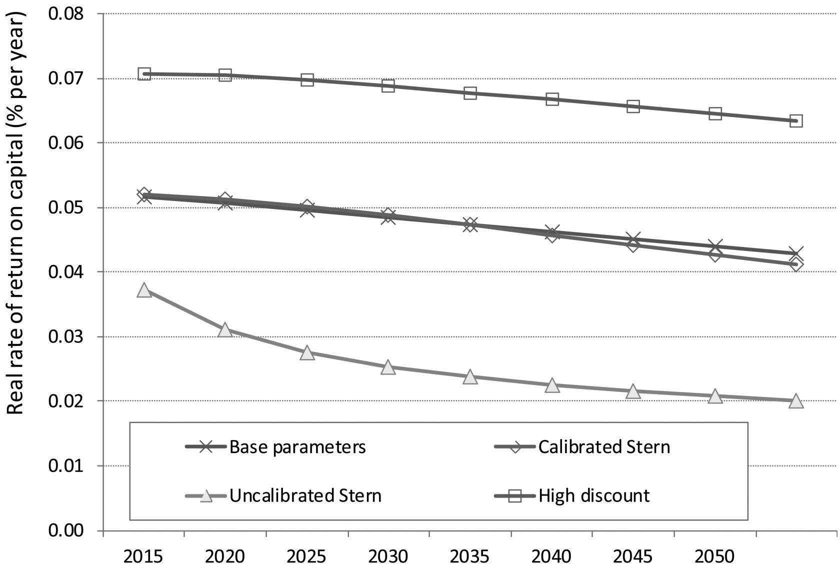

Figure 4. Rate of return on capital for alternative discount-rate scenarios. This figure shows the rates of return on capital in four scenarios. These are also the consumption discount rates because there are no distortionary taxes or regulations in the DICE model. A color version of this figure is available online.

Figure 5 is a scatter plot of the growth-corrected return on capital and the 2015 SCC. The growth-corrected discount rate, defined as the rate of return on capital minus the growth rate of output, uses the period 2010–2100 for the calculation. Figure 5 shows dramatically how the growth-corrected discount rate enters in a way suggested by the little algebraic example at the beginning of this section. The intuition is to recognize that damages tend to be proportional to the size of the economy in most studies on damages. In effect, if the goods discount rate is equal to the growth rate of output, this means that an increase in the damage-output ratio will be undiscounted. This shows why very low growth-corrected discount rates have very high SCCs.

2.2.5. Regional SCCs

Several models calculate the SCCs of different regions. These are the marginal impact of emissions on the economic welfare of a particular country or region. These estimates are important for understanding the problem of noncooperative behavior as well as the issues of using the SCC in domestic regulations, both of which are discussed later. Table 2 shows the global SCC for the baseline case (line 1 of table 1).

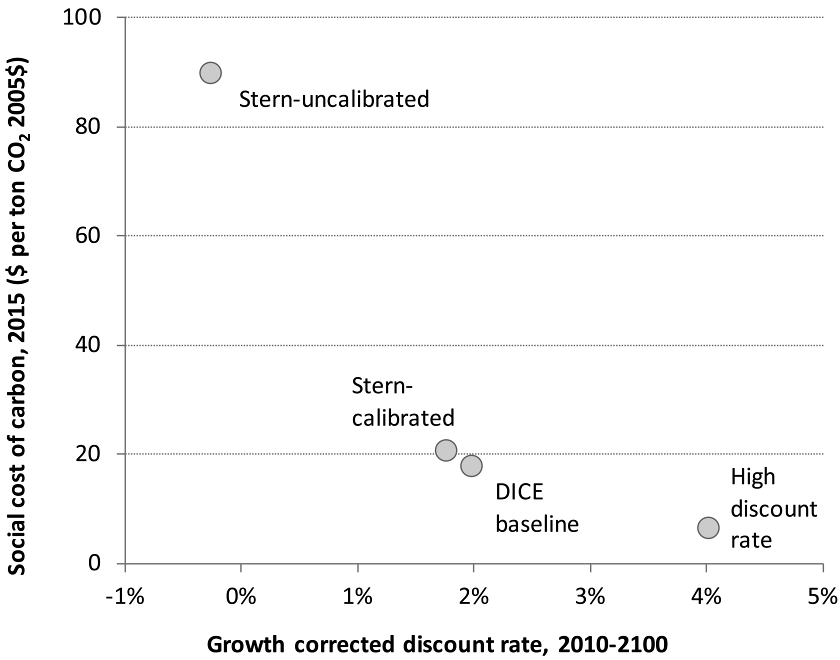

Figure 5. Social cost of carbon- and growth-corrected discount rate in DICE model. This figure shows the central role of the growth-corrected discount rate in determining the SCC. The growth-corrected discount rate equals the discount rate on goods minus the growth rate of consumption for 2010–2100. A color version of this figure is available online.

The regional estimates use a hybrid of the DICE-2013R model presented above and the regional estimates from the RICE-2010 model. More precisely, the estimates use the regional SCC from the 2010 model and adjust them proportionally so that the sum equals the global total for the 2013R version. Because the externality is a pure global public good, the global SCC exactly equals the sum of the regional SCCs. While the two models are not completely harmonized, experience with earlier versions of the models indicates that the ratios of the national SCCs to the global average are relatively stable.

China is estimated to have the highest regional SCC primarily because it has high future output. Several other regions are close to China in their region's SCCs. Damages are roughly proportional to discounted GDPs, with some countries deviating from this rule because of different climate impact sensitivities. Alternative estimates from the FUND and PAGE models are also shown in table 2. These numbers indicate that there is little consensus on the distribution of the SCC by region

Table 2. Region Social Costs of Carbon

			Percent of Global SCC		
Region	Emissions (Billions of Tons CO_2, 2005)	SCC (2015)	RICE 2010 (U)	FUND 2013	PAGE 2011
United States	6.11	1.94	10	17	7
European Union	4.14	2.32	12	24	9
Japan	1.28	.43	2	3	NA
Russia	1.54	.18	1	10	NA
Eurasia	.92	.16	1	NA	NA
China	6.14	3.02	16	8	11
India	1.48	2.21	12	5	22
Middle East	2.14	1.89	10	NA	NA
Africa	.69	2.09	11	6	26
Latin America	1.54	1.30	7	NA	11
OHI	1.93	.74	4	NA	NA
Other	1.38	2.29	12	NA	NA
Weighted country average		1.92			
Global	29.30	18.6	100	100	100

Note.—This table distributes the global SCC by region. It uses the global estimate of the SCC from DICE-2013R and the regional distribution from RICE-2010. The weighted country average is the average of the country-specific SCCs. The results from other studies indicate that the regional distribution is poorly understood. FUND results are from Anthoff (2013) and PAGE results are from Hope (2011). Note that the regions do not always conform exactly across the models. **OHI = other high-income countries; NA = not available**.

except that no region dominates the total. The different estimates reflect the poor understanding of the impacts by region.

The estimated SCC for the United States is \$1.94 per ton CO_2 (2015 in 2005 prices), or 10% of the global SCC. We will discuss the implications of this estimate below because it is a small fraction of the SCC used in regulatory impact analyses for the United States.

2.2.6. Regional SCCs and the Noncooperative (Nash) Equilibrium Carbon Price

The regional numbers are useful in providing an estimate of what countries would abate in a noncooperative equilibrium in which there was no reaction among different regions. For example, if each region sets its own regional carbon price equal to its regional SCC, the weighted average price would be \$1.9 per ton of CO_2, or about 10% of the global SCC (see the penultimate entry in col. 2 of table 2). Similar results have been found in earlier studies (see Nordhaus and Yang 1996; Bosetti, Massetti, and Tavoni 2007; Yang 2008).

3. ALTERNATIVE ESTIMATES

There have been many estimates of the SCC in different models. Those who would like to apply these to energy or climate policy face the daunting task of sorting through the different estimates and deciding which seem most appropriate. I discuss alternatives and compare them with the DICE-model estimates in this section.

3.1. Back to Basics

Estimates of the SCC come in different varieties. The primary sources are integrated assessment models. An examination of the literature finds that there are three models that are the basis of virtually all estimates. One is the DICE/RICE family of models, discussed above. A second is the PAGE model, originating with the work of Chris Hope of Cambridge University, which has several vintages. The third is the FUND model, developed by Richard Tol of Sussex University, with David Anthoff of the University of California, Berkeley, a coauthor of the current version.

Another set of SCC estimates come as "variations on a theme" of one of the three models. Some studies take one of the models and change parameters or do sensitivity analyses. For example, the *Stern Review* based its quantitative modeling and estimates of the SCC on a version of the PAGE model that varied primarily the discount rate in a fashion discussed in the last section. Some studies are reviews. Others are compilations of studies, which include primary models, variations of models, and reviews of models. One of the most influential of the estimates, prepared by the US Interagency Working Group and used in US regulatory analyses (discussed below), relied on their own runs of the three models discussed in the last paragraph.

Yet further estimates come from stylized models that simplify the structure of the economic-climate nexus. An excellent example of this is Golosov et al. (2014). They present a dynamic stochastic model with a climate externality. There are several insights from the model about important determining factors. For example, they derive a simple formula for the SCC that depends only on four factors: (i) the size of the global economy, (ii) discounting, (iii) the damage elasticity, and (iv) carbon depreciation in the atmosphere. While this is useful, the last three factors are likely to be variables rather than constants; moreover, the damage elasticity is extremely complicated to calculate. A similar but more complicated SCC formula is derived in Li and Nordhaus (2013). These stylized approaches cannot capture important aspects, such as the lags in geophysical and economic systems, as well as declining discount rates or nonstationarities. Moreover, analysts want to understand the logic behind a model and its correspondence to more detailed scientific models, and those are hidden in a stylized model.

As an example of the small number of independent analyses of the SCC, Li and Nordhaus (2013) did a systematic study 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 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 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.

3.2. The FUND Model and PAGE Model Estimates

In light of the central importance of the three standard models, I will briefly describe the other two and then provide a comparison of estimates of SCC from them. FUND and PAGE share the basic integrated structure of the DICE/RICE models in linking output, emissions, concentrations, temperature, and damages. The similarity stops there.

The FUND model (Climate Framework for Uncertainty, Negotiation, and Distribution) 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. There are 16 major regions. 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 1 year. The source code, data, and a technical description of the model are public, and the model has been used by other modeling teams (http://www.fund-model.org).

The PAGE model (Policy Analysis of the Greenhouse Effect) 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 greenhouse gases; 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.

Two features of FUND and PAGE are worth highlighting. First, the models are output-based, not utility-based. The metrics for measuring monetary values of output, impacts, and abatement over space and time are in constant US dollars, and they are evaluated using discounted output or consumption.

Second, the models have elaborate treatment of uncertainties. However, most of the distributions of the uncertain variables are judgmental and difficult to assess. On occasion, the specification has produced extreme results, and the interaction of the many uncertainties with highly nonlinear dynamic models is not fully understood.[2]

In sum, the three standard models used for calculating SCCs are very different in their structures, assumptions, treatments of uncertainty, and economic modelings. These differences mean that there is no easy way to judge the relative reliability of the models or their results.

3.3. Meta-analysis of Different SCC Estimates

In deciding on the appropriate SCC, policy makers may want to examine systematic surveys of different estimates. One approach is a "meta-analysis" of existing studies, of which a leading example is Tol (2008). This study collected 211 estimates of the SCC from 47 studies. The results were run through several statistical filters, with the mean SCC of \$34–\$42 per ton of CO_2 and median of \$5–\$25 per ton CO_2, depending upon the aggregation procedure.[3]

While it is valuable to examine alternative estimates, it is misleading to call this a meta-analysis in the usual sense.[4] The basic structure of a meta-analysis is that there are several samples from a population, and those samples can be combined to estimate a parameter or other statistics more efficiently. The standard example would be a clinical trial with multiple sites to test the effect of a treatment. The effects of the treatment can be more efficiently estimated in a meta-analysis by combining the observations from the different sites.

We can see from this description why a classical meta-analysis cannot be properly used to combine different estimates of the SCC. First, as we saw from the description of the sources of the SCC in the last section, the different studies are not independent samples from some underlying distribution. For example, the Tol sample includes studies that take a model and change some parameters. An example is the SCC estimate in Cline (1997), which used the DICE model and changed the discount rate. Interpreting this estimate is particularly complicated because it was primarily used to defend a particular view on discounting. A similar difficulty is the estimate from the *Stern Review* discussed above. Second, there is no clear mechanism by which the data are generated. Third, there is no sense in which there is a sample size applied to a given study. Yet a fourth problem arises when a meta-analysis includes surveys or other meta-analyses. For example, Tol includes Clarkson and Deyes

2. For example, an earlier version of the FUND model had an assumption that led to one of the uncertain variables being a noncentral Cauchy distribution, so the theoretical value of the SCC was unbounded (see Ackerman and Munitz 2012).

3. The year of emissions and price level are not provided, but in other work, Tol has used 1995 dollars.

4. A useful reference for the social sciences is Hedges and Olkin (1985).

(2002), which is a review of earlier estimates and included other studies included in the Tol meta-analysis. So the meta-analysis has triple-counted some studies included in the review.

The main conclusion on the use of meta-analyses for the SCC is that these definitely do not meet the standard requirements for a statistical meta-analysis and should be treated with caution. They would be more accurately described as research syntheses or quantitative summaries of the literature that show some of the important factors driving the estimates. The results are especially questionable because they double-count and even triple-count different model estimates.

3.4. The US Interagency Working Group Estimates

A particularly influential and important set of estimates of the SCC was provided by the Interagency Working Group on Social Cost of Carbon, US Government, hereafter "Interagency Working Group" or "IWG" (IWG 2010; Greenstone, Kopits, and Wolverton 2013). This was updated in IWG (2013).

The original analysis was developed by technical experts from numerous agencies of the US federal government,[5] 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" (IWG 2010, 1). The 2013 estimates update the models but use the same methodology as the 2010 estimates. The analysis has been used for rule making by the US government, and the application of the SCC in those rules is considered in a later section.

The procedure used by IWG was particularly interesting because it obtained the three standard models used to calculate the SCC and developed a harmonized analysis by standardizing two sets of input parameters. The equilibrium temperature climate sensitivity, or TSC (temperature sensitivity coefficient; see eq. [7] and eq. [8]) was harmonized using the Roe-Baker analysis (Roe and Baker 2007) with a mean equilibrium TSC of 3.5°C.[6]

5. The participants were the Council of Economic Advisers, Council on Environmental Quality, Department of Agriculture, Department of Commerce, Department of Energy, Department of Transportation, Environmental Protection Agency, National Economic Council, Office of Energy and Climate Change, Office of Management and Budget, Office of Science and Technology Policy, and Department of the Treasury.

6. One strange feature of the treatment of the TSC by the IWG should be noted. The IWG assumed a "most likely value of about 3°C." The IWG harmonized the Roe-Baker distribution by setting the median at a target level of 3.0°C, and for the Roe-Baker distribution this implied that the mean TSC was 3.5°C. This choice of median rather than mean was casually thrown out in a spirit that it did not much matter whether the central tendency was mean, median, or mode. This procedure is indefensible, as we will see below.

Second, the IWG used five sets of output, population, and emissions trajectories based on a model comparison study (the EMF-22 runs discussed above). It then took the resulting changes in output and consumption and calculated the SCC using discount rates of 2.5%, 3%, and 5% per year. This procedure is valuable because it is to my knowledge the only SCC estimates that have undertaken partial harmonization of different models.

Third, the IWG used an output-based method, while the DICE model uses a utility-based approach. The two will give equivalent results if the discount rate on goods is the same. However, in virtually all models with endogenous discount rates, the discount rate is declining over time, while the IWG assumes a constant discount rate. The rationale for a declining discount rate is explained in Arrow et al. (2013).

Table 3 shows the results of the IWG estimate and compares them with the DICE-model calculations presented above. Here are some of the highlights of table 3. All figures in table 3 are the global SCC for 2015 in 2005 US dollars.

- Begin in panels A and B, which are the results of the IWG calculations (2010, 2013). These use the IWG estimates and discounting methodology. The 2013 estimates are revised upward substantially for the FUND and PAGE 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.
- Panel C adopts the IWG assumption of a constant discount rate but imbeds this in the DICE model so that it is generated endogenously and used consistently. In these calculations, the pure rate of time preference is set equal to the goods discount rate, and the consumption elasticity is set equal to zero. This approach assumes linear utility, that is, that there is no inequality aversion. It is consistent with the approach of projecting output and damages and not relying on utility calculations.
- The first line of panel C is most comparable to the IWG's 2013 estimates in line 1 of panel B. The DICE-2010 constant-discount-rate-scenario is virtually identical to the comparable IWG calculation, which indicates that the DICE output and emissions projections are close to the average used in the IWG scenarios. The second line of panel C uses the RICE-2013R model with the IWG TSC average of 3.5. It is 40%–50% higher than the IWG estimate of the DICE model largely because of the upward revision of output and emissions in the DICE-2013R model.
- The last line of panel C uses the DICE-2013R model and the 2013R TSC, which is 2.9°C. The bottom line here is that the DICE-2013R model estimates (including the DICE TSC) are somewhat higher than the latest IWG estimates for the DICE model.
- Panel D moves to the DICE-2013R model's utility approach from the output approach of the IWG. This uses the DICE model baseline

Table 3. Estimates of the Social Cost of Carbon for 2010 from US Interagency Working Group and Comparison with Alternative Model Estimates

Model and Scenario	Constant Discount Rate on Goods 5%	4.2%*	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
C. DICE model estimates: working group methodology (constant discount rate):					
DICE-2010 (TSC = 3.5)	10.4		16.8	31.1	46.2
DICE-2013R (TSC = 3.5)	14.8		25.8	50.0	72.5
DICE-2013R (TSC = 2.9)	12.3	18.5	21.0	40.2	58.0
D. DICE 2013R model estimates (DICE model declining discount rate):					
DICE-2013R (baseline)		18.6			

Note.—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. Panel C shows the results of the DICE-2013R model using a constant discount rate and a consistent modeling framework as described in the text. The first two lines use the Working Group average TSC of 3.5, while the third line uses the DICE-2013R TSC of 2.9. Panel D uses the standard endogenous declining discount rate of the DICE-2013R model. With an average discount rate to 2100 of 4.2% per year, the estimates are the same as the estimates using the constant discount rate approach in panel C.

* Note that the Interagency Working Group did not present estimates for a 4% or 4.2% discount rate. These numbers for the Interagency Working Group are interpolated between the 3% and 5% estimates to compare with other estimates. The 2015 estimates are interpolated from the given figures in the 2010 and 2013 reports.

economic and geophysical estimates and TSC and the standard declining discount rate on goods (seen in fig. 4). The estimated SCC is the same as the IWG's constant-discount-rate approach for a constant discount rate of 4.2% per year.

- What is the bottom line? These results indicate that the revised IWG and the revised DICE estimates are virtually identical conditional on the discount rate. (Compare the average of the three models in the line 4 of panel B with line 3 of panel C.)

Taking all these results together, five major points stands out. First, the most recent IWG estimates of the SCC are close to the 2013R DICE model conditional on the discount rate. While there are numerous methodological and economic differences, the final products are within 10% of each other.

Second, there remain substantial differences in panels A and B of table 3 among the models—even after harmonizing for emissions, output, population, and temperature sensitivity. While the IWG was unable to determine the source of the differences, it is likely that a major component is the damage function. For example, FUND has negative damages up to 2°C, which suggests why the FUND SCC is very low (in the 2013 estimate) or negative (in the 2010 estimate) at high discount rates. The PAGE model assumes catastrophic damages in the tails, which leads to substantially higher estimates of the SCC in the most recent vintage. These results suggest that a major remaining task is to compare models with a harmonized damage function.

Third, a remaining issue in the IWG methodology is the risk of making implicit assumptions that would be questionable if made explicitly. One example was the decision to make independent assumptions about economic growth and discounting. Virtually all economic models would link the two, but the IWG took them as independent. One result is that the growth-corrected discount rates differ greatly across scenarios. At the low end of the discount range (2.5%), three of the five scenarios (IMAGE, MESSAGE, and 550 ppm [parts per million] average) have negative growth-corrected discount rates over the period 2000–2050; this assumption can induce unbounded present values if extrapolated. Additionally, the IWG generally relied on US rates of return on investment but then calculated global welfare and damage estimates. The underlying problem is that the harmonization undertaken by the IWG took place outside of the models rather than inside the models. That is, the modifications and harmonizations were made externally and were not linked to structural parameters in the models. In future work, it would be better to integrate the underlying assumptions.

Fourth, the IWG makes much of including an elaborate Monte Carlo exercise in the temperature sensitivity coefficient (TSC). The IWG did not indicate whether uncertainty about the TSC makes any difference for estimates of the SCC. While that question will differ across models, I have run a simple experiment for the DICE-

2013R model estimating the impact of a mean-preserving spread of TSC on the SCC. The result is that the value of the SCC is virtually unaffected by uncertainty about the TSC. For example, a binomial distribution with a standard deviation of 1°C has a SCC of 0.7% higher than the certainty equivalent. At least for the DICE model, introducing uncertainty about the temperature sensitivity has essentially no impact on the SCC.

Finally, the role of the discount rate is again central to the differences in the estimates of the SCC. All the alternative estimates show the continuing difficulties from lack of clarity on how to discount future damages.

4. CRITIQUES AND MAJOR OPEN ISSUES FOR THE SCC

The concept and estimates of the SCC have been widely criticized on several grounds. The criticisms fall into two general categories. First are those holding that the models exclude major dangerous or potentially catastrophic impacts of climate change. In these, the SCC is thought to be underestimated, perhaps dramatically so. A second category holds that the models and estimates are so flawed that the SCC estimates are worthless. I address each of these in turn.

4.1. Tipping Points, Fat Tails, and Potential Catastrophes

There have been several critiques of the SCC calculations in the DICE model (as well as FUND and PAGE), arguing that the models omit significant issues. For a particularly sharp critique, see Ackerman and Stanton (2010, 2012).

One of the most vexing issues in climate change is the potential for abrupt, irreversible, or catastrophic climate change (see National Research Council, Committee on Abrupt Climate Change 2002; Lenton et al. 2008; IPCC Extremes 2012; IPCC Fifth Assessment, Science 2013). Estimates for the economic costs of such scenarios are included 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 there is virtually no basis for determining the size, timing, or probability of such events or the economic damages that would ensue. Work on investigating the impact on policy in the DICE model of thresholds with and without irreversibilities is underway, but this project involves many scientific, economic, and algorithmic obstacles.

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 (see the symposium in *Review of Environmental Economics and Policy*, summer 2011, for several articles, as well as 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 SCC may be unbounded or extremely large.

The impact of catastrophic damages or a fat-tailed distribution of important parameters can have major impacts on the SCC. Take as a simple example a case with catastrophic damages above a threshold temperature increase T^*. To be concrete, assume that the catastrophic damage function is highly convex and takes the form $D/Y = 0.01(T/T^*)^8$ (this being the eighth power, not a footnote). With a threshold of $T^* = 2°C$, this leads to damages equal to 20% of output at 3°C and 72% of output at 4°C. While useful for illustrative purposes, currently no plausible damage estimates would approach these numbers.

Table 4 shows the SCC with and without abatement policies for different thresholds. An important and generally neglected feature of catastrophic damages is that the "catastrophic" social cost of carbon depends critically on whether adequate policies are taken. For the threshold of 2°C and no climate change policies, the SCC is $1,046 per ton CO_2. However, when optimal policies are taken immediately, the social cost of carbon is only $54 per ton of CO_2. This result—that fat tails or catastrophic damages generally have extreme results on the SCC only when good policies are not taken—is a warning for both policy and analysis. (For a more detailed discussion and further examples, see Nordhaus [2012].)

4.2. Warming and Modeling Skeptics

The issues surrounding the debates about the existence, extent, and causes of climate change are beyond the scope of this article. They are fully addressed in the IPCC Fifth Assessment, Science (2013), which presents a detailed review of the science and evidence. This review indicates that the basic science and trends are well established but that there remain vast uncertainties about the scope, scale, and regional dimensions of climate change.

Criticisms aimed specifically at IAMs and the SCC are exemplified by a recent article by Pindyck (2013). He concludes that IAMs "are of little or no value for

Table 4. Social Cost of Carbon with Catastrophic Threshold, with and without Climate Policy

	Social Cost Carbon (2015 in 2005$)	
Threshold Temperature, T^*	With Optimal Policy	With No Policies for 100 Years
1.5°C	125	1,495
2°C	54	1,046
3°C	24	197
4°C	19	33

Note.—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.

evaluating alternative climate change policies and estimating the SCC" (870). It will be useful to review the Pindyck critiquem as it states, albeit in an exaggerated form, many of the reservations about calculations of the SCC.

Pindyck's attack on IAMs touches both empirical and conceptual issues. Beginning with the empirical questions, he highlights (1) the social preference function, particularly the discount rate, (ii) the damage function, (iii) the potential for catastrophic changes, and (iv) the temperature sensitivity to greenhouse gas increases.

The centrality of these issues for both IA models and the SCC has been clear for many years. Let us begin with the issue of discounting. Nordhaus (1991) and Cline (1992) showed the sensitivity of the SCC to the discount rate. The dilemma of the prescriptive versus the descriptive views was described in an excellent review in an early IPCC chapter (Arrow et al. 1996). The role of discounting was carefully addressed in a series of studies in a volume edited by Portney and Weyant (1999). I showed above the role of the discount rate in affecting the calculations in the DICE-2013R model. Unsettled issues about discounting are not an excuse for discounting the SCC.

A second important issue discussed by Pindyck is the issue of the catastrophic impacts of climate change. Pindyck states that "the models ignore the possibility of a catastrophic climate outcome" (869). This is simply wrong. The DICE model contains an adjustment for nonmonetized and potentially catastrophic damages; the PAGE model has a specific treatment for catastrophic damages and for the uncertainties of those; the FUND model has elements of catastrophic damages, such as sea-level rise and agricultural losses. There have been many studies of the impact of catastrophic impacts and its implications for the SCC (as described earlier in this section).

Pindyck continues, "IAMs cannot tell us anything about catastrophic outcomes" (869). Well, of course they cannot. The issue is not "the models." The issue is that scientific understanding about the likely trajectory and impact of catastrophic impacts is still highly conjectural. For example, natural scientists are highly uncertain about the threshold and timing of the disintegration of the Greenland ice sheet. The latest IPCC review of the issue concluded that warming beyond a threshold "greater than 2°C but less than 4°C" of global warming "would lead to the near-complete loss of the Greenland Ice Sheet over a millennium or longer" (IPCC Fifth Assessment, Science 2013, TS-37). This provides little guidance for IAMs.

Another important uncertain factor is climate sensitivity to CO_2 increases. The recent IPCC review concludes that "1.5°C–4.5°C is assessed to be the likely range of equilibrium climate sensitivity"—this being exactly the range found in the Charney Report of 1979 (National Research Council 1979, TS-33).

Yet a further insight on catastrophic damages comes from studying the IPCC Fifth Assessment Report. This report reviews several components of the earth system susceptible to abrupt changes. These include the strength of the Atlantic Meridional Overturning Circulation, clathrate methane release, tropical and boreal forest dieback, disappearance of summer sea ice in the Arctic Ocean, long-term drought, and monsoonal circulation. The report concluded that "in general there is low confidence and little consensus on the likelihood of such events over the 21st century" (TS-35). Without reliable estimates of the geophysical aspects, economic models can hardly make reliable estimates about the impact and costs of catastrophic, abrupt, or irreversible events.

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, nonlinear, 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. The idea of the social cost of carbon is a natural consequence of considering the economics of a global externality as well as policies to correct for this market failure.

IAMs have improved our understanding of the importance of cost effectiveness, the value of market instruments as compared to command and control, the value of information about new technologies and improved science, the importance of broad participation, the potential volatility of cap-and-trade systems, and the costs of alternative approaches to reducing emissions. Perhaps the most important contribution is the ability of systematic modeling to highlight the critical issues (such as discounting and damages) and to bring new findings into account in an orderly fashion.

A useful analog is the concept of the fiscal multiplier in macroeconomics. Even after decades of research, economists are unsure about the exact value of the fiscal multiplier in recessions. But that does not imply that fiscal policy or macroeconomic analysis is useless. Similarly, even though the IA models and estimation of the SCC raise daunting scientific and economic issues—some unresolved—this does not diminish their importance for climate change economics and policy.

5. CURRENT APPLICATIONS OF THE SCC IN CLIMATE CHANGE POLICIES

Estimates of the SCC are a critical ingredient in climate change policy. They currently play two roles. At the broadest level, they provide guidance as to the appropriate level of emissions controls or carbon pricing in policies to reduce emissions either at a national or an international level. For example, policy makers can use estimates of the SCC to determine the optimal carbon taxes or the target rate of emissions reductions under a cap-and-trade regime.

A second application is for rule making where countries do not have comprehensive policies covering all GHGs. In this context, regulators might use the SCC in a calculation of social costs and benefits of policies involving energy or climate-affecting decisions. I will illustrate this for the United States, although parallel policies have been used in the United Kingdom and the European Union.

Under US law and practice, major regulations must be accompanied by a "regulatory impact analysis," or RIA.[7] 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 greenhouse gas (GHG) emissions were not included in monetary estimates of costs and benefits. As a result of a 2007 Supreme Court decision, the US EPA (Environmental Protection Agency) was required to regulate CO_2 and other GHG emissions as "air pollutants" under the Clean Air Act. After an initial set of uncoordinated estimates, the US federal government established the Interagency Working Group that reviewed and determined a set of estimates of the SCC to be used in federal regulations (IWG 2010). I discussed the methods and results of the IWG in a previous section.

As of January 2014, there were 58 proposed or final rules that have used the SCC in calculating benefits. Table 5 provides a list of proposed or final regulations for the United States through 2012.[8] In addition to the agency, date, and name of the rule, the table shows both the total benefits and the share of total benefits from reducing CO_2 emissions. The rules shown are estimated to be of great significance, with total benefits in the rules over the 3 years totaling \$520 billion. The CO_2 benefits totaled \$92 billion. The last column shows the percent of total monetized benefits that come from including climate benefits. Particularly important are regulations such as fuel economy standards and new stationary sources (primarily power plants).

It is useful to illustrate the calculations for a specific rule, the 2012 standard for new cars and light trucks as estimated in the RIA. (For this calculation, we provide EPA/DOT's preferred methodology, which includes fuel savings; see EPA, Vehicles 2010.) Over model years 2017–25, the regulation is estimated to cost \$150 billion. Fuel savings and other benefits realized by owners are estimated to total \$556 billion, so the regulation is estimated to benefit owners even without any external considerations. Pollution benefits total \$52 billion, of which \$47 billion are from reduced CO_2 emissions at a SCC averaging \$35 per ton of CO_2 and \$5 billion are from reduced local air pollution. So for this regulation, it would pass a benefit-cost test primarily on the basis of behavioral benefits (consumers overdiscounting fuel

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7. The source of regulatory analyses dates to the 1970s. The current relevant rule is Executive Order 12866, 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).

8. I am grateful to Elizabeth Kopits of the Environmental Protection Agency for providing the total list and the shorter list, which have benefits estimates in table 5.

savings). It would not pass a benefit-cost test on the basis of external costs alone. Roughly 90% of the external benefits are CO_2 emissions.

Regulations generally set the cost of externalities at the marginal damage of a pollutant. For example, in each of the cost-benefit studies listed in table 5, the climate change costs are calculated using the SCC without any adjustments. Three important issues that arise are the adjustments due to leakage from incomplete harmonization, the adjustments for existing distortions of the tax system, and the issue of whether to apply global or domestic SCC in regulations.

5.1. Leakage and Incomplete Harmonization

The first adjustment would need to recognize that the SCC is applied to only a small part of the national economy and the global economy, and this fact will generally lead to a "leakage discount." For example, a rough estimate is that the implicit carbon pricing through regulations that include the SCC in the United States applies to less than one-tenth of new tangible investment and to virtually no existing capital. The importance of incomplete harmonization is recognized in the extensive literature on "leakage," but the implications of leakage for policy applications of the SCC in government analysis and regulation have been largely ignored. There is no mention of greenhouse gas "leakage" in any of the major EPA rule makings or in the US Working Group calculations of the SCC.

An analysis in Baylis, Fullerton, and Karney (2014) shows that the extent of leakage depends on the substitution properties in production and consumption as well as on the carbon intensity of the different sectors. An example using the abatement structure of the DICE model will illustrate the point.

Suppose that national output is produced with two goods, A and B, with equal CO_2 intensity and constant costs of production. The two goods have identical constant elasticities of substitution in demand (σ). Marginal damages are assumed to be \$20 per ton of CO_2 and are invariant to the level of emissions because we are dealing with a stock pollutant. The regulatory authority can apply a tax on sector A but cannot tax sector B. Sector A might be automobiles, while sector B is air travel. Assuming that the tax on CO_2 in sector B is zero, we can calculate the optimal tax in sector A. With constant costs of production in each sector, the optimal tax on sector A will be \$20 per ton with no substitution ($\sigma = 0$), while it would be zero with perfect substitution ($\sigma = \infty$). A calculation shows that the optimal tax in sector A would be about \$2 per ton (or 10% of the SCC) if the $\sigma = 4$, while it would be about \$15 per ton (or 75% of the SCC) if the $\sigma = 1/2$.

However, as Baylis et al. show, the result is sensitive to the assumptions. Take an alternative where the emissions intensity is much higher in the regulated than the nonregulated sector, as, for example, with power plants. Here, the optimal tax would be very close to the SCC. All of this is quite intuitive, even if the exact magnitudes will depend upon the details of the technology and preferences. Unfortunately,

Table 5. Data for Major US Regulations Including a Social Cost of Carbon in Estimating Benefits

Agency	Rule	Date	Total Benefits (Billions of $)	Total CO_2 Benefits (Billions of $)	CO_2 as Share of Total Monetized Benefits (%)
EPA	Final Cross-State Air Pollution Rule (CSAPR) (vacated by courts, in review)	8/8/2011	183.3	.6	.3
EPA/DOT	Final Light Duty Vehicle GHG Standards (2017–25)	10/15/2012	126.0	46.6	37.0
EPA/DOT	Final Light Duty Vehicle GHG Standards (2012–16)	5/7/2010	58.4	17.0	29.1
EPA	Final MATS Rule	2/16/2012	57.7	.4	.6
EPA	Final Boiler MACT (CO2 disbenefits)	12/20/2012	42.5	(.0)	−.1
EPA	Proposed GHG Standards for New Stationary Source EGUs	4/13/2012	21.4	11.0	51.3
EPA	Final Cement NESHAP/NSPS (CO2 disbenefits) (under reconsideration)	9/9/2010	11.5	.0	.2
DOE	Final ECS for Residential Refrigerators and Freezers	9/15/2011	9.9	9.0	91.0
EPA/DOT	Final Medium-Heavy Duty Vehicles GHG Standards	9/15/2011	7.3	5.7	78.1
DOE	Final ECS for Fluorescent Lamp Ballasts	11/14/2011	1.3	1.3	96.6
DOE	Final ECS for Residential Water Heaters	4/16/2010	.2	.2	95.3
DOE	Proposed ECS for Battery Chargers and External Power Supplies	3/27/2012	.1	.1	94.1
DOE	Final ECS for Small Electric Motors	4/9/2010	.1	.1	95.2
DOE	Final ECS for Residential Dishwashers	5/30/2012	.1	.1	96.6
EPA	Final Sewage Sludge Incinerators NSPS/Emissions Guidelines (CO2 disbenefits)	3/21/2011	.0	(.0)	−.3
EPA	Proposed (supplemental) NESHAP: Mercury Cell Chlor-Alkali Plants Amendments	3/14/2011	.0	.0	21.1

Note.—The estimates in this table generally exclude fuel or energy savings from benefits. They are based on the government's central SCC value from the 2010 study of $22 per ton for 2015 reductions in 2005$. EPA = Environmental Protection Agency; DOT = Department of Transportation; DOE = Department of Energy; GHG = greenhouse gases; MATS = Mercury and Air Toxics Standards; NESHAP = National Emission Standards for Hazardous Air Pollutants; NSPS = New Source Performance Standards; ECS = Energy Conservation Standards; NESHAPS = National Emission Standards for Hazardous Air Pollutants. Data were provided by the staff of the US Environmental Protection Agency.

estimating the optimal second-best carbon price in the face of incomplete harmonization is extremely complex.[9] This is an important piece of unfinished business.

5.2. Existing Tax Distortions

A second qualification concerns existing economic distortions, particularly those involving taxes. As has been extensively discussed in the environmental literature (e.g., see Bovenberg and Goulder 1996), the presence of existing tax distortions will generally lead to an optimal pollution tax below the ideal Pigovian tax; for conciseness, I will call this the "distortion discount." In the present context, this implies that an optimal carbon tax would be below the SCC. The reason is that imposing a carbon tax raises the prices of goods and increases the tax wedge between taxed and nontaxed sectors. The extent of the divergence is extremely complicated, as has been shown in Barrage (2013). Using the economic and climate parameters of the DICE model combined with a simple tax system, Barrage finds a range of distortion discounts up to one-third, with the size of the discount depending upon the structure of existing tax distortions as well as the way the revenues are used or recycled (also see Jorgenson et al. 2013).

The distortion discount will be even larger when climate policies are implemented with regulatory emissions limitations rather than taxes. Or, more generally, as Fullerton and Metcalf (2001) show, a discount would apply when policies create rents that are not appropriated by the government. This implies that a distortion discount should apply to cap-and-trade regulations in which allowances are allocated. Indeed, a distortion discount would appear to apply to each of the regulations shown in table 5. The reasoning behind this result is that rent-creating regulations increase the wedge between the taxed and nontaxed sectors just as pollution taxes do, but, raising no revenues, they cannot reduce distortions by reducing other distortionary taxes. In an analogous environmental market, Goulder, Parry, and Burtraw (1997) showed that the costs of reducing sulfur dioxide emissions under Title IV of the 1990 Clean Air Act could have been reduced by about 25% if the tradable permits had been auctioned (and revenues recycled) rather than given out for free. Under some conditions, the distortions are greater than the environmental benefits.

At present, there are no reliable estimates of the distortion discounts that should be applied to regulations that apply the SCC, but they are clearly larger than the tax distortion discounts, such as calculated by Barrage cited above.[10] The EPA has reviewed the issue of tax distortions and concluded that it was "prema-

9. See Copeland and Taylor (2000) for an analysis showing how international trade introduces additional complexities. Felder and Rutherford (1993) show that leakage can be negative if carbon taxes affect fuel switching to high-carbon-intensity fuels.

10. This is discussed in Goulder, Parry, and Burtraw (1997), Goulder et al. (1999), Parry, Williams, and Goulder (1999), Fullerton and Metcalf (2001), and Murray, Keeler, and Thurman (2005).

ture" to make any adjustment "given the current state of knowledge and existing doubts about current results and their broad applicability" (Murray, Thurman, and Keeler 2000). Here, apparently, the EPA has decided that "no number is better than an uncertain number," an approach seldom followed in its regulatory philosophy.

5.3. National versus Global Damages in a Regulatory Framework?

In most regulatory proceedings, a benefit-cost analysis would compare the national benefits and the national costs. For global externalities, the question arises as to the domain of the economic analysis. Should the costs, benefits, and discount rates refer to the United States alone or to the entire globe?

The US regulatory framework is clear that the focus should be domestic. In the Office of Management and Budget's (OMB's) guidance to federal agencies on the development of regulatory analysis, it states that the "analysis should focus on benefits and costs that accrue to citizens and residents of the United States. Where you [i.e., the regulator] choose to evaluate a regulation that is likely to have effects beyond the borders of the United States, these effects should be reported separately" (OMB 2003).

This question arose in the determination of whether CO_2 endangered public health or welfare and should therefore be regulated under the Clean Air Act (the "endangerment" finding). The EPA stated that it considered foreign impacts only insofar as they had an effect on domestic health and welfare: "EPA's consideration of international effects for purposes of determining endangerment is limited to how those international effects impact the health and welfare of the US population" (EPA, Endangerment 2009).

The reasoning behind the endangerment finding was inconsistent with the application of the SCC in regulations. In applying the SCC, EPA has used a domestic measure of costs and a global measure of benefit; benefits include foreign as well as domestic benefits of emissions reductions. This practice was based on the recommendations of the US Interagency Working Group:

> The interagency group concluded that a global measure of the benefits from reducing US emissions is preferable because the climate change problem is highly unusual in at least two respects. First, it involves a global externality. . . . Consequently, to address the global nature of the problem, the SCC should incorporate the full (global) damages caused by GHG emissions. Second, climate change presents a problem that the United States alone cannot solve. Even if the United States were to reduce its greenhouse gas emissions to zero, that step would be far from enough to avoid substantial climate change. (IWG 2010)

These reasons do not address the legal or economic grounds for using global benefits in a cost-benefit analysis. The first reason is a simple statement about the global nature of climate change. The second is a factual statement about the inability of a single country acting alone to solve the problem.

The legal question of whether global benefits can or should be used in US regulatory framework is unsettled. The answer depends in part on the statutory framework because the requirements for balancing costs and benefits differ across statutes.

From a practical point of view, the use of global rather than national valuations would be a major departure for most countries. In almost all areas, countries design policies that benefit their own residents and (except where there are treaties or major harmful spillovers) ignore the impacts on other nations. Whether we examine trade, agriculture, military, tax, or macroeconomic policies, there are few cases where the welfare in other regions weighs as heavily as that of citizens and residents. To take an extreme example, income transfers to low-income persons in the United States average $3,000, while those outside the United States average about $3 per person.[11] The proposed use of a global SCC would weigh domestic and foreign impacts equally.

Are there economic or strategic reasons to use global benefits for domestic regulatory purposes? From an ethical point of view, taking a global welfare perspective is a welcome departure from the usual norm of nationalistic policies. It is not clear whether this stance would long survive legislative scrutiny unless there are other grounds.

A more convincing rationale would be strategic. There might be grounds for using a global SCC as a signaling device, wherein it would serve as a "golden rule" for regulators that would lead to a globally efficient solution if universally followed. However, doing that through uncoordinated actions would appear an inefficient device compared to explicit international agreements on harmonizing regulatory SCCs.

It should be emphasized that the decision to use global rather than national SCC is of great empirical importance. The regional DICE model has a SCC for the United States that is about 10% of the global SCC, and that number is approximately the same for the two other major regional models (FUND and PAGE). This is clearly a key issue for climate change policy.

5.4. Conclusion on Qualifications

While the SCC of slightly below $20 per ton of CO_2 would be an appropriate target for a harmonized carbon tax in a first-best world, it is likely to be higher than the appropriate number when realistic factors are included. Using national rather than global benefits would reduce the number by an order of magnitude. Tax dis-

11. OMB (2013), table 3.2—Outlays By Function and Subfunction, FY 2011. The domestic budget includes functions 550, Health (excluding Medicare), and 600, Income Security. The foreign budget includes function 151, International Development and Humanitarian Assistance.

tortions, the use of non-revenue-raising regulations, and leakage would also lead to the use of a smaller regulatory price. While the sign of these changes is clear, because of complexities of the regulatory, tax, and energy systems, the size of the adjustment is highly uncertain.

6. CONCLUSION

The present study presents a new set of estimates of the social cost of carbon. The distinguishing features of the present modeling are the following. First, it presents an updated version of the DICE model, including revisions of all economic and geophysical variables and modules. Second, it is a general equilibrium approach in which important variables (such as the real interest rate, the economic growth rate, consumption, and climatic variables) are determined endogenously rather than as exogenous assumptions.

The most important results are as follows. First, the estimated social cost of carbon for the current time (2015) is \$18.6 per ton of CO_2 in 2005 US international prices. Second, the DICE model results are lower than one of the other two major modeling estimates (the PAGE model) but higher than the other (the FUND model). Third, the major open issue concerning the SCC continues to be the appropriate discount rate. Fourth, use of the SCC in regulatory policies in the energy sector is increasingly important, but analyses of its application have not sufficiently considered issues such as leakage, distortionary taxes, and the question of whether to use global or domestic SCCs.

REFERENCES

Ackerman, Frank, and Charles Munitz. 2012. Climate damages in the FUND model: A disaggregated analysis. *Ecological Economics* 77:219–24.

Ackerman, Frank, and Elizabeth A. Stanton. 2010. The social cost of carbon: A report for the Economics for Equity and the Environment Network. Stockholm Environment Institute, US Center (April 1). http://www.climate-economics.org/papers/SocialCostOfCarbon_SEI_20100401.pdf.

———. 2012. Climate risks and carbon prices: Revising the social cost of carbon. *Economics: The Open-Access, Open-Assessment E-Journal* 6, no. 2012–10.

Anthoff, David. 2013. Personal communication with current estimates of regional SCC in the FUND model.

Anthoff, David, and Richard S. J. Tol. 2010. On international equity weights and national decision making on climate change. *Journal of Environmental Economics and Management* 60, no. 1:14–20.

Arrow, K. J., W. R. Cline, K-G. Maler, M. Munasinghe, R. Squitieri, and J. E. Stiglitz. 1996. Intertemporal equity, discounting, and economic efficiency. In *Climate change, 1995: Economic and social dimensions of climate change, contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, ed. James P. Bruce, Hoe-song Yi, and Erik F. Haites, 125–44. Cambridge: Cambridge University Press.

Arrow, K. J. J., M. Cropper, C. Gollier, B. Groom, G. Heal, R. Newell, W. Nordhaus, R. Pindyck, W. Pizer, P. Portney, T. Sterner, R. S. J. Tol, and M. Weitzman. 2013. Determining benefits and costs for future generations. *Science* 341, no. 6144:349–50.

Barrage, Lint. 2013. Optimal dynamic carbon taxes in a climate-economy model with distortionary fiscal policy. PhD diss., Yale University.

Baylis, Kathy, Don Fullerton, and Daniel H. Karney. 2014. Negative leakage. *Journal of the Association of Environmental and Resource Economists* 1:51–73.

Bosetti, Valentina, Emanuele Massetti, and Massimo Tavoni. 2007. The WITCH Model: Structure, baseline, solutions. Working Paper no. 010.2007. FEEM (Fondazione Eni Enrico Mattei), Milan.

Bovenberg, A. Lans, and Lawrence H. Goulder. 1996. Optimal environmental taxation in the presence of other taxes: General equilibrium analyses. *American Economic Review* 86, no. 4:985–1000.

Clarke, Leon, Jae Edmonds, Volker Krey, Richard Richels, Steven Rose, and Massimo Tavoni. 2009. International climate policy architectures: Overview of the EMF 22 International Scenarios. *Energy Economics* 31, suppl. 2 (December 2009): S64–S81.

Clarkson, Richard, and Kathryn Deyes. 2002. Estimating the social cost of carbon emissions. Government Economic Service Working Paper 140, Enquiry Unit, HM Treasury, London.

Cline, William. 1992. *The economics of global warming*. Washington, DC: Institute of International Economics.

———. 1997. Modeling economically efficient abatement of greenhouse gases. In *Environment, energy, and economy*, ed. Yoichi Kaya and Keiichi Yokobori, 99–122. Tokyo: United Nations University Press.

Copeland, Brian, and R. M. Scott Taylor. 2000. Free trade and global warming: A trade theory view of the Kyoto Protocol. NBER Working Paper 7657 (April), National Bureau of Economic Research, Cambridge, MA.

EPA (Environment Protection Agency), Endangerment. 2009. Environmental Protection Agency, 40 CFR, chapter 1: Endangerment and cause or contribute findings for greenhouse gases under Section 202(a) of the Clean Air Act; final rule, *Federal Register*, Tuesday, December 15, pt. 5, 66514.

EPA, Vehicles. 2010. US Environmental Protection Agency final rulemaking to establish light-duty vehicle greenhouse gas emission standards and corporate average fuel economy standards: Regulatory impact analysis, EPA-420-R-10–009, April.

Felder, Stefan, and Thomas F. Rutherford. 1993. Unilateral CO2 reductions and carbon leakage: The consequences of international trade in oil and basic materials. *Journal of Environmental Economics and Management* 25, no. 2:162–76.

Fullerton, Don, and Gilbert E. Metcalf. 2001. Environmental controls, scarcity rents, and pre-existing distortions. *Journal of Public Economics* 80, no. 2:249–67.

FUND. 2013. The Climate Framework for Uncertainty, Negotiation and Distribution (FUND). Documentation at www.fund-model.org.

Gollier, Christian. 2013. *Pricing the planet's future: The economics of discounting in an uncertain world*. Princeton, NJ: Princeton University Press.

Golosov, Mikhail, John Hassler, Per Krusell, and Aleh Tsyvinski. 2014. Optimal taxes on fossil fuel in general equilibrium. *Econometrica* 82, no. 1:41–88.

Goulder, Lawrence H., Ian W. H. Parry, and Dallas Burtraw. 1997. Revenue-raising versus other approaches to environmental protection: The critical significance of preexisting tax distortions. *RAND Journal of Economics* 28, no. 4:708–31.

Goulder, Lawrence H., Ian W. H. Parry, Roberton C. Williams III, and Dallas Burtraw. 1999. The cost-effectiveness of alternative instruments for environmental protection in a second-best setting. *Journal of Public Economics*, 72, no. 3:329–60.

Greenstone, Michael, Elizabeth Kopits, and Ann Wolverton. 2011. Estimating the social cost of carbon for use in U.S. federal rulemakings: A summary and interpretation. NBER Working Paper 16913, National Bureau of Economic Research, Cambridge, MA.

———. 2013. Developing a social cost of carbon for US regulatory analysis: A methodology and interpretation. *Review of Environmental Economics and Policy* 7, no. 1:23–46.

Hedges, Larry V., and Ingram Olkin. 1985. *Statistical methods for meta-analysis*, San Diego, CA: Academic Press.

Hope, Chris. 2011. The social cost of CO_2 from the PAGE09 Model. Economics Discussion Papers, no. 2011-39 (September), Kiel Institute for the World Economy.

IPCC (Intergovernmental Panel on Climate Change) Extremes. 2012. *Managing the risks of extreme events and disasters to advance climate change adaptation: Special report of the intergovernmental panel on climate change*, ed. Christopher B. Field, Vicente Barros, Thomas F. Stocker, and Qin Dahe. Cambridge: Cambridge University Press. http://www.ipcc.ch/pdf/special-reports/srex/SREX_Full_Report.pdf.

IPCC Fifth Assessment, Science. 2013. *Intergovernmental Panel on Climate Change, climate change, 2013: The physical science basis, contribution of Working Group I to the Fifth Assessment Report of the IPCC*. http://www.ipcc.ch/report/ar5/wg1/#.Ukn99hCBm71.

IPCC Fourth Assessment, Science. 2007. *Intergovernmental Panel on Climate Change, climate change, 2007: The physical science basis, contribution of Working Group I to the Fourth Assessment Report of the IPCC*, Cambridge: Cambridge University Press. http://ipcc-wg1.ucar.edu/wg1/wg1-report.html.

IWG (Interagency Working Group). 2010. Interagency Working Group on Social Cost of Carbon, US Government, technical support document: Social cost of carbon for regulatory impact analysis under Executive Order 12866. http://www.epa.gov/oms/climate/regulations/scc-tsd.pdf.

———. 2013. Interagency Working Group on Social Cost of Carbon, US Government, technical support document: Technical update of the social cost of carbon for regulatory impact analysis under Executive Order 12866, May 2013. http://www.whitehouse.gov/sites/default/files/omb/ inforeg/social_cost_of_carbon_for_ria_2013_update.pdf.

———. 2013. Technical support document: Technical update of the social cost of carbon for regulatory impact analysis. US Government, Washington, DC.

Johnson, Laurie T., and Chris Hope. 2012. The social cost of carbon in U.S. regulatory impact analyses: An introduction and critique. *Journal of Environmental Studies and Sciences* 2, no. 3:205–21.

Jorgenson, Dale W., Richard J. Goettle, Mun S. Ho, and Peter J. Wilcoxen. 2013. *Double dividend: Environmental taxes and fiscal reform in the United States*. Cambridge, MA: MIT Press.

Koopmans, Tjalling C. 1965. On the concept of optimal economic growth. *Academiae Scientiarum Scripta Varia* 28, no. 1:1–75. Available for download at http://cowles.econ.yale.edu/P/au/p_koopmans.htm.

Lenton, Timothy M., et al. 2008. Tipping elements in the Earth's climate system. *Nature* 105, no. 66: 1786–93.

Li, Zhimin, and William Nordhaus. 2013. The social cost of carbon: Methods and a survey of estimates. Unpublished manuscript, University of California, Berkeley.

Mehra, Rajnish. 2008. *The handbook of the equity risk premium*. Amsterdam: Elsevier.

Murray, Brian C., Andrew Keeler, and Walter N. Thurman. 2005. Tax interaction effects, environmental regulation, and "rule of thumb" adjustments to social cost. *Environmental and Resource Economics* 30:73–92.

Murray, Brian C., Walter N. Thurman, and Andrew Keeler. 2000. Adjusting for tax interaction effects in the economic analysis of environmental regulation: Some practical considerations. White paper, US Environmental Protection Agency, prepared for US Environmental Protection Agency, Office of Air Quality Planning and Standards, Innovative Strategies and Economics Group.

National Research Council. 1979. *Carbon dioxide and climate: A scientific assessment*. Washington, DC: National Academies Press.

National Research Council, Committee on Abrupt Climate Change. 2002. *Abrupt climate change: Inevitable surprises*. Washington, DC: National Academy Press.

Nordhaus, William D. 1991. To slow or not to slow: The economics of the greenhouse effect. *Economic Journal* 101, no. 407:920–37.

———. 1992. An optimal transition path for controlling greenhouse gases. *Science* 258 (November 20): 1315–19.

———. 1994. *Managing the global commons: The economics of climate change*. Cambridge, MA: MIT Press.

———. 2007. A review of the *Stern review on the economics of climate change*. *Journal of Economic Literature* 45, no. 3:686–702.

———. 2008. *A question of balance: Weighing the options on global warming policies*. New Haven, CT: Yale University Press.

———. 2010. Economic aspects of global warming in a post-Copenhagen environment. *Proceedings of the U.S. National Academy of Sciences* 107, no. 26:11721–26.

———. 2012. Integrated economic and climate modeling. In *Handbook of computable general equilibrium modeling*, ed. Peter B. Dixon and Dale W. Jorgenson. Amsterdam: North-Holland.

Nordhaus, William, and Joseph Boyer. 2000. *Warming the world: Economic modeling of global warming*. Cambridge, MA: MIT Press.

Nordhaus, William, and Paul Sztorc. 2013. *DICE 2013R: Introduction and User's Manual*, available from at http://www.econ.yale.edu/~nordhaus/homepage/, October 2013.

Nordhaus, William, and Zili Yang. 1996. A regional dynamic general-equilibrium model of alternative climate-change strategies. *American Economic Review* 86, no. 4:741–65.

Nordhaus, William, and Gary Yohe. 1983. Future carbon dioxide emissions from fossil fuels. In *Changing climate: Report of the Carbon Dioxide Assessment Committee*, 87–153. Washington, DC: National Research Council, National Academy Press.

OMB (Office of Management and Budget). 2003. Office of Management and Budget: Circular A-4, September 17. http://www.whitehouse.gov/omb/circulars_a004_a-4.

———. 2013. *The budget of the United States for fiscal year 2013*. OMB: Washington, DC. Available at http://www.whitehouse.gov/omb/budget/Historicals.

Parry, Ian W. H., Roberton C. Williams III, and Lawrence H. Goulder. 1999. When can carbon abatement policies increase welfare? The fundamental role of pre-existing factor market distortions. *Journal of Environmental Economics and Management* 37:52–84.

Pindyck, Robert S. 2013. Climate change policy: What do the models tell us? *Journal of Economic Literature* 51, no. 3:860–72.

Portney, Paul R., and John Weyant, eds. 1999. *Discounting and intergenerational equity*. Washington, DC: Resources for the Future.

Ramsey Frank P. 1928. A mathematical theory of saving. *Economic Journal* 38:543–59.

Roe, Gerard, and Marcia Baker. 2007. Why is climate sensitivity so unpredictable? *Science* 318, no. 5850: 629–32.

Stern Review. 2007. *The economics of climate change: The Stern review*. Cambridge: Cambridge University Press.

Stern, Nicholas. 2008. The economics of climate change. *American Economic Review* 98, no. 2:1–37.

———. 2013. The structure of economic modeling of the potential impacts of climate change: Grafting gross underestimation of risk onto already narrow science models. *Journal of Economic Literature* 51, no. 3:838–59.

Tol, Richard S. J. 2008. The social cost of carbon: Trends, outliers and catastrophes. *Open-Access, Open-Assessment E-Journal* 2, no. 25:1–22.

———. 2009. The economic impact of climate change. *Journal of Economic Perspectives* 23, no. 2:29–51.

United Nations. 2009. Copenhagen Accord. http://unfccc.int/resource/docs/2009/cop15/eng/l07.pdf.

Weitzman, Martin L. 1998. Why the far-distant future should be discounted at its lowest possible rate. *Journal of Environmental Economics and Management* 36, no. EE981052:201–08.

———. 2009. On modeling and interpreting the economics of catastrophic climate change. *Review of Economics and Statistics* 91, no. 1:1–19.

———. 2013. Tail-hedge discounting and the social cost of carbon. *Journal of Economic Literature* 51, no. 3:873–82.

Yang, Zili. 2008. *Strategic bargaining and cooperation in greenhouse gas mitigations: An integrated assessment modeling approach*. Cambridge, MA: MIT Press.