



Climate Risks and Carbon Prices: Revising the Social Cost of Carbon

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ENVIRONMENT

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Executive Summary

Climate Risks and Carbon Prices: Revising the Social Cost of Carbon

How much economic damage is done by one ton of carbon dioxide emissions? That number, called the “social cost of carbon,” or SCC, provides one measure of the urgency of the problem of climate change. It has been estimated by a federal government working group at a mere \$21 as of 2010 – the equivalent of just \$0.21 for every gallon of gasoline.

This is not a large number. It seems to suggest that we don’t need to do much about climate change: if a proposed climate policy would cost more than \$21 per ton of reductions in carbon dioxide emissions, then, according to this calculation, it’s not worth doing.

The government’s calculation of the \$21 SCC, however, omits many of the biggest risks associated with climate change, and downplays the impact of our current emissions on future generations. Our re-analysis, including those factors, shows that the SCC could be much higher. In our worst case, it could be almost \$900 in 2010, rising to \$1,500 in 2050. If the damages per ton of carbon dioxide are that high, then almost anything that reduces emissions is worth doing.

It is unequivocally less expensive to reduce greenhouse gas emissions than to suffer climate damages.

For our re-analysis of the SCC, we used the DICE model, the best-known of the models used by the government working group. We repeated the working group analysis, changing it only where needed to represent four big uncertainties.

First, scientists remain uncertain about how rapidly global warming will progress as we fill the atmosphere with greenhouse gases. “Climate sensitivity,” defined as the global average warming that results from doubling the carbon dioxide concentration in the atmosphere, is most commonly estimated to be 3.0°C (5.4°F) – but there is a significant risk that it is larger, and we won’t know for certain until it is too late to do anything about it. In this case, the working group analysis does a careful job of addressing uncertainty, estimating that there’s a 1-in-20 chance (95th percentile) that climate sensitivity is 7.1°C (12.8°F) or higher; they calculate, but do not emphasize, SCC estimates based on this higher value of climate sensitivity. We followed their method without change, calculating the SCC both for average and for 95th percentile climate sensitivity.

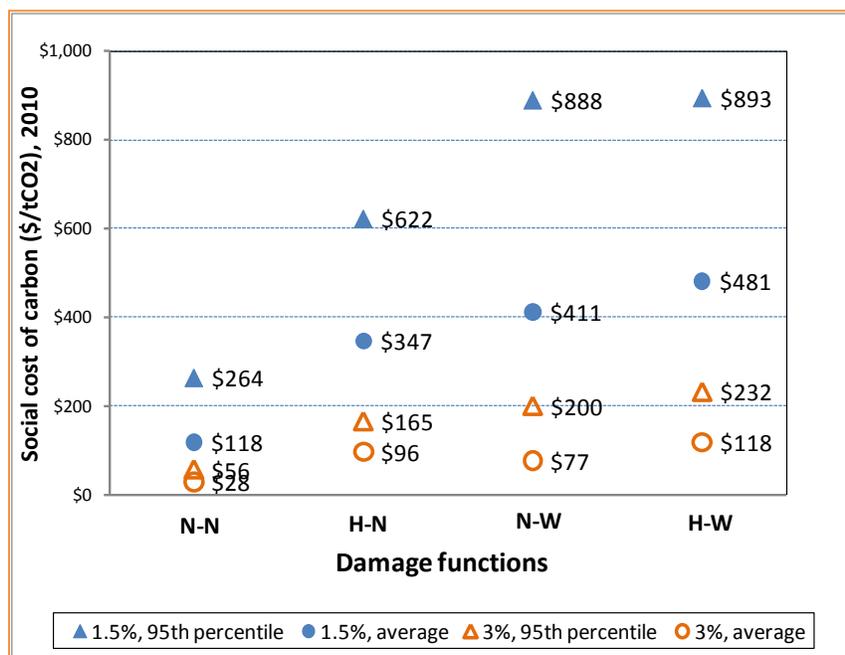
Second, economists are uncertain about the severity of the damages that will result from the early stages of warming. The DICE model, developed by William Nordhaus, estimates that 2.5°C (4.5°F) of warming will cause a loss of only 1.8 percent of world GDP. Another economist, Michael Hanemann, has done a detailed review of the DICE damage estimate as it applies to the United States, and concluded that it should be four times as large. We ran the DICE model both with the Nordhaus (original) estimate and the Hanemann estimate of damages at 2.5°C.

Third, economists have very little information about damages at the much higher temperatures that will eventually result from unchecked climate change. DICE simply extrapolates from its low-temperature estimate, implying that only when 1.9°C (34°F) of warming has occurred do damages reach one half of world GDP. Martin Weitzman argues that this is a drastic understatement of high-temperature damages and suggests an estimate more in keeping with recent climate science: losses due to global warming could reach half of world GDP at 6°C (11°F), and 99 percent of world GDP at 12°C (22°F). This dire forecast may seem more plausible in light of a recent study showing that at 12°C average warming, large parts of the world will, at least once a year, reach temperatures that human beings cannot survive. We ran the DICE model both with the Nordhaus (original) method of extrapolation to high temperatures, and with the Weitzman guesses for high-temperature damages.

Finally, there is no consensus in the longstanding controversy on the appropriate way in which to value the future costs and benefits of climate change. (A lower discount rate gives greater importance to the future; a higher rate, less importance.) The working group analysis prefers a constant 3 percent discount rate, and does not examine any rates below 2.5 percent. The prestigious Stern Review, among others, argued for much lower discount rates, in order to reflect the damage that climate change could do to future generations. As an alternative to the 3 percent rate, we also ran the SCC analysis at a 1.5 percent discount rate, approximating the Stern rate.

Our estimates for the SCC in 2010, using all combinations of these four factors, are shown in Figure ES-1. They range from \$28 (the working group estimate from DICE alone) up to \$893.

Figure ES-1: Alternative SCC values for 2010



Source: Authors' calculations.

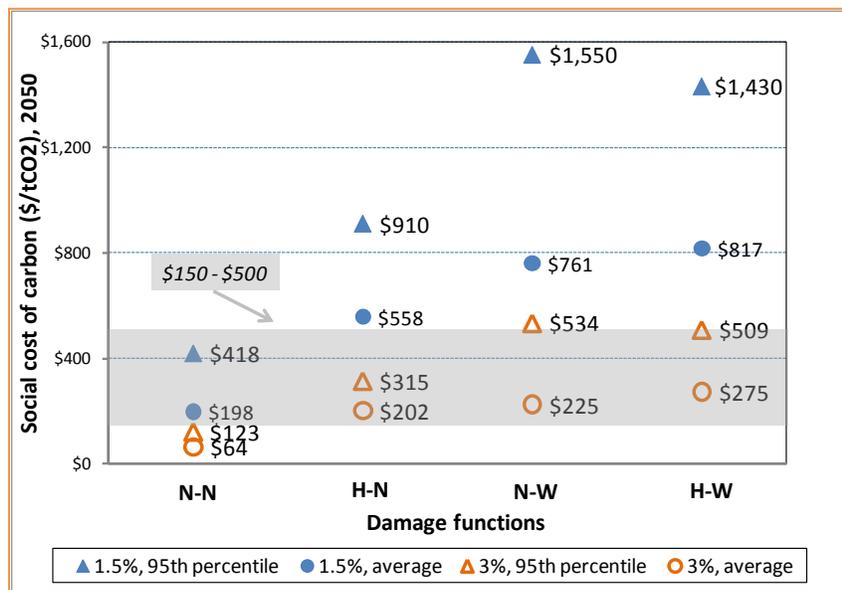
The four damage functions, from left to right, are:

- The original DICE version (i.e., Nordhaus estimates at both low and high temperatures)
- Hanemann’s alternative at low temperatures, no change at high temperatures
- Nordhaus’ estimate at low temperatures, Weitzman’s at high temperatures
- Hanemann’s estimate at low temperatures, Weitzman’s at high temperatures.

Circles represent average climate sensitivity; triangles are 95th percentile. Solid blue shapes are estimates at a 1.5 percent discount rate; orange outlines are at a 3 percent discount rate.

While many of these values are quite high, they are not the end of the story. The SCC is projected to rise over time, since emissions that occur later will do more damage – because they will come at a time when the concentration of greenhouse gases in the atmosphere is already higher. Our SCC estimates for 2050 are shown in Figure ES-2.

Figure ES-2: Alternative SCC values for 2050



Source: Authors’ calculations.

Under some of the assumptions explored in our analysis, the SCC could be as high as \$1,500 per ton – equivalent to \$15 per gallon of gas and more than 70 times as high as the working group’s estimate of \$21. How should such extraordinarily high estimates be interpreted?

As long as there is a credible risk that the SCC [social cost of carbon], or damages from a ton of emissions, could be above the cost of maximum feasible abatement, then it is worth doing everything we can to reduce emissions.

In recent years, a number of researchers have explored ambitious scenarios for eliminating carbon dioxide emissions as rapidly as seems technologically feasible; most of these scenarios reach zero or negative net global emissions by the end of this century. While details vary from one study to another, they typically require spending up to \$150 to \$500 per ton of reductions in carbon dioxide emissions by 2050 – the gray band shown in Figure ES-2. Most of our SCC estimates for 2050 are at or above this level, some far above it.

That is, under many of the assumptions we explored, the damages from a ton of carbon dioxide emissions in 2050 could equal or exceed the cost of reducing emissions at the maximum technically feasible rate. In other words, it is unequivocally less expensive to

reduce greenhouse gas emissions than to suffer climate damages. Once this is the case, the exact value of the SCC no longer matters, and cost-benefit analysis of proposals for emission reduction conveys no additional information. All that is needed is a cost-effectiveness analysis of the least-cost strategy for eliminating carbon emissions as rapidly as possible.

In a controversial theoretical analysis, Martin Weitzman argued that under certain plausible assumptions the marginal damages from a ton of emissions, or marginal benefits from reducing emissions, could be infinite. Our estimates are not literally infinite, but they may be close enough to infinity for all practical purposes. As long as there is a credible risk that the SCC, or damages from a ton of emissions, could be above the cost of maximum feasible abatement, then it is worth doing everything we can to reduce emissions. Cost-benefit analysis under such conditions coincides with a precautionary approach that calls for taking immediate, large-scale action to phase out carbon emissions and protect the Earth's climate.

1. Introduction

The Obama administration has taken a historic step toward regulation of greenhouse gas emissions. Cost-benefit analyses of proposed regulations can now include an estimate of damages done by greenhouse gas emissions – or conversely, the benefits of reducing those emissions. It is, however, a very small step: the “social cost of carbon” (SCC), i.e. the damage per ton of carbon dioxide, is estimated at \$21 for 2010 (Interagency Working Group on Social Cost of Carbon 2010).¹ This is equivalent to a mere \$0.21 per gallon of gasoline.² Such low costs are difficult to reconcile with the belief that it is urgent to take action to address serious climate risks (Ackerman and Stanton 2010).

The analysis by the federal Interagency Working Group is significant for its role in setting U.S. climate policy. It is also noteworthy as a rare instance where economic theories and analyses have been newly introduced into the public policy debate.³ Thus it is important to examine the uses of climate economics in the Working Group analysis, particularly the treatment of the crucial uncertainties that characterize the field. This paper presents an examination and re-analysis of the SCC, finding that four major uncertainties in the economics of climate change could imply much larger estimates. In each case, the Working Group has chosen the option that minimizes estimates of climate risks and damages.

We begin with a discussion of the choice of models and scenarios for the SCC calculation. Our re-analysis relies on DICE, one of the models used by the federal Interagency Working Group that produced the \$21 estimate; we use the Working Group’s modified version of DICE, and the same five scenarios on which they based their calculations.

We then introduce four major areas of uncertainties that affect the calculation: the sensitivity of the climate to greenhouse gases; the level of damages expected at low temperatures; the level of damages expected at high temperatures; and the discount rate. We recalculate the SCC based on combinations of high and low alternatives for each of these factors, yielding an array of 16 possible values, both for 2010 and for 2050.

Some of the values for the SCC are extremely high; the highest ones exceed \$800 per ton in 2010 and \$1,500 in 2050. In contrast, a review of scenarios that reach zero or negative net global emissions within this century finds that they often imply carbon prices, and marginal abatement costs, of \$200 to \$500 per ton of CO₂ by 2050. Several of our alternative SCC values are well above this range.

¹ All dollar figures in this article are in constant 2007 U.S. dollars.

² According to the U.S. Environmental Protection Agency, there are 8.8 kg of CO₂ emissions from a gallon of gasoline, implying that 114 gallons of gasoline yield one metric ton of emissions (the standard unit for analysis of emissions); 103 gallons yield one short ton of emissions (see <http://www.epa.gov/oms/climate/420f05001.htm>, accessed April 22, 2011). Thus a useful rule of thumb is that \$1 per ton of CO₂ is equivalent to roughly \$0.01 per gallon of gasoline. The estimate in the text of \$0.21 per gallon is offered solely for the sake of comparison; there are no existing or proposed federal regulations that would add a carbon charge to the price paid for gasoline.

³ It is new only for U.S. policy; other countries, notably the United Kingdom, are several years ahead of the United States in this respect. The U.S. policy process is unfortunately parochial, however, so that the introduction of climate economics into policy analysis is presented with almost no reference to other countries’ experience.

We conclude with a discussion of the meaning of very high SCC estimates. Once the SCC exceeds the cost of bringing net emissions to zero, its exact value becomes less important; if the SCC were twice as large, it would have the same policy implications. At such high SCC values, cost-benefit analysis of individual policies provides no useful information; what is needed instead is a cost-effectiveness analysis of the least-cost, most efficient pathway to reach zero or negative net emissions.

2. Choice of models

The Interagency Working Group used three well-known models of climate economics: DICE, PAGE, and FUND. They ran each of the models on the same five scenarios, and averaged the results. Under their “central case” or preferred assumptions, the value of the SCC, averaged across the five scenarios, was \$28 in DICE, \$30 in PAGE, and \$6 in FUND, for a three-model average of \$21.

FUND is an outlier in several respects. It is by far the most complex and least transparent of the three models. A comparison of standard Intergovernmental Panel on Climate Change (IPCC) scenarios modeled in DICE, PAGE, and FUND found that FUND was less sensitive to differences between scenarios, and projected lower temperature increases than the other models for high-emission scenarios (Warren et al. 2010). Another comparison of these and other models found that in several instances FUND predicted the lowest temperature increase for a given scenario, and had a slower response than other models to increases in CO₂ concentrations, perhaps due to FUND’s use of dated information on climate dynamics (van Vuuren et al. 2011).

A recent examination of the treatment of climate damages in FUND found that it projects that warming will create net global benefits in agriculture, offsetting much of the model’s (surprisingly small) estimate of damages in other areas (Ackerman and Munitz 2011). FUND’s calculation of agricultural impacts contains several problematical features, including a poorly formulated equation that could lead to division by zero, an unrealistic treatment of temperature effects on crop yields, and a very large estimate of carbon fertilization benefits, based on dated research.

In short, FUND appears to be the wrong model to use: it offers climate projections that are out of line with current scientific assessments, and includes flawed damage calculations that are in need of substantial revision.

The other two models, DICE and PAGE, yield quite similar SCC estimates under the Working Group’s “central case” assumptions, \$28 versus \$30. We have used DICE for our analysis, because its software design makes it easier to introduce the alternative damage assumptions discussed below. This is a conservative choice since, under many of the alternative assumptions we explore, PAGE would produce higher SCC estimates.

Of the two models, PAGE has a more explicit treatment of potential climate catastrophes, using a Monte Carlo analysis that allows variation in the size of catastrophes, the temperature threshold at which they become possible, and the likelihood of catastrophe once the threshold has been passed. DICE, in contrast, simply includes the certainty-equivalent or expected value of catastrophe in its damage function. As a result, PAGE

estimates a higher SCC than DICE at lower discount rates or higher climate sensitivity.⁴ Our analysis includes both lower discount rates and higher climate sensitivity, so our SCC estimates would have been even higher if we had used PAGE.

3. Choice of scenarios

The Working Group analysis rejects, with little discussion, the widely used IPCC climate scenarios, and instead uses scenarios from four other models: the business-as-usual scenarios from IMAGE, MERGE, MESSAGE, and MiniCAM, and a 550 ppm stabilization scenario.

The strangest aspect of this choice is the inclusion of the 550 ppm scenario. Does it imply a guess that under business-as-usual conditions, there is a 20 percent chance that the world will reach agreement on stabilization at that level? No explanation is offered. Moreover, the 550 ppm scenario is not even a single, internally consistent scenario; rather, its GDP, population, and emissions trajectories are averages of the values in the 550 ppm scenarios from the other four models (see Interagency Working Group on Social Cost of Carbon 2010, p.16).

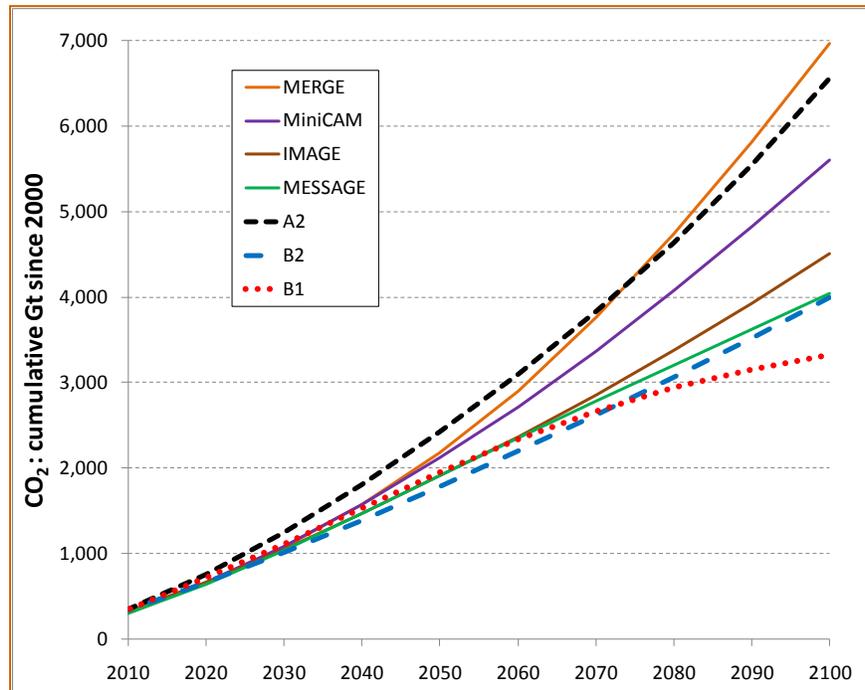
Nonetheless, inclusion of the 550 ppm scenario makes little difference in practice. Excluding it would cause only a \$1 increase in the \$21 SCC estimate from DICE, FUND, and PAGE, and the \$28 estimate from DICE alone. For the SCC estimates in our analysis, presented below, exclusion of the 550 ppm scenario would cause an average increase of 1 percent; no individual estimate would change by more than 15 percent in either direction. Thus we have retained the 550 ppm scenario in our calculations, to increase comparability with the Working Group results.

The four business-as-usual scenarios used by the Working Group were adopted from an Energy Modeling Forum (EMF) exercise which compared ten models; nothing is said about why these four were selected from among the ten EMF models. The more familiar IPCC scenarios are dismissed in a single sentence, on grounds of their age and the unexplained assertion that they now appear to be extreme outliers in some variables.

⁴ A lower discount rate increases the importance of events farther in the future, when temperatures are higher and catastrophes are more likely. Higher climate sensitivity makes higher temperatures and increased risks of catastrophe occur sooner. For these reasons, PAGE estimates a larger SCC than DICE at a 2.5% discount rate, and at 95th percentile climate sensitivity; see Interagency Working Group on Social Cost of Carbon (2010), Table 3.

For those who are not familiar with EMF, it may be helpful to contrast the selected EMF scenarios with standard IPCC scenarios.⁵ Figures 1 and 2 compare the cumulative carbon dioxide emissions and current methane emissions from the four EMF scenarios and three IPCC scenarios, A2, B2, and B1.⁶ As Figure 1 shows, carbon dioxide emissions in the four EMF scenarios (solid lines) are close to the B1 and B2 scenarios for the first half of this century, spreading out to roughly span the interval from A2 to B2 by 2100.

Figure 1: Cumulative CO₂ emissions in selected EMF scenarios and IPCC scenarios



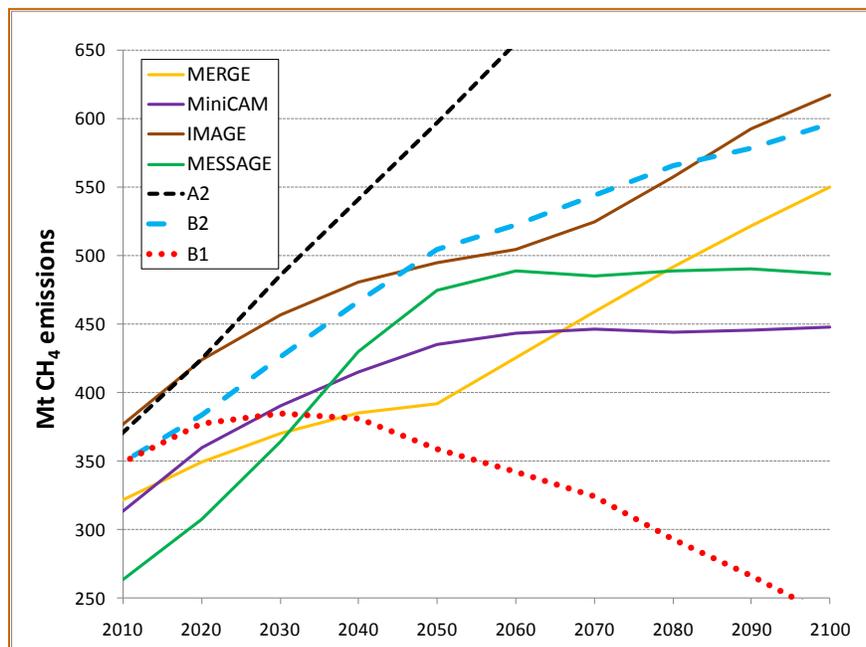
Sources: *Energy Modeling Forum (2009), Nakicenovic et al. (2000).*

For methane emissions, Figure 2 shows that three of the four EMF scenarios start out well below the level of the B1 and B2 scenarios; by 2100, all four are roughly at or below the level of B2. Thus the emissions trajectories of the EMF scenarios are broadly within, but toward the lower end of, the spectrum of IPCC scenarios, perhaps closest to B2. Achieving the IPCC's B2 scenario would require substantial mitigation; business-as-usual emissions – growing at the current pace – might result in A2 or even higher concentrations.

⁵ IPCC scenario data are from http://sres.ciesin.org/final_data.html, downloaded March 1, 2011. EMF scenario data are from http://emf.stanford.edu/events/emf_briefing_on_climate_policy_scenarios_us_domestic_and_international_policy_architectures, downloaded February 15, 2011.

⁶ Figure 1 presents cumulative emissions because CO₂ persists in the atmosphere for long periods of time; Figure 2 presents current emissions because methane is removed from the atmosphere much more quickly.

Figure 2: Cumulative methane emissions in selected EMF scenarios and IPCC scenarios



Sources: *Energy Modeling Forum (2009)*, *Nakicenovic et al. (2000)*.

All else being equal, lower emissions imply lower damages, and therefore a lower estimate of the SCC. Use of an IPCC scenario in which emissions grow more rapidly, such as A2, would likely have led to higher values for the SCC. Relative to IPCC scenarios, the EMF emission trajectories are particularly low in the first half of this century; this is of greatest importance at high discount rates, which weight the earlier years more heavily.

For the sake of comparability with the Working Group results, we have adopted the same five scenarios in our analysis of uncertainties. Note that this is a conservative choice of scenarios, as well as models; repetition of our analysis with the PAGE model and higher-emission IPCC scenarios would lead to larger SCC values.

4. Four uncertainties

This section explores four major uncertainties that affect the SCC calculation: the value of the climate sensitivity parameter; the level of climate damages expected at low temperatures; the level of damages at high temperatures; and the discount rate. The next section presents multiple estimates of the SCC, based on alternatives for each of these uncertainties.

4.1. Climate sensitivity

The climate sensitivity parameter is the long-term temperature increase expected from a doubling of the concentration of carbon dioxide in the atmosphere. This crucial parameter, which measures the pace of global warming, remains uncertain, and there are reasons to believe that significant uncertainty about climate sensitivity is inescapable (Roe and Baker 2007).

On this topic, the Working Group analysis is impressively thorough. They discuss the scientific evidence on likely values of climate sensitivity, and adopt a probability distribution which assumes a two-thirds probability that climate sensitivity is between 2.0°C and 4.5°C. The minimum is zero and the maximum is 10°C; the distribution has a median of 3.0°C and a 95th percentile of 7.14°C. They then perform a Monte Carlo analysis, repeatedly selecting a climate sensitivity value from this probability distribution and running the model with that value; the final SCC estimate is the average result from these runs.⁷

The Working Group reports, but does not emphasize, the 95th percentile results as a measure of the potential impact of uncertainty about climate sensitivity. Results for DICE, and for the three-model average used by the Working Group, are presented in Table 1.

Table 1: Model results used by the Working Group

SCC estimates, 2010 and 2050, 3% discount rate			
Emissions year	Climate sensitivity	DICE	3-Model Average
2010	Average	\$28	\$21
2010	95 th percentile	\$56	\$65
2050	Average	\$64	\$45
2050	95 th percentile	\$123	\$136

Source: *Interagency Working Group (2010)*.

We follow the Working Group in reporting results for both average and 95th percentile climate sensitivity, in each of the variations described below. In practice, these results may correspond to climate sensitivity somewhat below 3.0°C and 7.1°C, respectively, since actual climate sensitivity in DICE (and several other integrated assessment models) is lower than the reported values. DICE uses a default climate sensitivity of 3.0°C, but actually responds to a doubling of atmospheric carbon dioxide with a long-run temperature increase of 2.77°C (van Vuuren et al. 2011).

⁷ In PAGE and FUND, there are other Monte Carlo variables that are drawn from probability distributions for each run; in DICE, as used by the Working Group, climate sensitivity is the only Monte Carlo variable.

4.2. Damage function estimates

The Working Group says little about the estimates of economic damages from climate change, except to call for additional research. Implicitly, it adopts without question the approach taken by each model; this alone can explain the difference between the SCC estimates from FUND and DICE (Ackerman and Munitz 2011).

DICE assumes that as temperatures rise, an increasing fraction of output is lost to climate damages. We will use D for damages as a fraction of the GDP that would be produced in the absence of climate change; $R = 1 - D$ for the net output ratio, or output net of climate damages as a fraction of output in the absence of climate change; and T for global average temperature increase in °C above 1900. The DICE damage function is

$$(1) \quad R = \frac{1}{1 + .00284T^2}$$

Or equivalently,

$$(2) \quad R = \frac{1}{1 + (T/18.8)^2}$$

The DICE net output ratio can be viewed as combining two separate estimates: first, for low temperatures, William Nordhaus, the creator of DICE, estimates that damages are 1.8 percent of output at 2.5°C (Nordhaus 2007); second, at high temperatures, it is assumed by default that the quadratic relationship of damages to temperature in (1) or (2) continues to apply. Separate research addresses the low-temperature and high-temperature estimates, suggesting alternatives to each.

The DICE low-temperature damage estimate is based on an evaluation of several categories of climate damages at 2.5°C (Nordhaus 2008; Nordhaus and Boyer 2000). In a review and critique of the Nordhaus estimates as applied to the United States, Michael Hanemann develops alternative estimates for damages at 2.5°C, which are, in total, almost exactly four times the Nordhaus value (Hanemann 2008). If the same relationship applies worldwide, then a reasonable alternative at low temperatures is to keep the form of equation (1) or (2), but recalibrate damages to 7.1 percent of output at 2.5°C. This yields the equation

$$(3) \quad R = \frac{1}{1 + (T/9.1)^2}$$

Neither the Nordhaus nor the Hanemann 2.5°C estimate provides a basis for projecting damages at much higher temperatures.⁸ It has become conventional to extrapolate the same quadratic relationship to higher temperatures, but there is no economic or scientific basis for that convention. The extrapolation implies that damages grow at a leisurely pace, especially in the Nordhaus version: from equations (2) and (3), it is easy to see that half of world output is not lost to climate damages until temperatures reach 18.8°C according to DICE, or 9.1°C in the Hanemann variant.

In a discussion of damage functions and catastrophic risks, Martin Weitzman argues that even if the Nordhaus estimate is appropriate for low-temperature damages, the increasingly ominous scientific evidence about climate risks implies much greater losses at higher temperatures (Weitzman 2010). He suggests that damages should be modeled at 50 percent of output at 6°C and 99 percent at 12°C as better representations of the current understanding of climate risks; the latter temperature can be taken as representing the end of modern economic life, if not human life in general. In support of this disastrous projection for 12°C of warming, Weitzman cites recent research showing that at that temperature, areas where half the world's population now lives would experience conditions, at least once a year, that human physiology cannot tolerate – resulting in death from heat stroke within a few hours (Sherwood and Huber 2010).

Weitzman creates a damage function that matches the DICE estimate at low temperatures, but rises to his suggested values at 6°C and 12°C. He modifies (2) by adding a higher power of T to the denominator:⁹

$$(4) \quad R = \frac{1}{1 + (T/20.2)^2 + (T/6.08)^{6.76}}$$

When T is small, the quadratic term in (4) is more important, providing a close match to the original DICE damage function; when T is large, the higher-power term is more important, allowing the damage function to match Weitzman's values for higher temperatures.

The same method can be applied to the Hanemann low-temperature estimate in (3); calibrating to Hanemann's value at 2.5°C, and Weitzman's values at 6°C and 12°C, we obtain

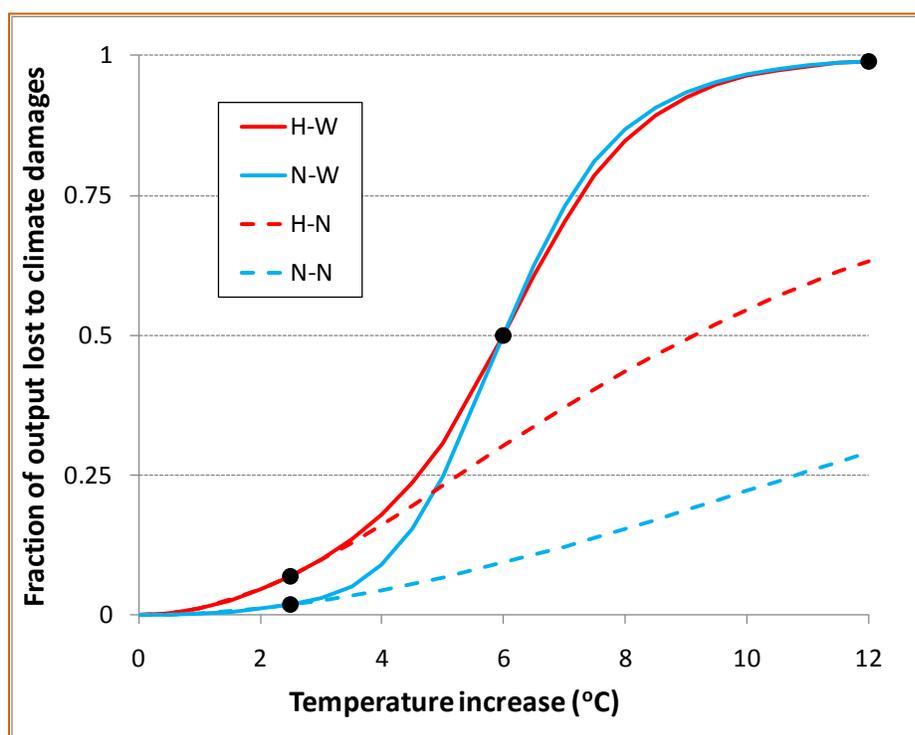
$$(5) \quad R = \frac{1}{1 + (T/9.2)^2 + (T/6.47)^{7.41}}$$

⁸ Nordhaus presents some numerical estimates of damages at 6°C, suggesting they are between 8 percent and 11 percent of output (Nordhaus 2007); these estimates are not well documented, and do not appear to be used in the calibration of DICE.

⁹ This equation follows Weitzman's method but differs slightly from his numerical estimates. He appears to have taken the DICE coefficient in (1) to be .00239 rather than .002839. Our equations (4) and (5) were fitted to minimize the sum of squared deviations from the Nordhaus and Hanemann damage estimates, respectively, at 2.5°C, and the Weitzman point estimates at 6°C and 12°C.

Equations (2), (3), (4), and (5) incorporate all combinations of two low-temperature alternatives (Nordhaus and Hanemann), and two high-temperature alternatives (Nordhaus and Weitzman). Using their initials, these can be labeled as the N-N, H-N, N-W, and H-W damages functions, respectively. They are displayed in Figure 3 (the graph presents damages as a share of GDP, not R), with large dots indicating the points used for calibration. Below 3°C, the low-temperature alternatives are dominant, and the high-temperature alternatives make no visible difference; at 6°C and above, the high-temperature alternatives determine the shape of the damage function. In particular, the two damage functions with the Weitzman high-temperature assumption are nearly identical above 6°C.¹⁰

Figure 3: Four damage functions contrasted



Source: Authors' calculations.

4.3. Discount rates

The Working Group's analysis of the SCC is based on projected costs and benefits extending 300 years into the future, as is our re-analysis. Across such spans of time, the discount rate is crucial to the bottom-line evaluation: the lower the discount rate, the more important the outcomes in later years will be. It seems safe to say that there is

¹⁰ A small anomaly is that between 6°C and 12°C the N-W damage function, despite its lower low-temperature damages, is slightly higher than H-W; the gap is greatest at 6.9°C, where N-W damages are 3.8 percent above H-W. This anomaly, which is an artifact of our curve-fitting procedure, may explain one aspect of the results presented below: under conditions where high-temperature damages are likely to be important, the SCC can be greater with the N-W than with the H-W damage function. See, in particular, the upper estimates in Figure 5.

ongoing controversy and a lack of consensus on the appropriate discount rate to use in climate economics.

The Working Group discusses the discount rate at length, justifying their choice of a fixed rate of 3 percent. This is one of the discount rates normally recommended for use in U.S. government policy analyses. In addition, it can be supported within either of the two frameworks used to determine the discount rate, the descriptive and prescriptive approaches (Arrow et al. 1996). The descriptive approach calls for use of an appropriate market interest rate; the Working Group estimates the real risk-free rate of return, after tax, at 2.7 percent. The prescriptive approach deduces the discount rate from first principles, as the sum of “pure time preference” (the discount rate that would apply if per capita consumption were constant) plus a multiple of the rate of growth of per capita consumption. The Working Group concludes that “arguments made under the prescriptive approach can be used to justify discount rates between roughly 1.4 and 3.1 percent” (Interagency Working Group on Social Cost of Carbon 2010, p.23), and expresses skepticism about the lower end of that range.

Both descriptive and prescriptive arguments can be made for discount rates below 3 percent. The risk-free rate is often estimated to be lower than 2.7 percent.¹¹ In addition, if climate mitigation, like insurance, is most valuable in circumstances that reduce incomes, then the discount rate should be lower than the risk-free rate of return. Using the prescriptive approach, the *Stern Review* spells out in detail the arguments for a low discount rate, on grounds of intergenerational equity (Stern 2006). Stern’s recommended formula for the discount rate is 0.1 percent plus the rate of growth of per capita consumption; this implies an average of 1.4 percent per year, in the *Stern Review’s* model.

To explore the effect of discount rates on the SCC, we use two rates, 3 percent and 1.5 percent per year. Our lower rate is close to the *Stern Review’s* rate; moreover, it is the average rate that would result from applying Stern’s formula, 0.1 percent plus the rate of growth of per capita consumption, to the first 200 years of the Working Group’s four business-as-usual scenarios.¹²

5. Results

The previous section identified two alternatives for each of four major factors influencing the SCC:

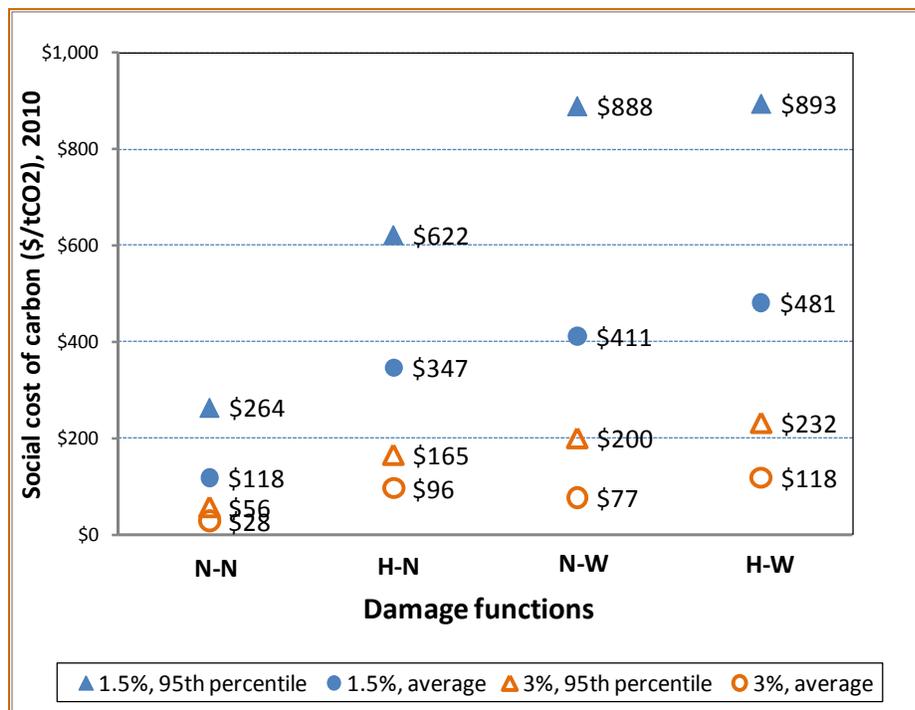
- Average versus 95th percentile climate sensitivity
- Nordhaus versus Hanemann damage estimates at low temperatures
- Nordhaus versus Weitzman damage estimates at high temperatures
- 3.0 versus 1.5 percent fixed discount rate

¹¹ Since World War II, real returns have averaged 1.4 percent per year on Treasury bills and 1.1 percent on government bonds (DeLong and Magin 2009).

¹² The EMF scenarios adopted by the Working Group are designed to have declining rates of growth in the second and third centuries. Using Stern’s formula, or any version of the prescriptive approach, this should call for a time-varying, declining discount rate. We follow the Working Group’s practice of using a fixed discount rate, for the sake of comparability with their results and minimization of changes to their version of the DICE model.

We calculated the SCC under each combination of these alternatives, making no other changes to the Working Group's version of DICE. The results are shown in Figure 4 for 2010, and Figure 5 for 2050. Circles represent average climate sensitivity, and triangles represent 95th percentile; solid blue symbols represent 1.5 percent discount rates, and outlined orange symbols represent 3 percent. Results for the four damage functions are shown in four columns on the graphs, as marked.

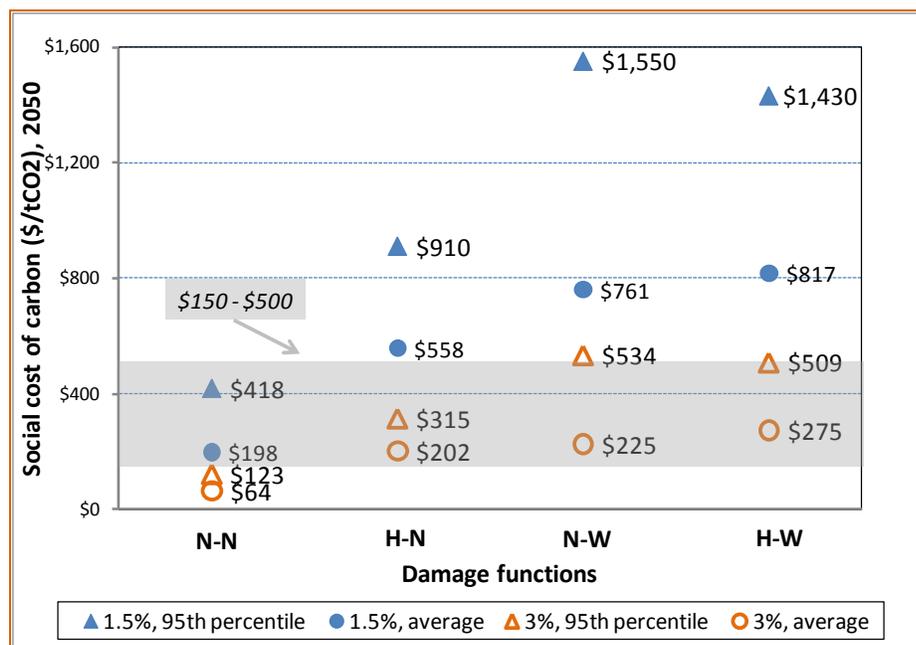
Figure 4: Alternative SCC values for 2010



Source: Authors' calculations.

The SCC is generally higher for later years, since atmospheric concentrations of greenhouse gases, and temperatures, will be higher at that time – implying that the incremental damage from another ton of emissions will be greater as well. Thus it is not surprising that the SCC estimates for 2050 are much higher than the corresponding figures for 2010.

In both graphs, the N-N (original DICE) damage function leads to lower estimates than any of the alternatives. If either Hanemann is right about low-temperature damages, or Weitzman is right about high-temperature damages, then the SCC in 2050 is above \$200 at a 3 percent discount rate, or above \$500 at 1.5 percent. The worst case, with Weitzman damages and 95th percentile climate sensitivity, is 2.5 – 3 times higher than these minimum values.

Figure 5: Alternative SCC values for 2050

Source: Authors' analysis.

6. Abatement costs

In a cost-benefit analysis of climate policy, the costs of doing nothing about climate change – i.e., the SCC – should be compared to the costs of doing something to mitigate it – i.e., the cost of reducing emissions. In several ambitious scenarios for drastic reduction in global emissions, the marginal cost per ton of abatement is lower than many of the SCC estimates presented above.

An inter-model comparison project, run by researchers at the Potsdam Institute for Climate Change Research (PIK) in Germany, compared scenarios from five models that stabilize carbon dioxide concentrations at 400 ppm by 2100.¹³ Because carbon dioxide remains in the atmosphere for decades or centuries, and we are already at 390 ppm, these scenarios have to achieve negative net global emissions before 2100, through measures such as reforestation and biomass burning with carbon capture and sequestration (CCS). In general, the 400 ppm scenarios strain the limits of plausible rates of technological and socioeconomic change. Their carbon prices reach \$150 - \$500 per ton of carbon dioxide by 2050, with an average of \$260 per ton.

A similar, though slightly more pessimistic, scenario from the International Energy Agency (IEA) stabilizes the atmosphere at 450 ppm of CO₂. This scenario – IEA's "BLUE

¹³ See Edenhofer et al. (2010); Kitous et al. (2010); Magne et al. (2010); Leimbach et al. (2010); Barker and Scricciu (2010); and van Vuuren et al. (2010).

Map” – again strains the limits of possible technical change, and is meant to represent the maximum feasible pace of abatement. The marginal abatement cost in 2050 is between \$175 and \$500 per ton of CO₂, depending on the degree of technological optimism or pessimism in cost forecasts (IEA 2008, 2010).

A more optimistic variant on this theme, from McKinsey & Company, projects rapid abatement leading to eventual stabilization at 400 ppm CO₂-equivalent; atmospheric concentration peaks at 480 ppm CO₂-e in the 2060s before declining. McKinsey estimates the marginal abatement cost of this scenario at \$90 - \$150 per ton of CO₂-e in 2030 (McKinsey & Company 2009).

Comparing these abatement cost estimates to our SCC calculations, both the 400 ppm model scenarios compared by PIK, and the IEA BLUE Map, imply abatement costs of \$150 to \$500 per ton by 2050 – the region shaded in gray in Figure 5. On any damage function except N-N, our SCC estimates for 2050 are within this range at a 3 percent discount rate, and well above it at a 1.5 percent discount rate. With the N-N damage function and a 1.5 percent discount rate, the SCC is also in the range of the abatement costs in the rapid abatement scenarios.

The McKinsey estimate of the marginal cost for rapid abatement, \$90 - \$150 per ton in 2030, is a range that has already been reached or exceeded by most of our SCC estimates for 2010. Again, any damage function except N-N is in this range at 3 percent, and far above it at a 1.5 percent discount rate. With the N-N damage function and a 1.5 percent discount rate, the SCC in 2010 also exceeds the McKinsey estimate for 2030.

In short, if either low-temperature or high-temperature damages are worse than DICE assumes, then the SCC is roughly at the marginal abatement cost for a maximal abatement scenario at a 3 percent discount rate, or well above that level at a 1.5 percent discount rate. Even with the original DICE damage function, a 1.5 percent discount rate makes the SCC roughly equal to the marginal cost of a maximal abatement path.

7. Conclusions

We began by reviewing the U.S. government’s estimate of the SCC, developed for use in cost-benefit analysis of regulatory proposals. We have ended with alternate estimates that are not just minor revisions to the published figure of \$21 per ton, but are higher, in most cases, by more than an order of magnitude. These estimates appear to be well outside the bounds of realistic short-term policy options, in the United States or elsewhere. How should these ultra-high SCC values be interpreted?

The SCC represents the marginal cost of climate damages, or the cost of doing nothing about climate change. In the cost-benefit framework, it should be compared to the marginal cost of climate protection. In the previous section we compared our SCC estimates to the marginal abatement cost on several versions of a maximum feasible abatement scenario, which would lead to zero or negative net global emissions before the end of this century. In the federal Working Group’s analysis, the SCC is well below the abatement cost for these scenarios. We found that if either climate damages are higher than DICE assumes, or the discount rate is closer to the *Stern Review’s* level, then

the SCC is roughly equal to the cost of maximum feasible abatement. If climate damages are higher than DICE assumes *and* a *Stern Review* discount rate is used, then the SCC is far above the cost of maximum feasible abatement.

Once the SCC is high enough to justify maximum feasible abatement in cost-benefit terms, then cost-benefit analysis becomes functionally equivalent to a precautionary approach to carbon emissions. All that remains for economic analysis of climate policy is to determine the cost-minimizing strategy for eliminating emissions as quickly as possible. This occurs because the marginal damages from emissions have become so large; the uncertainties explored in our analysis, regarding damages and climate sensitivity, imply that the marginal damage curve could turn nearly vertical at some point, representing a catastrophic or discontinuous change.

The factors driving this result are uncertainties, not known facts. We cannot know in advance how large climate damages, or climate sensitivity, will turn out to be. The argument is analogous to the case for buying insurance: it is the prudent choice, not because we are sure that catastrophe will occur, but because we cannot be sufficiently sure that it will not occur. By the time we know what climate sensitivity and high-temperature damages turn out to be, it will be much too late to do anything about it. The analysis here demonstrates that plausible values for key uncertainties imply catastrophically large values of the SCC.

This result can be generalized to other environmental issues: when there is a credible risk that the marginal damage curve for an externality turns vertical at some point (representing discontinuous, extremely large damages), then the shadow price of the externality, such as the SCC, becomes so large that cost-benefit analysis turns into cost-effectiveness analysis of the least-cost strategy for staying safely below the threshold.

Our results offer a new way to make sense of the puzzling finding by Martin Weitzman: his “dismal theorem” establishes that under certain assumptions, the marginal benefit of emission reduction could literally be infinite (Weitzman 2009). The SCC, which measures the marginal benefit of emission reduction, is not an observable price in any actual market. Rather, it is a shadow price, deduced from an analysis of climate dynamics and economic impacts. Its only meaning is as a guide to welfare calculations; we can obtain a more accurate understanding of the welfare consequences of policy choices by incorporating that shadow price for emissions.

Once the shadow price is high enough so that maximum feasible abatement is a welfare improvement, there is no additional meaning to an even higher price. Doubling or tripling the SCC beyond that level would have exactly the same implications for market behavior and policy choices: it would still be optimal to eliminate emissions as rapidly as possible. In this sense, it bears some resemblance to infinity, which is unaffected by doubling or tripling.¹⁴ Our highest SCC estimates are clearly not infinite – but they may be close enough to infinity for all practical purposes.

¹⁴ These SCC values bear an even closer resemblance to the concept of “machine infinity” in computer science, i.e. the largest number that a computer can represent. Doubling machine infinity cannot increase it (within that computer), but dividing by two decreases it. The same is true for the practical significance of an SCC estimate which is, for instance, 1.5 times the marginal cost of maximum feasible abatement.

What's left, finally, of the economic arguments for gradualism in climate policy, which seem to be endorsed by the Working Group's \$21 SCC? To support this approach, given our results, one would have to endorse both the original DICE damage function and a discount rate of 3 percent or more. Either a higher damage estimate or a lower discount rate pushes the SCC up to roughly the level that justifies the maximum feasible pace of abatement of \$150 – \$500 (lower in this range with average climate sensitivity, toward the top at the 95th percentile). At this level or above, cost-benefit analysis provides a result that is identical to a precautionary approach that endorses immediate, large-scale action to reduce emissions and avoid dangerous levels of climate change.

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Comments

Climate Risks and Carbon Prices: Revising the Social Cost of Carbon

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Introduction

In this note I offer some comments on the recently established “social cost of carbon” (SCC) for analysis of federal regulations in the United States (Interagency Working Group on Social Cost of Carbon 2010), and consider the importance of Frank Ackerman and Elizabeth Stanton’s new paper in that context (Ackerman and Stanton 2011). While thorough in some respects, I argue that the analysis of the Interagency Working Group on Social Cost of Carbon did not go far enough into the tail of low-probability, high-impact scenarios, a point that Ackerman and Stanton bring out clearly in their paper. This immediately raises questions about the treatment of risk and uncertainty in benefit-cost analysis. I argue that, via their approach to discounting, the Interagency Working Group mis-estimated climate risk, possibly hugely, and I also show that recent insights from the theory of decision-making under uncertainty caution against simple averaging of the estimates of different models, something the Interagency Working Group relied on. Finally, drawing on experience in the UK, I argue that, given the uncertainty about estimating the SCC, there is much to commend an approach whereby a quantitative, long-term emissions target is chosen (*partly* based on what we know about the SCC), and the price of carbon for regulatory impact analysis is then based on estimates of the marginal cost of abatement to achieve that very target. By means of a disclaimer, I willfully ignore some other important issues, such as how to weigh the impacts of US carbon dioxide (CO₂) emissions in other countries.

While the United States does not lead the world in making climate-change mitigation policies, it has been a pioneer in the use of benefit-cost analysis to inform the making of federal regulations more generally. The intention is that regulations are adopted only if they provide benefits in excess of their costs. Perhaps unsurprisingly, the reality of carrying out benefit-cost analysis of federal regulations falls short of best practice, and it does not appear to be having a significant impact on many regulatory decisions, except higher-profile cases (Hahn and Tetlock 2008). Nevertheless, the introduction of an SCC is a potentially significant step in the development of US climate-mitigation policy, especially in the continuing absence of dedicated, overarching mitigation policy instruments whose costs to individuals and firms could more directly enter benefit-cost calculations in other policy areas.

The damage function and the SCC

The SCC is the present value of the impact of an additional ton of CO₂ emitted to the atmosphere. In order to estimate it, one needs to use a simulation model connecting emissions of CO₂ with changes in individual utility and social welfare, expressed in terms of an equivalent change in consumption. It is very well known that such models, called “integrated assessment models”, face huge uncertainties. To its credit, the Interagency Working Group appears to have been well aware of the issue of uncertainty. First, it chose to use the three most prominent integrated assessment models, rather than opting for just one. Second, the models were submitted to Monte Carlo simulation methods, such that (some) uncertain parameters were treated as random variables, and the models eventually produced probability distribution functions for the SCC. Among these random variables, it is particularly noteworthy that the Working Group treated

the climate sensitivity, i.e. the change in the global mean temperature in equilibrium accompanying a doubling in the atmospheric stock of CO₂, as random, and specified a probability distribution with a large positive skew (p14-15). The climate sensitivity is known to be a very important parameter in estimating the SCC.

However, arguably the Working Group did not go far enough in its exploration of the uncertainty about another crucial set of parameters in the models, namely those establishing the “damage function” that links atmospheric temperature to economic impacts. This is where I believe Ackerman and Stanton’s new paper makes a significant contribution. The damage function, which may be sector-specific (as in the FUND model) or of a reduced form that aggregates across sectors (as in the DICE and PAGE models), is calibrated on more detailed impacts studies. Unfortunately, these studies give data points for low temperature changes only. To estimate the economic impact of larger temperature changes in the region of 5°C above pre-industrial and beyond, one simply extrapolates, making an assumption about functional form on which there is almost no data basis.

Recently, the work of Martin Weitzman (2010), and indeed of Frank Ackerman and his colleagues (2010), has questioned the prevailing assumptions made about functional form. To take the DICE model as an example (Nordhaus and Boyer 2000; Nordhaus 2008), it can be easily shown that the assumption of a quadratic relationship between damages and temperature, together with the modelers’ specific coefficient values, implies that global warming can reach more than 18°C before the equivalent of 50% of global GDP is lost. This seems remarkable: as Ackerman and Stanton remind us, such temperatures seem likely to test the limits of human physiology. While the parameters of the damage function in PAGE are modeled as random, such that damages reach up to around 10% of global GDP when global warming reaches 5°C, it has equally been argued that 5°C constitutes an environmental transformation, being a larger change in global mean temperature than exists between the present day and the peak of the last ice age. Surely it is at least *possible* that climate damages will exceed 10% of global GDP upon 5°C warming? As far as FUND is concerned, Figure 1A of the Interagency Working Group shows that its more complex, sectorally disaggregated approach implies total damages are actually *slowing* as warming passes 5°C, and at 8°C above pre-industrial they are only about 7% of GDP.¹⁶

Clearly this begs the question of how much higher the SCC might be, if the damage function becomes steeper, and Ackerman and Stanton attempt to answer it using the DICE model, applying a functional form proposed by Weitzman (2010). Furthermore, they also question the damage estimates of the models at low temperatures, drawing on work by Michael Hanemann (2008) that argues damages could also be significantly higher in this realm. Looking at these changes separately and together, they show that the SCC could be several times, even orders of magnitude, higher. This result is in fact corroborated by some recent analysis of my own. Combining steeply increasing damages with a positively skewed distribution on the climate sensitivity parameter, I otherwise replicated the analysis with PAGE for the Stern Review (Stern 2007) to also find that the SCC could be hundreds of dollars higher than previously estimated (Dietz forthcoming).

16 Some of the damage-function parameters in FUND were submitted to Monte Carlo simulation, but, while this informed estimation of the SCC, it was not used to generate a range or confidence interval around the aggregate damage function in Figure 1A. It is also worth noting that FUND’s damage functions are dependent on more factors than just temperature (e.g. income), and these vary along with temperature in the data presented in Figure 1A.

Discounting, risks to welfare, and uncertainty

The consequence of Ackerman and Stanton's modeling is thus to increase the range of possible climate damages, specifically to increase the upper limit, and this in turn increases the importance of properly handling risk and uncertainty. I will define these two terms in the sense introduced by Knight (1921), whereby the distinction turns on whether states of nature can be assigned precise probabilities¹⁷ (risk) or not (uncertainty, or, as it is often known nowadays, ambiguity). Using this distinction, it has become fairly common practice to conduct risk analysis around the SCC by performing Monte Carlo simulation using one particular model. What is less readily acknowledged is that having multiple models, which are structurally different (as in this case) and/or take different parameter distributions as their inputs (also true of this case), raises the issue of uncertainty.¹⁸

First consider risk. Within each of the integrated assessment models, the Working Group opted to use Monte Carlo simulation in conjunction with a fairly standard discounted cash flow analysis, of the sort used routinely in financial appraisal of private investments and social benefit-cost analysis of public projects. Each draw of the Monte Carlo simulation produced a stream of forecast monetary damages from climate change into the future, which was discounted back to the present at an exogenous, constant rate (2.5, 3 or 5%). The mean/expectation of the resulting probability distribution of present values of climate damage was used to estimate the SCC. It will be useful to keep in mind that this approach is identical to calculating a single stream of expected damages, treating this single stream as if it is deterministic, and discounting.

At first glance, this is an elegantly simple approach. Unfortunately it breaks down in the face of the sorts of large risk to future (welfare-equivalent) consumption prospects outlined in the previous section. To see why this is so, recall that, in making the final steps in an integrated assessment model from monetary climate damages to changes in social welfare, the transformation of consumption per capita into individual utility is non-linear, specifically the utility function is concave, because of the assumption that marginal utility is diminishing in rising consumption. In estimating the SCC, diminishing marginal utility plays at least two roles: it is a reason for discounting the future, if the future is forecast to be richer, and it implies risk aversion, and a consequent premium on individual willingness to pay to mitigate climate change, if climate change increases the spread on consumption prospects.¹⁹ Thus matters are somewhat complicated, and changes in the elasticity of the marginal utility of consumption have ambiguous effects in principle.

However, what is clear when looking at a set of draws from a Monte Carlo simulation is that diminishing marginal utility results in relatively more weight being placed on outcomes (i.e. draws) in which consumption is low. Indeed, outcomes in which consumption is exceptionally low can come to practically dominate the calculus. In the

17 These precise probabilities may be objective or subjective.

18 Having said that, even if we only had one model at our disposal, it would be natural to question whether the probabilities we have specified resolve all uncertainty, and the answer in the case of physical forecasts of future climate (and by implication economic forecasts) would have to be in the negative (Smith 2002). Ultimately, then, we cannot be sure how well our Monte Carlo simulations and our inter-model comparisons represent uncertainty in the real world.

19 It is also a reason to place greater weight on climate impacts on poor regions. However, the Working Group's analysis ignored this aspect.

context of integrated assessment models, outcomes in which consumption is exceptionally low are caused by catastrophic climate change, usually either due to high climate sensitivity and/or a steeply increasing damage function. This is why some have drawn the analogy between climate mitigation and insurance (e.g. Weitzman 2009), since low-probability, high-impact scenarios drive overall willingness to pay for mitigation.

The problem with the Working Group's analysis is that, by imposing an exogenous, constant discount rate, they are very likely to have completely mis-estimated the effect of low-probability, catastrophic consumption losses, allied to risk aversion. The exogenous discount rate is calibrated on a particular assumption about the future rate of consumption growth, which is usually put in the region of 1.5-2%. This is true whether a "prescriptive" approach is used to set the discount rate, in which the future rate of consumption growth must be explicitly estimated, or whether a "descriptive" approach is used, in which case observed market consumption interest rates are used, which of course depend on past rates of growth. The problem is that these rates of growth will be inconsistent with any scenarios in the Monte Carlo simulation where consumption does not grow as fast, or even falls. Moreover the discount rate is very sensitive to changes in consumption growth, because of diminishing marginal utility.

To put all of this another way, when there is risk around consumption and risk aversion, the expected utility of consumption is less than the utility of expected consumption, and in the presence of catastrophic climate change, with only a small probability of occurring, this difference can be very large indeed. The Working Group would have been advised not to use discounted cash flow methods, but rather to directly estimate social welfare in each draw of the Monte Carlo simulation, and then calculate the mean or expectation. In terms of the discount rate, this implies that there would have been one discount rate for each and every simulation draw, where the discount rate was based on actual consumption growth, allied to assumptions about pure time preference and diminishing marginal utility.

There remains the question of how to aggregate across models. It is quite natural to assume that the best way to do so is simply to average them, yet doing so requires at least two assumptions to be made, which may in practice be rather strong. The first is that the models should be assigned equal weight. This is a tricky issue to address, not least because, in forecasting economic outcomes centuries into the future, as a result of a climate system that has not been observed in the past, it is very difficult to validate the models. Furthermore, the various integrated assessment models have not been developed independently of each other. Faced with such difficulties, the Interagency Working Group appears to adhere to the principle of insufficient reason, assigning the models equal weight. With some trepidation, I will do likewise.

In outlining the second assumption, note that simple averaging runs counter to most economic research on ambiguity, which shows that individuals are averse to ambiguity (as summarized in Camerer and Weber 1992). Loosely speaking, this means that they prefer courses of action with known probabilities to those with unknown probabilities. While there are competing models of ambiguity aversion, what a number of them share is the concept that, in the presence of ambiguity aversion, pessimistic models that yield lower estimates of expected utility from a course of action demand more of the decision-maker's attention. In the present context, this means that the decision-maker focuses more on models yielding higher estimates of the SCC (see also Millner, Dietz and Heal 2010). It is important to stress that this weighting does not stem from a prior belief that one model is more likely to be correct in its forecast than another: in fact it will emerge even if the

models are given equal weight. Rather, the weighting stems from the decision-maker's preferences. The second assumption is then that the decision-maker is ambiguity-neutral.

A formal analysis of the ambiguity-weighted SCC would thus be desirable, although it is clearly a considerable undertaking. And, in fact, once one opens up this line of argument, there is no reason just to look at differences between the three integrated assessment models: within the models, the various uncertain parameters could doubtless all be assigned multiple probability distributions. A comprehensive exercise such as this might be considered infeasible at the present time. Nevertheless, there is general theoretical support for placing particular focus on the models yielding the highest estimates of the SCC.

Target-driven prices

All of this might leave the reader to draw the understandably fatalistic conclusion that estimation of the SCC is a fool's errand. I would not go nearly as far, but there is a sense in which setting a price of carbon for use in regulatory impact analysis could be made simpler.

The key observation here is that uncertainty about the SCC is currently a –great deal larger than uncertainty about the corresponding marginal abatement cost (MAC) of CO₂. Using recent reviews of the literature, we concluded that the range of estimates of the present SCC was a factor of ten larger than the corresponding range of estimates of the present MAC (Dietz and Fankhauser 2010). Since recent research, such as that of Ackerman and Stanton, has stretched out the upper tail of SCC estimates, this ratio could now be even greater.²⁰ Another observation is that all models, whether of the SCC or MAC or both, are imperfect, and few would disagree with the need to look to other forms of evidence in setting the stringency of climate policies. Given these two observations, it is possible to recommend an approach whereby a quantitative long-run emissions target is set, and insofar as prices are used to meet that target, they are based on the MAC, rather than the SCC (although clearly to avoid circularity the SCC needs to inform target setting). Doing so permits greater confidence that the target will be met, while the existence of a long-run quantity target in the first place can be supported by reasoning about the efficiency of price and quantity instruments under uncertainty (Stern 2007).²¹ This is the approach to carbon pricing that the UK has followed (Department of Energy and Climate Change (DECC) 2008), after several years of (mixed) experience in using the SCC (beginning with Clarkson and Deyes 2002). The Obama administration has set a target of reducing US greenhouse gas emissions by 80% by 2050 (which admittedly is not legally binding, unlike the UK's corresponding 80% target), so the question should be what price of carbon is required to deliver that target. The more consistent and robust source of that price is currently estimates of the MAC.

20 Using Tol (2007), we set the maximum SCC today to \$654/tCO₂ for our comparison. The maximum SCC in 2010 in Ackerman and Stanton (2011) is \$893/tCO₂. Unfortunately how the range of estimates of the MAC has evolved over the past few years is not known.

21 To expand, the comparative efficiency of price and quantity instruments under uncertainty is known to depend in a general setting on the relative slopes of the marginal cost and benefit functions (Weitzman 1974). In the context of carbon abatement, this insight has generally been used to recommend price instruments in the short run, since the short-run marginal benefit function for a long-lived stock pollutant (e.g. CO₂) is flat, compared with a short-run marginal cost function that is steep (Pizer 1999). However, in the long run, with the existence of possibly catastrophic climate change, the opposite seems to hold: marginal benefits are steeply increasing upon reaching some stock of CO₂, while marginal costs are fairly flat.

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