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The social cost of carbon in U.S. regulatory impact analyses: an introduction and critique

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Abstract In 2010, as part of a rulemaking on efficiency standards, the U.S. government published its first estimates of the benefits of reducing CO_2 emissions, referred to as the social cost of carbon (SCC). Using three climate economic models, an interagency task force concluded that regulatory impact analyses should use a central value of \$21 per metric ton of CO_2 for the monetized benefits of emission reductions. In addition, it suggested that sensitivity analysis be carried out with values of \$5, \$35, and \$65. These estimates have been criticized for relying upon discount rates that are considered too high for intergenerational cost–benefit analysis, and for treating monetized damages equivalently between regions, without regard to income levels. We reestimate the values from the models (1) using a range of discount rates and methodologies considered more appropriate for the very long time horizons associated with climate change and (2) using a methodology that assigns "equity weights" to damages based upon relative income levels between regions—i.e., a dollar's worth of damages occurring in a poor region is given more weight than one occurring in a wealthy region. Under our alternative discount rate specifications, we find an SCC 2.6 to over 12 times larger than the Working Group's central estimate of \$21; results are similar when the government's estimates are equity weighted. Our results suggest that regulatory impact analyses that use the government's limited range of SCC estimates will significantly understate potential benefits of climate mitigation. This has important implications with respect to greenhouse gas standards, in which debates over their stringency focus critically on the benefits of regulations justifying the industry compliance costs.

Keywords Social cost of carbon · Cost–benefit analysis · Climate change · Regulatory impact analysis

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Introduction

In February of 2010, an interagency committee of the U.S. government published its first estimates of the "social cost of carbon" (SCC), a monetized value of the marginal benefit of reducing 1 ton of CO_2.[1] This committee, established in 2009 under the direction of the Obama Administration, was created after the U.S. Court of Appeals for the Ninth Circuit in 2007 ruled, essentially, that the National Highway Transportation Traffic Safety Administration (NHTSA) had to assign a dollar value to benefits from reducing CO_2 emissions (i.e., "monetize" them) when the agency issued fuel economy standards.

NHTSA had taken the position that because there was a range of values for the benefits from CO_2 emission reductions in the economics literature, the agency should exclude any monetary value for them in its analysis of costs and benefits. The Court said: "NHTSA's reasoning is arbitrary and capricious for several reasons. First, while the record shows that there is a range of values, the value of carbon emissions reduction is certainly not zero" (Center for Biological Diversity v. NHTSA, 538F.3d 1172, 1200; 9th Cir., 2008).

The court's decision highlighted the need for an SCC estimate that could be used consistently across all

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[1] Models are being developed for other gases as well; in the meantime, their impacts are approximated by multiplying the SCC by a gas's CO_2 equivalency, or its "global warming potential." See the Intergovernmental Panel on Climate Change's Fourth Assessment Report (2007).

government agencies. Toward this end, the Obama Administration formed the committee, called the Interagency Working Group on the Social Cost of Carbon, in 2009 ("Working Group"). The Working Group, comprised of six executive branch offices and six regulatory agencies, was charged with developing the first official estimates of the SCC.

The SCC estimates published by the Working Group included a central value of $21 per metric ton of CO_2, with a range of alternatives to use for sensitivity analysis, equal to $5, $35, and $65.[2] Though the Working Group did not require agencies use a particular value, it did give some guidance: "…the central value that emerges is [$21 per ton of CO_2]…For purposes of capturing the uncertainties involved in regulatory impact analysis, we emphasize the importance and value of considering the full range." (US Government 2010, pp. 3, 25, 33).

Government regulatory agencies are now routinely using these estimates to calculate greenhouse gas reduction benefits in regulatory impact analyses (RIAs). While some statutes (e.g., the Clean Air Act) prohibit using the results of cost–benefit analysis in determining health-based standards, agencies still monetize benefits and present them, pursuant to several executive orders. (An executive order is a directive from the President to executive branch agencies, in this case, concerning procedures for developing regulations; an executive order does not change the agency's substantive obligations under the statute that it is enforcing).

The Working Group's SCCs have been widely criticized by economists, climate scientists, and environmental advocates, among others, for significantly understating future climate damages. This article focuses on two factors that substantially reduced the Working Group's estimates: its chosen discount rates and discounting methodology, and its decision not to weigh damages by the income levels of where they occur.[3]

Because compliance costs are usually incurred in the near term but benefits accrued much farther out, the discount rate is especially critical in climate policy analysis: the compounding effect of interest rates heavily penalizes estimated benefits, while costs are much less impacted. A high discount rate thus favors critics of greenhouse gas regulations and weakens the case regulatory agencies can make in setting stringent standards.

The Working Group chose high discount rates from a range of observed market interest rates (i.e., upper end values from the range were selected). Lower market interest rates, as well as alternative discount rates based upon intergenerational concerns, were not considered, despite their acceptance in both the economics literature and official government guidelines.

A well-established methodology for equity weighting was also available to the Working Group, but not used. Equity weighting assigns a higher value to a dollar's worth of damage occurring in a poor region than to one occurring in a wealthy one. With the majority of climate impacts expected to occur in low-income countries, this significantly lowered the Working Group's estimates.

In this paper, we reestimate the SCC models using discount rates that weigh future generations' costs and benefits more heavily than those used by the Working Group. Separately, we also reestimate the models using equity weights. Under our alternative discount rate specifications, we find an SCC 2.6 to over 12 times larger than the Working Group's central estimate of $21; results are similar when the government's estimates are equity weighted.

In addition to demonstrating the importance of these key assumptions, we hope to provide a useful introduction to the social cost of carbon accessible to an interdisciplinary audience. Because the SCC involves a number of deeply ethical and philosophical issues, and depends critically on the SCC models accurately capturing climate science, it is essential that its further development includes input from a broad range of disciplines spanning both the social and physical sciences.

The second section ("The social cost of carbon models used by the Working Group") describes the general structure of social cost of carbon models, and the overall framework used by the Working Group. The next section ("Technical background on discounting") provides background on discounting, followed by a detailed discussion in the fourth section of related parameters (discount rates and equity weights) chosen by the Working Group. In the fifth section, "Discount rates and methodology as implemented by the Working Group" we critique the Working Group's assumptions, and in "Re-estimating the WG's estimates using alternative discounting and equity weighting" re-estimate their SCCs using criteria we consider more appropriate for intergenerational climate damages. "Policy implications" examines cost–benefit calculations in two federal regulatory impact analyses utilizing the SCC. We conclude in the final section.

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[2] All figures in this article are given in 2007 dollars, and rounded to the nearest dollar.

[3] As discussed further below, other variables are also important in explaining the Working Group's low SCCs, including the limited number of damages represented in the SCC models, a limited representation of catastrophic risks, and a lack of accounting for risk aversion—which generally increases the SCC (Kousky and Kopp, 2011). Unfortunately, re-estimating the SCC along any of these lines would require additional data currently unavailable, methodologies that are only in early stages of development within the literature, or both.

The social cost of carbon models used by the Working Group

The Working Group relied upon three climate economic models to estimate the SCC, called integrated assessment models (IAMs). IAMs, as suggested by their name, integrate climate science with economic analysis. Their overall architecture is relatively straight forward. First, they project future emissions based upon various socioeconomic (GDP and population) projections. Emissions are then translated into atmospheric concentration levels, concentration levels into temperature changes, and temperature changes into monetized economic damages. Damages increase over time as physical and economic systems become more stressed in response to greater climate change.

Damages are only included to the extent that they impact human welfare in some way (i.e., the SCC is an anthropocentric measure of well-being), and are based upon monetized estimates of impacts as published in the economics literature. These include damages such as property value losses due to rising sea levels, positive and negative impacts on agriculture, changes in heating and cooling expenditures, climate-related diseases such as malaria and dengue fever, and ecosystem losses.

It is generally acknowledged that the SCC is likely to understate impacts by excluding a large number of factors that would increase it while excluding only a very small number of countervailing forces. This is reflected in how the Working Group summarizes potential biases, and their implications for future SCC estimates:

> … Current IAMs do not assign value to all of the important physical, ecological, and economic impacts of climate change recognized in the climate change literature…because of lack of precise information on the nature of damages and because the science incorporated into these models understandably lags behind the most recent research. Our ability to quantify and monetize impacts will undoubtedly improve with time. But it is also likely that even in future applications, a number of potentially significant damage categories will remain non-monetized. (Ocean acidification is one example of a potentially large damage from CO_2 emissions not quantified by any of the three models. Species and wildlife loss is another example that is exceedingly difficult to monetize).
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> …As noted above, the damage functions underlying the three IAMs used to estimate the SCC may not capture the economic effects of all possible adverse consequences of climate change and may therefore lead to underestimates of the SCC (Mastrandrea 2009). In particular, the models' functional forms may not adequately capture: (1) potentially discontinuous "tipping point" behavior in Earth systems,[4] (2) inter-sectoral and inter-regional interactions,[5] including global security impacts of high-end warming, and (3) limited near-term substitutability between damage to natural systems and increased consumption.
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> It is the hope of the interagency group that over time researchers and modelers will work to fill these gaps and that the SCC estimates used for regulatory analysis by the Federal government will continue to evolve with improvements in modeling (US Government 2010, pp. 29, 31)

Against these sources of downward biases, the Working Group notes two factors that might bias the SCC in either direction:[6]

> [The] models do not adequately account for potential adaptation or technical change that might alter the emissions pathway and resulting damages. In this respect, it is difficult to determine whether the incomplete treatment of adaptation and technological change in these IAMs under or overstate the likely damages (US Government 2010, p. 30).

The three models the Working Group relied upon were three popular IAMs used in the peer-reviewed literature: DICE, Policy Analysis of the Greenhouse Effect (PAGE), and Climate Framework for Uncertainty, Negotiation, and Distribution (FUND). DICE (Dynamic Integrated Climate and Economy) evolved from a series of energy models, and was developed by William Nordhaus (Nordhaus and Boyer 2000; Nordhaus 2008); PAGE has been used by European decision makers in assessing the marginal impact of carbon

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[4] The PAGE model used by the Working Group (see below) does include potential damages from tipping points. For any given temperature increase above some tolerable threshold, the model assigns a positive probability of reaching a tipping point. It then specifies a percentage of world GDP that would be lost in that instance. See Hope (2006, 2008) for a more detailed description.

[5] These impacts refer to interactions between events, where one type of climate damage can lead to, or exacerbate, another. For example, extreme weather events could lead to various public health damages ("inter-sectoral") or mass migration, which in turn could lead to socio-political international conflicts ("inter-regional").

[6] In the case of downward biases, the Working Group notes several ways in which the models may be overly optimistic with respect to adaptation and technology assumptions. DICE, for example, assumes healthcare technologies improve over time, so that health impacts are reduced. In PAGE, an explicit parameter specifies the percentage of damages that can be adapted to, with especially large amounts assumed in the version of PAGE used by the Working Group, so much so that Ackerman et al. (2009) questioned whether so much adaptation would actually occur in reality (the model has since been updated with reduced percentages). In both DICE and FUND, assumed changes in agricultural practices mitigate some climate impacts, but these calibrations do not account for negative effects of increased climate variability, pests, or diseases.

emissions, and was developed by Chris Hope (Hope 2006, 2008); FUND was originally developed to study international capital transfers in climate policy and is now widely used to study climate impacts (e.g., Tol 2002a, b, 2009; Anthoff et al. 2009), and developed initially by Richard Tol.[7]

While the models differ in certain respects,[8] the Working Group treated them identically with respect to three factors: (1) uncertainty in future emission levels and the resulting climate sensitivity; (2) inclusion of global impacts; and (3) discount rates and discounting methodology.

Uncertainty in future emissions and climate sensitivity

To reflect uncertainty in future emission levels and climate response, the Working Group selected five socioeconomic and emissions trajectories. The trajectories were developed by the Stanford Energy Modeling Forum (EMF).[9] Four represent possible business-as-usual (BAU) scenarios varying by population, wealth, and emissions growth; these produced CO_2 concentration levels ranging from 612 to 889 ppm by 2100. The fifth scenario represents an emissions pathway that achieves stabilization at 550 ppm CO_2-equivalency (CO_2-only concentrations of 425–484 ppm) in 2100, a lower-than-BAU trajectory the Working Group considered consistent with widespread action by countries to mitigate ghg emissions, or unexpected advances in low-carbon technologies.

The Working Group further treated uncertainty in climate projections by using a statistical procedure known as a Monte Carlo simulation. A Monte Carlo simulation runs any given model repeatedly, each time randomly picking values for uncertain parameters with specified probability distributions. In this case, the random parameter was climate sensitivity, defined as the long-term increase in the annual global-average surface temperature from a doubling of atmospheric CO_2 concentration relative to pre-industrial levels (or stabilization at a concentration of approximately 550 parts per million (ppm)). For each emissions scenario, a model was run 10,000 times. This produced 150,000 "sub" SCC estimates, which were then further averaged to produce a final SCC (3 models × 5 emissions scenarios × 10,000 runs per emission scenario), for each of the Working Group's three discount rates (discussed further below).

To determine a probability distribution to use for climate sensitivity, the Working Group consulted with lead authors of the International Panel on Climate Change (IPCC). The most authoritative statement about equilibrium climate sensitivity appears in the IPCC's Fourth Assessment Report:

> Basing our assessment on a combination of several independent lines of evidence…including observed climate change and the strength of known feedbacks simulated in [global climate models], we conclude that the global mean equilibrium warming for doubling of CO_2, or 'equilibrium climate sensitivity', is likely to lie in the range 2 °C to 4.5 °C, with a most likely value of about 3 °C. Equilibrium climate sensitivity is very likely larger than 1.5 °C.[10] For fundamental physical reasons as well as data limitations, values substantially higher than 4.5 °C still cannot be excluded, but agreement with observations and proxy data is generally worse for those high values than for values in the 2 °C to 4.5 °C range (US Government 2010, p. 13).

The Working Group selected the Roe and Baker (2007) probability distribution among four candidate distributions (Roe and Baker, log-normal, gamma, and Weibull), and calibrated it to be consistent with IPCC text above (US Government 2010).

Global social cost of carbon

One of the most important decisions made by the Working Group was its choice to estimate a "global" SCC rather than a "domestic" one. A domestic SCC value is meant to reflect the value of damages in the U.S.A. resulting from a unit change in carbon dioxide emissions, while a global SCC value is meant to reflect the value of damages worldwide. Because a majority of damages are expected to occur outside the U.S., estimated global SCCs are usually much higher than domestic ones.[11]

Legally, the relevant statutory provisions are usually ambiguous as to whether a domestic or global SCC is permissible (US Government 2010). However, empirical, theoretical, and ethical arguments strongly support the use of a global value.

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[7] David Anthoff now co-develops revised versions of FUND with Tol.

[8] While similar in overall architecture, the models differ in some important ways that explain the different SCCs they produce. A discussion of these is beyond the scope of this article. A summary can be found in the Working Group's analysis; Ackerman and Stanton (2011) also provide a comprehensive overview of climate economics that includes a detailed discussion and critique of the three models. Full descriptions of the models published by their developers are available as cited above.

[9] The Working Group chose the EMF scenarios over those developed by the United Nation's Intergovernmental Panel on Climate Change (IPCC) on the rationale that they were more recent (the IPCC scenarios date back to the 1997 Second Assessment Report), while at the same time also peer-reviewed, published, and publicly available. See http://emf.stanford.edu/ for a description.

[10] This is in accord with the judgment that it "is likely to lie in the range 2 to 4.5 °C" and the IPCC definition of "likely" as greater than 66 % probability (Le Treut et al. (2007)). "Very likely" indicates a greater than 90 % probability.

[11] For example, in a 2009 regulation of fuel economy standards, the Department of Transportation calculated a separate $2 domestic SCC and a $33 global SCC (US Government 2010, p. 3).

First, from a purely self-interested standpoint, excluding global damages is not in U.S. interests, as greenhouse gas emissions have effects in other countries that will likely spill over to the U.S.A. For example, national security could be threatened from international disputes resulting from conflicts over stressed resources, humanitarian crises, sea level rise, epidemics, and mass migration from heavily impacted areas. Studies on national security and climate change describe global warming as a "threat multiplier," and warn of impacts on the U.S.A. resulting from climate damages in the rest of the world.[12,13]

From a public goods perspective, only a global SCC makes sense. If all countries conducted regulatory analyses using domestic SCCs, the result would be mitigation levels far below the optimum, creating a massive public goods failure.[14] Strategically, emissions reductions the U.S.A. undertakes could lead other countries to reduce their emissions. If that turns out to be true, a domestic SCC will greatly underestimate the total benefits of emissions reductions.

Finally, it is difficult to ethically justify that the U.S.A. should value the damages it imposes upon other countries at zero. Many countries, especially poor ones, did not contribute to current CO_2 levels in the atmosphere, yet will suffer the worst consequences. Further, developed countries obtained their income status by emitting greenhouse gases, and as a result have more resources to absorb climate damages, while the opposite is true of the poor countries.

Discounting methodology

The Working Group used constant discount rates of 2.5, 3, and 5 %, and considered the value from 3 % as the mean, or "central," SCC value. It also gave as an upper-bound sensitivity the 95th percentile estimate from the 3 % discount rate case. Before presenting the Working Group's rationale for its discounting methodology, our critique of it, and our alternative estimates, we first provide necessary technical background in the next section.

Technical background on discounting

Discounting is a standard practice in economics when calculating costs and benefits over time. Because money today is more valuable than the same amount of money in the future due to interest and economic growth, a dollar today is not directly comparable to one received in the future. Economists therefore "discount" future income streams to express them in the same year's value, or their "present value."

The formula for discounting is straight forward. If \$100 is invested today with a 5 % real (inflation-adjusted) annual return, in 1 year it will be worth \$105. In two, it will be worth \$105 plus 5 % of \$105, or \$110.25. Mathematically, this can be represented by a simple equation, $FV=PV\times(1+r)^t$, where FV stands for future value, PV for present value, r for the discount rate, and t for the year in which a cost or benefit occurs. Inverting the formula for the present value gives $PV=FV/(1+r)^t$. The discount rate is often estimated from market interest rates, discussed further below.

Applying this formula to climate damages that occur many years in the future shows why the discount rate is so critical. Twenty-five years from now, \$100 worth of climate damage has a present value of only \$30 ($\$100/(1.05^{25})$) if a 5 % annual discount rate is used, due to the effect of compound interest. Occurring 100 years from now it is practically 0, at 76 cents.

The interest rate

The Working Group concluded that climate damages are expected to primarily affect consumers through higher prices of goods and services, rather than capital investments. As such, the SCC was discounted using what is referred to as a "consumption" discount rate,[15] which reflects how much households are willing to sacrifice in consumption today in order to have more in the future, or how much they are willing to pay to borrow from future consumption. Broadly speaking, that amount will depend upon how

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[12] The CNA Corporation, (2007). National Security and the Threat of Climate Change. http://securityandclimate.cna.org.

[13] National Intelligence Council, (2008). National Intelligence Assessment on the National Security Implications of Global Climate Change to 2030. As presented at the Permanent Select Committee on Intelligence and the Select Committee on Energy Independence and Global Warming, 25 June 2008, in the testimony of Dr. Thomas Fingar, Deputy Director of National Intelligence for Analysis and Chairman of the National Intelligence Council. http://www.dni.gov/testimonies/20080625_testimony.pdf.

[14] Public goods failure in this context refers to a situation in which it is in one's self interest to ignore negative externalities s/he is imposing on others; with everyone behaving this way, everyone is worse off than they would have been had they taken into account the effects of their choices on others.

[15] The U.S. Office of Management and Budget distinguishes between projects that impact consumption verses investment flows. Specifically: "…the average before-tax rate of return to private capital in the U.S. economy…is a broad measure that reflects the returns to real estate and small business capital as well as corporate capital. It approximates the opportunity cost of capital, and it is the appropriate discount rate whenever the main effect of a regulation is to displace or alter the use of capital in the private sector…The effects of regulation do not always fall exclusively or primarily on the allocation of capital. When regulation primarily and directly affects private consumption (e.g., through higher consumer prices for goods and services), a lower discount rate is appropriate…This simply means the rate at which a society discounts future consumption flows to their present value." (OMB 2003, p. 33).

impatient individuals are, the size of their incomes now versus what they expect them to be in the future, and the risk of default perceived by lenders for a given type of asset.

The Ramsey equation

Consumption discount rates are modeled in economic theory with a well-known equation developed by Frank Ramsey (1928):

$$r = \rho + \eta g,$$

where r is the discount rate, ρ the "pure rate of time preference" (PRTP), η the "elasticity of marginal utility," and g the per capita rate of growth in consumption.

The parameter ρ ("rho") captures the psychological tendency to prefer experiencing utility from consumption today over delaying it into the future (i.e., how "impatient" an individual is). With multiple generations being affected by climate change, many argue that the only value for ρ that is both theoretically coherent and morally defensible is 0: ρ represents an individual's preference for when *he or she* consumes wealth and income, not when others do; the person emitting greenhouse gases today is not the same person experiencing climate damages in the future. Ramsey himself argued that it is "ethically indefensible" to apply a positive rate of pure time preference across different generations. To our knowledge, the only potentially ethical justification put forth for doing so is the unlikely possibility that the human race becomes extinct in the future (for a reason unrelated to climate change).[16]

"Eta" (η) captures the utilitarian concept that as one's income increases, each additional dollar gives less utility. Conversely, as income decreases, each additional dollar lost brings more "disutility."

In the instance of social cost–benefit analysis, where a policy analyst is evaluating choices that affect multiple individuals over time, η takes on an additional, and important role: it weighs costs and benefits *between* individuals living in different time periods according to their income levels. For the SCC, damages would be weighed less over time the richer society becomes, as each additional dollar's worth of damage brings less disutility at higher income levels. Conversely, if society becomes poorer over time, each additional dollar's worth of damage would bring a *higher* disutility, justifying weighing future damages more heavily than present ones. In practice, this means that if future consumption is assumed to grow (decline), each additional dollar's worth of damage in the future will be weighed less (more) than if it had occurred earlier in time.

Finally, the growth term, g, correspondingly captures changes in income and consumption. If g is positive, the discount rate increases; if it is negative, it decreases. This relationship is also important, since climate damages could negatively interfere with economic productivity, resulting in a contraction of output and therefore lower discount rate. In the extreme, if the rate of time preference is 0, the Ramsey equation would yield a negative discount rate if output per capita is expected to decrease over time.

Ethical justifications for discounting future climate damages

From this discussion, we can see that one justification for discounting climate impacts is if people in the future are wealthier than people today. An example using the present value equation demonstrates the point. Suppose per capita consumption is equal to \$35,000 today, and grows by 2 % per year. One hundred years from now, per capita consumption would be almost \$254,000 ($\$35{,}000 \times 1.02^{100}$). The average person in 100 years would be almost \$219,000 richer than the average person today. Assuming all things can be measured quantitatively in monetary units, only if damages exceed \$219,000 will that future person be worse off than today as a result of climate change.

Another justification for discounting damages, one perhaps not as obvious, is based upon the concept of the opportunity cost of forgone investments. By investing in climate mitigation, society gives up the opportunity to invest that money in alternative assets, and as a result could actually *lower* future generations' income relative to what it would have been otherwise. For instance, suppose the return on alternative investments is 5 % per year. If society spent \$10 on mitigation to prevent the \$100 in damages 100 years from now, that implies a return of approximately 2.33 % (at 2.33 % per year, \$10 grows to \$100 in future value). Had the \$10 been invested at 5 % instead, there would be a 2.67 % higher return (5 % less 2.33 %), equal to \$140. Only if it cost less than 76 cents to mitigate the \$100 of damage would mitigation be a better investment (recall from above that 76 cents is the present value of \$100 at 5 % interest over 100 years; any cost less than 76 cents would give a return higher than 5 %).

While these two reasons, wealthier future generations and the potential for higher returns elsewhere, might seem more justified than time preference discounting, they also rely upon value judgments. We take this up further below, after explaining the discount rates and methodology chosen by the Working Group.

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[16] The Stern Review (2007) used a rate of pure time preference of 0.1 % per year, based on an arbitrary estimate of the annual probability that the human race will not survive.

Discount rates and methodology as implemented by the Working Group

The Working Group chose three discount rates, based largely upon empirically observed interest rates, of 2.5, 3, and 5 %.

The core rate of 3 % was chosen on the basis that it is the average "risk-free" rate savers and borrowers use to discount future consumption, approximated by the long-term return on 10 year U.S. Treasury notes. A "risk-free" rate is justified if one assumes that individuals would be satisfied with a return on mitigation similar to one found on a "safe" asset, i.e., an asset that yields, with high confidence, a small but positive return.

The 2.5 % rate was based upon historical data showing that, due to interest rate (and, indirectly, growth rate) uncertainty, investors implicitly use declining discount rates over long time periods that imply lower effective constant discount rates. The Working Group noted that this rate was also consistent with (1) the U.S. Office of Management and Budget guidelines specifying that rates lower than 3 % can be used for sensitivity analysis in instances of intergenerational discounting; and (2) the possibility that the economy could be performing worse at higher future temperatures; in this instance, the marginal disutility of damages would be higher due to lower future income levels, justifying a lower discount rate.[17]

Finally, the highest value of 5 % was justified on the grounds that some borrowers are willing to pay higher interest rates than the risk-free rate: "the high interest rates that credit-constrained individuals accept suggest that some account should be given to the discount rate revealed by their behavior" (US Government 2010). The Working Group also noted that 5 % would be appropriate if the economy were performing better at higher future temperatures, perhaps due to higher growth rates associated with higher emission levels; in this instance, the marginal disutility of damages would be lower due to larger future income levels, justifying a higher discount rate.

In explaining its preference for market interest rates over a Ramsey formulation, the Working Group noted that there was wide disagreement as to what values parameters in the Ramsey equation should take, in particular ρ and η. Not only is there a range of estimates of values as they apply to an individual's own income over time, there is also a range of estimates over what individuals think these values should be when applied to individuals other than themselves. Choosing among different empirical or theoretical estimates would require normative judgments as to the appropriate Ramsey discount rate. The Working Group argued that, in contrast, market interest rates reflect actual preferences, and spare the decision maker from having to impose his or her own subjective values: "Advocates of this approach generally call for inferring the discount rate from market rates of return 'because of a lack of justification for choosing a social welfare function that is any different than what [individuals] actually use' (Arrow et al. 1996)" (US Government 2010). The Working Group thus concluded that market discount rates would be more "defensible and transparent."

Critique of Working Group's discount rates and methodology

Our critique of the Working Group's discounting is straight forward. First, it did not consider the full range of consumption interest rates observed in markets, nor intergenerational discount rates established in the economics literature and recognized in government guidelines. Second, it treated every dollar worth of damages occurring in poorer regions as having equal impact as one occurring in wealthier ones. The Working Group failed to adequately justify its choices.

In this section, we discuss the alternative discount rates the Working Group elected not to use, as well as the rationale for equity weighting—a sound cost–benefit principle, for which a widely applied methodology is available to use when estimating the SCC.

The Working Group's discount rates

The Working Group provided a rationale for the upper end discount rates it selected, but did not do the same for *excluding* lower values. Guidelines for economic analysis written by two prominent members of the Working Group, the Environmental Protection Agency (EPA) and the Office of Management and Budget (OMB), both consider lower rates appropriate in special circumstances, where benefits and costs are incurred by future generations. Britain's government used a constant rate of 1.4 % in the Stern Review's SCC estimate (Stern 2007).

In a 2008 technical support document, EPA suggests a lower end value of 0.5 % (and an upper end no greater than 3 %),[18] noting the following:

> A review of the literature indicates that rates of three percent or lower are more consistent with conditions associated with long-run uncertainty in economic growth and interest rates, intergenerational considerations, and

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[17] Put another way, if there is any uncertainty in future consumption levels, mitigation pays off the most in bad states of the world, increasing its value. For a mathematical derivation of the relationship between uncertainty in income and marginal utility, see Cochrane (2001). Howarth (2003) also provides a helpful discussion.

[18] EPA's Guidelines for Preparing Economic Analyses (2000) also note that estimates of intergenerational discount rates "generally range from one-half to three percent (p50)." Interestingly, the most recently published Guidelines (2010) do not provide estimates of intergenerational discount rates.

> the risk of high impact climate damages (which could reduce or reverse economic growth) (EPA 2008, p. 9)[19]

OMB suggests sensitivity analysis from 1 to 3 % would be reasonable:

> Special ethical considerations arise when comparing benefits and costs across generations. Although most people demonstrate time preference in their own consumption behavior, it may not be appropriate for society to demonstrate a similar preference when deciding between the well-being of current and future generations. Future citizens who are affected by such choices cannot take part in making them, and today's society must act with some consideration of their interest… estimates of appropriate discount rates in this case, from the 1990s, [range] from 1 to 3 % per annum (OMB 2003, p. 35).

OMB writes further that lower rates can be justified on the basis of uncertainty about the appropriate rate to use over long time horizons:

> A second reason for discounting the benefits and costs accruing to future generations at a lower rate is increased uncertainty about the appropriate value of the discount rate, the longer the horizon for the analysis. Private market rates provide a reliable reference for determining how society values time within a generation, but for extremely long time periods no comparable private rates exist (OMB 2003, p. 36).

With respect to the 3 and 2.5 % discount rates, the Working Group selected from the higher end of available estimates that each of these rates were intended to represent.

The 3 % discount rate was chosen to approximate the post-tax "risk-free" rate of return. It represents the long-run average return on 10-year U.S. Treasury notes, which carry significantly more inflation risk than shorter-term low-risk assets.[20] In the finance literature, Treasury bills are often interpreted as a risk-free asset, because their real returns are highly stable over time, and adjust rapidly to changes in inflation (Howarth 2003). Between 1926 and 2000, these paid an average pre-tax return of 0.7 % per year, and 0 % post-tax (Ibbotson Associates, 2001). Similarly, returns lower than the 3 % used by the Working Group are observed on safe private-sector assets, such as money market accounts and certificates of deposit. Even low-risk corporate bonds generate lower returns than the Working Group's 3 %: over the same time period, Ibbotson finds an average return of 2.6 % pre-tax and 1.5 % post-tax.

The Working Group's lowest discount rate of 2.5 %, based upon the work of Newell and Pizer (2003), was also the highest among available estimates of declining discount rates.[21] Two alternatives imply lower effective (constant) discount rates: one officially published by the UK Treasury in guidelines for government analyses, and another estimated by Weitzman (2001), from a broad survey of economists.[22] Weitzman elicited 2,800 responses from Ph.D. economists, who stated what discount rates they felt should be used for climate change damages the farther into the future they occur. The percentage of surveys returned was high (77 %), and his results published in the top economics journal in the profession. Notably, the top 50 preeminent scholars in his sample (the "blue ribbon" economists, e.g., some with Nobel prizes) prescribed rates comparable to the other respondents.

In short, the full range of intergenerational discount rates (0.5 to 3 %, per EPA's 2008 technical support document and OMB guidelines, the UK's SCC estimate using 1.4 %, and the UK Green Book and Weitzman's declining discount rate schedules) justify discount rates much lower than the Working Group's lower bound of 2.5 %. The Working Group consistently chose the highest discount rates available, without explaining its rejection of alternative lower ones.

To review, the discussion above and in the previous section point to several justifications for low discount rates: (1) individuals may view mitigation investments similarly to how they value "safe" assets, i.e., assets that yield, with high certainty, small but positive returns; (2) to allow for the possibility that future generations will have a preference for alternative discount rates and methodologies; (3) to allow for the possibility that private market rates for extremely long time horizons, were they to exist, may be lower than observed interest rates; (4) to reflect the fact that investors implicitly use declining discount rates over long time periods, implying lower effective constant discount rates;

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[19] Technical support document, U.S. EPA (2008). EPA notes in the beginning of the document that it began developing most of the information in the report in support of the Executive Order 13432, for developing Clean Air Act regulations that would reduce GHG emissions from motor vehicles. The report does not reflect an official agency decision and, to the authors' knowledge, EPA has not since released any documents specifying an official range for intergenerational discount rates. We also note that the 2000 guidelines discussion of intergenerational discount rates, similar to OMB, is not an agency directive specifying these discount rates must be used in agency analysis.

[20] On Treasury notes, OMB cites evidence of a 3.1 % average pre-tax rate (2003); after adjusting for Federal taxes, the Working Group (p20) estimates a post-tax return of about 2.7 %; Newell and Pizer (2003) find pre-tax interest rates between 3.5 and 4 %, while Arrow (2000) suggests roughly 3–4 %.

[21] Newell and Pizer estimated two declining discount that gave equivalent constant discount rates of 2.2 and 2.8 %; the Working Group took 2.5 as a mid-point.

[22] As shown in the next section, using either alternative discount rate schedule produces higher SCC estimates than the Working Group's at 2.5 %.

and (5) to take into account the possibility that the economy could be performing worse at higher future temperatures, so that the marginal disutility of damages would be higher due to lower future income levels.

To this list, one more factor can be added: private investors (and hence market interest rates) do not take into account pollution externalities resulting from production, such as the depreciation of natural capital (e.g., loss of natural habitats to development and pollution) and public health damages, or other potentially negative social impacts related to economic production, such as inequality. They therefore tend to overestimate the impact growth has on real social welfare.

Sterner and Person (2008) provide an interesting and related argument: as access to environmental goods and services is reduced by climate damages, their relative value will increase substantially so that the "public bads" from climate change, and therefore the SCC, will be much higher. Indeed, they find that adjusting relative prices could have equally powerful impacts on the SCC as discount rates.

We can get a sense of the distortion in market interest rates caused by negative externalities by examining past efforts made to adjust gross domestic product (GDP) for them. Estimates vary widely, depending upon the year(s) examined and the methodologies employed, but all find adjusted growth to be lower than unadjusted. Goodstein (2004) summarizes three studies of adjusted annual GDP per capita growth, finding a range of 0.2 to 3.1 percentage points lower, for various time periods.[23] A more recent analysis by Talberth et al. (2007) found annual per capita adjusted growth rate 2.5 percentage points below GDP. This data suggests that, based upon historical data alone (which may be more forgiving than the future under climate change), adjusting the real growth rate term in the Ramsey equation, or the growth implicit in market interest rates, could significantly lower the discount rate.

Equity weighting

As with lower discount rates, equity weighting is strongly justified in the academic literature, and common in policy analysis. Extensive research finds that many individuals believe that inequality reduces their welfare even if their own income level is unaffected, referred to as "inequality aversion." Correspondingly, equity weights are discussed extensively in the economics literature, and widely used in policy analysis (Azar and Sterner 1996; Fankhauser et al. 1997), including by Great Britain (Clarkson and Deyes 2002), Germany (Umweltbundesamt 2007), and the European Commission. As Anthoff et al. (2009) argue, the question is not whether to use equity weights, but rather what equity weights to use. Contrary to the Working Group's argument, there is simply no way of avoiding the issue: by failing to equity weight of the SCC, the Working group effectively assumed an equity weight of unity, i.e., a dollar's worth of damage to a poor person is equivalent to one experienced by a wealthier person.

Inequality aversion is particularly relevant with climate change: poorer regions are expected to have far less income to cope with damages than are wealthier regions, a problem compounded by the fact that they are also expected to bear more of the damages while having contributed the least to the problem.[24] The methodology used by the Working Group neglects this inequality, both at any given point in time, as well as with respect to changes in wealth over time.[25,26]

The Working Group acknowledged the validity of arguments in favor of equity weighting, but countered those with what we view as a weak rationale. Specifically, it noted that emissions reductions also impose costs that would need to be equity weighted, in order to completely account for equity impacts of mitigation, i.e., a given cost of emissions reductions would impose a greater utility or welfare loss on a poor region than on a wealthy one (US Government 2010, footnote 7). The problem with this argument is that regulations mitigating greenhouse gases in the U.S.A. will impose costs predominantly on the U.S.A.;[27] a global policy with different mitigation costs across countries is not what is being evaluated.

Objectivity and transparency

In the final analysis, the Working Group's claim, that using observed market interest rates allows the decision maker to

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[23] Goodstein summarizes Nordhaus and Tobin (1972), who estimate a 0.7 percentage point difference in annual per capita growth between 1929 and 1965, and a 1.8 percentage point difference between 1947 and 1965; Zolatas (1981), who estimates 1.8 % (1947–1965), 1.6 % (1950–1965), and 1.5 % (1965–1977) differences; and Daly and Cobb (1989), who estimate differences of 0.2 (1950–1960), 0.6 (1960–1970), 3 (1970–1980) and 3.1 (1980–1986).

[24] Though a majority of these regions are expected to remain poor in the future, some inequality will be mitigated by the fact that a few countries are projected to grow so rapidly that they eventually catch up with today's wealthier countries.

[25] Although not the focus of this paper, it is important to note that the Working Group's use of constant discount rates is internally inconsistent the EMF-22 scenarios in the IAM models specifying growth rates that vary by regions.

[26] An extensive discussion of questions related to equity weighting can be found in Dietz et al. (2009).

[27] Theoretically, it is possible that U.S. regulations could increase prices of internationally consumed goods, but we would argue such effects would be orders of magnitude smaller than costs to the U.S., if any at all.

avoid imposing his or her own normative judgments, cannot be sustained. In effect, it assumes that future generations will have a preference for consumption discount rates; that these rates should be approximated by market interest rates rather than through the Ramsey equation; that the rate of time preference should be greater than 0 (a positive time preference is embedded in market rates); and that inequality aversion is not important. All of these assumptions require ethical judgments by the decision maker that cannot be avoided.

Nor are market interest rates "transparent": one cannot determine what is implicitly being assumed regarding impatience preferences (the rate of time preference), versus what is being assumed about preferences to smooth income, and hence consumption, over time.

Re-estimating the WG's estimates using alternative discounting and equity weighting

Alternative discount rates and declining discount rates

We re-ran the Working Group's SCC models using constant discount rates of 1, 1.5, and 2 %, rates consistent with those suggested by both EPA and OMB; we also re-ran them using the UK Green Book and Weitzman declining discount rate schedules.[28,29] Table 1 presents our results, alongside the Working Group's SCC estimates using 2.5, 3, and 5 %. In addition, we provide the 95th and 99th percentile estimates at all discount rates.

Our alternative estimates find the highest SCC using the 1 % constant discount rate, equal to $266 ($758 and $1,774 at the 95th and 99th percentiles, respectively), and the lowest at $55 using the UK Green Book schedule ($156 and $304 at the 95th and 99th percentiles, respectively). Our five estimates exceed the Working Group's main estimate of $21 by factors ranging from 2.6 (Green Book) to 12.7 (1 % discount rate). Three exceed the Working Group's 95th percentile estimate of $65 at the 3 % discount rate by factors ranging from 1.9 (1.5 % discount rate) to 4 (1 % discount rate), one is almost identical ($62 at the 2 % discount rate), and the fifth 15 % lower ($55 using Green Book). All of the Working Group's 99th percentile values are lower than ours; the former range from $29 to $221, and the latter $304 to $1,774.

Table 1 2010 Social cost of carbon of CO_2 (2007$) using alternative discount rates

	SCC
Constant discount rate of 1%	$266
(95th percentile)	($758)
(99th percentile)	($1,774)
Constant discount rate of 1.5%	$122
(95th percentile)	($357)
(99th percentile)	($810)
Constant discount rate of 2%	$62
(95th percentile)	($187)
(99th percentile)	($386)
Constant discount rate of 2.5%, Working Group	$35
(95th percentile)	($107)
(99th percentile)	($221)
Constant discount rate of 3%, Working Group	$21
(95th percentile)	($65)
(99th percentile)	($134)
Constant discount rate of 5%, Working Group	$5
(95th percentile)	($16)
(99th percentile)	($29)
UK Green Book declining rate schedule	$55
(95th percentile)	($156)
(99th percentile)	($304)
Weitzman declining discount rate schedule	$175
(95th percentile)	($380)
(99th percentile)	($702)

The Working Group's estimates were an average of three models, FUND, DICE, and PAGE; the estimates presented here are calculated in the same manner

Equity weights

To reestimate the Working Group's SCCs with equity weighting, we employ the most widely used methodology in the SCC literature, originally developed for the FUND model by its authors (Anthoff et al. 2009). The

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[28] The UK declining discount rate schedule (Lowe, 2008) is as follows[a,b]:

	0–30 years	31–75 years	76–125 years	126–200 years	201–300 years	301+ years
UK Treasury discount rate schedule, zero rate of time preference	3.00 %	2.57 %	2.14 %	1.71 %	1.29 %	0.86 %

[a] There are two declining discount rate schedules in UK guidelines, one that includes a positive value for the rate of time preference and one that excludes it. This schedule is the one that excludes it.

[b] The *Stern Review* used a constant discount rate of 1.4 %.

[29] The Weitzman (2009) schedule is as follows:

	1–5 years	6–25 years	26–75 years	76–300 years	300+years
Weitzman schedule	4 %	3 %	2 %	1 %	0 %

In addition, new versions of the models would need to be re-coded to use the socioeconomic scenarios used by the Working Group.

method uses the Ramsey equation to discount damages, to which we then apply an equity weight. We describe our approach here only very generally, with the equations and a fuller description given in the Appendix.

The FUND formula for equity weighting is incorporated into the newest versions of DICE and PAGE, but unfortunately was not in the versions used by the Working Group. As such, we were only able to demonstrate the potential impact of equity weighting on the Working Group's SCCs using FUND. Had we been able to apply our methodology to DICE and PAGE, results would not be identical. However, they would be qualitatively similar; that is, the SCC would increase relative to the original Working Group estimates.

Our overall method was as follows. We first solved for the same rate of time preference ρ (see The social cost of carbon models used by the Working Group section above) that reproduced the SCCs obtained by the Working Group, assuming a value of 1 for η, the elasticity of marginal utility and the realized consumption growth rates corresponding to the given EMF-22 socioeconomic scenario for different regions. We set η equal to 1 because it is a commonly used value in the literature, and the simplest way to do the calculation.[30,31] It is important to note, however, that in this exercise we are not advocating any particular value of η (or ρ); rather, we are demonstrating the potential impact of imposing regional equity weights. Different values of η would produce different SCCs (further discussed in the Appendix), so the estimates presented here should not be interpreted as the only possible values the Working Group would have obtained had it used regional equity weights.

We had to use an iterative process to solve for ρ, and therefore limited our search for solutions to be within the range of 0 to 4 % (each discount rate would produce a different ρ); the highest value used in the literature of which we are aware is 3 %, and this is from earlier work by Nordhaus and Boyer (2000). In his most recent work, Nordhaus uses 1.5 % (Nordhaus and Boyer 2000; Nordhaus 2011). We iterated as high as 4 % to see what the results might look like.

Next, using the ρ's corresponding to each discount rate, we re-ran FUND with equity weights. In effect, we isolate the impact of adding equity weights from the time discounting component of the Working Group's SCCs.

Table 2 presents our results, alongside the Working Group's original estimates. We include the rates of time preference corresponding to each discount rate. For the 2.5 and 3 % discount rates, we find that adding regional equity weights increases the SCC by more than tenfold, with average (over all five EMF socioeconomic scenarios) corresponding rates of time preference equal to 1.1 and 1.54 %, respectively.

Interestingly, to reproduce the Working Group's SCCs at the 5 % discount rate required very high rates of time preference—higher than the 3 % used in Nordhaus and Boyer's older work (2000), and significantly higher than Nordhaus's current 1.5 %. At the 5 % discount rate, the SCC switches from being positive to negative (i.e., there are net *benefits* from warming),[32] with a corresponding average rate of time preference of 3.2 %. For two EMF scenarios, there was no solution between 0 and 4 %—we would have had to iterate across values greater than 4 for the rate of time preference. For the three EMF scenarios for which we could solve, the corresponding rates of time preference were 3.4, 3.3, and 2.9 % (for the average of 3.2 %). Thus, if the Working Group had used Ramsey discounting, it would have had to assume rates of time preference unobserved in the literature (i.e., greater than 3) for four of its five socioeconomic scenarios, in order to reproduce its estimates under the 5 % discount rate.[33]

Policy implications

The SCCs we have calculated have important implications in setting emission standards. In this section, we examine cost–benefit calculations from two federal regulatory impact analyses (RIA) that utilized the Working Group's SCCs. The first is from an energy efficiency standard set for small electric motors, also the first rulemaking for which the Working Group's SCCs were used. The second looks at a recently proposed rule restricting carbon emissions from newly constructed electric power units, not yet finalized as of the time of this writing.

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[30] See, for example, Nordhaus (2011), Stern (2007), Hope (2008), and Anthoff et al. (2009).

[31] As discussed in the Appendix, while our equity weighting increases the Working Group SCCs, alternative values for eta could produce both higher and lower equity weighted estimates than those presented here.

[32] FUND is the only model of the three used by the Working Group to estimate a negative SCC. This is a result of a controversial benefit included in FUND that predicts CO2 fertilization will significantly increase agricultural yields in the early stages of warming. For research finding counterbalancing negative impacts of climate change on agriculture, see Lobell et al. (2011), Fisher et al. (2012), Roberts and Schlenker (2012), and Schlenker and Roberts (2009). Because these benefits come early, higher discount rates can have the effect of reversing the sign of the SCC, as relative to damages that occur much later in time, these benefits are less impacted by the compounding effect of discounting.

[33] The authors are currently examining whether this result holds for other values of η.

Table 2 Estimated 2010 Social Cost of CO_2, adding regional equity weights to Working Group (WG) estimates, assuming eta=1

	2.50 %	3 %	5 %
Constant consumption discounting (WG estimates)	\$14	\$6	−\$1.4[a]
Effective rate or time preference corresponding to WG estimates	1.10 %	1.54 %	3.2 %[b]
Revised WG estimates with regional equity weights[b]	\$145	\$70	\$1

[a] Footnote 33 above explains FUND's negative SCC estimates at high discount rates.

[b] Excludes two EMF socioeconomic solutions for which the solution for the rate of time preference would have exceeded our iteration range of 0 to 4 %

Energy efficiency standard

In a detailed examination of federal rulemakings, Masur and Posner (2010) demonstrate that, contrary to claims made in various RIAs, the standard which maximizes net benefits could depend upon which Working Group SCC is used. We borrow one of their examples, the energy efficiency standard for small electric motors, and extend the analysis using the alternative SCCs we have calculated.

The Energy Policy and Conservation Act instructs the U.S. Department of Energy (DOE) to adopt energy conservation standards that are technologically feasible and economically justified, and would result in significant energy savings. In accordance with this directive, DOE promulgated efficiency standards for small electric motors, published in the U.S. Federal Register in March of 2010 (DOE 2010).

The Department set standards for two types of motors. We present results here for one of those, polyphase small electric motors; qualitatively, conclusions are the same for the other motor (capacitor start).

For polyphase motors, DOE considered eight stringency levels, and presented calculations of total net benefits for each using the Working Group's four SCC values of \$5, \$21, \$35, and \$65. Table 3 below reproduces DOE's analysis. DOE justified the standard it ultimately chose, option 4b, on the basis that it maximized net benefits. The agency noted that this was the case at any carbon price.

This conclusion is an artifact of the options it examined, however. From Table 3, one can see that if option 4b had not been considered, or was not available, net benefits are maximized under option 4 at carbon prices of \$5 and \$21. At \$35, options 4 and 5 both provide the maximum (equivalent) net benefits. At \$65, level 5 is the economically efficient choice.

It is also the case that an SCC between \$35 and \$65 would have resulted in option 5 delivering a higher net benefit than option 4. This is because technology costs don't vary across different SCCs, but net gains do as emissions reduction increases with higher stringency levels. Thus, the relative benefits in emissions reduction outweigh the increased technology costs between options 4 and 5 (leaving out option 4b).

Any of the alternative SCCs we have estimated in this paper would justify the stringency level of option 5 in the absence of 4b; our lowest estimate, using the Green Book declining discount rate, was \$55 per metric ton. This is of significant consequence in regards to emission levels: CO_2 reductions are almost 20 % greater in option 5 compared to option 4b (18.3 versus 15.4 metric tons, respectively), and almost twice as high between 5 and 4 (18.3 metric tons of CO_2 versus 9.3, respectively). Table 4 presents the corresponding emissions reductions for each option, from 2015 to 2045.

Proposed carbon standards for new power plants

A pivotal role for the SCC can also be inferred from a recent proposed rule to restrict carbon emissions from new power plants.

Under Section 111(b) of the Clean Air Act, the Environmental Protection Agency (EPA) is required to set "new source performance standards" for new power plants. Accordingly, in March of 2012, the Agency proposed the first national limit on CO_2 emissions from new fossil fuel-fired electric generating units (U.S. Environmental Protection Agency 2012).

An emission limit of 1,000 lbs of CO_2 per megawatt hour (MWh) of generation was proposed, somewhat higher than the emission rate of a new natural gas plant (820 lbs/MWh) and significantly lower than that of a new uncontrolled coal plant (1,800 lbs/MWh).[34] As part of its regulatory impact analysis, the Agency calculated carbon damages for coal relative to natural gas.

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[34] These emission rates are for a model 600-MW plant operating at an assumed 85 % capacity factor and built in 2016. Capacity factor is the actual output of a power plant relative to the maximum generation it can produce if operating at full capacity over a given period of time.

Table 3 Total net benefits at various social costs of carbon for polyphase small electric motors (2015–2045)

Regulation level	Consumer Net Present Value (all benefits and costs; billions, 2009$)[a]			
	\$5/t CO_2	\$21/t CO_2	\$35/t CO_2	\$65/t CO_2
1	0.27	0.3	0.33	0.39
2	0.57	0.64	0.69	0.81
3	1.04	1.16	1.27	1.47
4	1.08	1.22	1.34	1.57
4b	1.49	1.73	1.92	2.29
5	0.83	1.11	1.34	1.79
6	0.13	0.42	0.66	1.14
7	−12.57	−12.26	−11.99	−11.47

[a] Private (e.g., compliance) costs and benefits (e.g., fuel savings) were discounted at 3 %. Net benefits are also presented in the regulatory impact analysis for 7 %. Our conclusions would be the same for these

The exercise was purely illustrative: because natural gas plants have become cheaper to build and operate than coal, natural gas, and therefore the proposed emissions limit, was cost-effective irrespective of its lower pollution levels. Carbon damages were not needed to justify the standard on cost–benefit grounds. The value of the SCC thus appears non-controversial.

However, similar to the energy efficiency standard discussed in the previous example, this conclusion is an artifact of the technologies compared, which the Agency limited to natural gas and coal. If instead the Agency had assessed the cost-effectiveness of either new wind or solar photovoltaic relative to fossil fuel generation, both the Working Group and our SCCs would justify a stronger emissions limit (or technology standard).

Table 5 shows total system costs in cents per kilowatt hour for new generation sources, taken from the Department of Energy's 2012 Annual Energy Outlook (U.S. Energy Information Administration 2012).[35] In Table 6, we use differences in generation costs to calculate the "breakeven" SCC needed to make a cleaner generation source cost-effective with a more polluting one. The first column in Table 6 shows a cost differential based upon the differences in generation costs given in Table 5, as well as damages from two other pollutants monetized in the RIA, sulfur dioxide (SO_2) and nitrogen oxide (NOx).[36] For example, the generation cost difference between solar photovoltaic and coal in Table 5 is 5.2 cents/kWh. After adding 1.2 cents/kWh in damages from SO_2 and NOx, the cost differential is lowered to 4 cents/kWh, as indicated in Table 6.[37]

In the second column of Table 6 we determine what additional carbon damages (i.e., SCC) corresponds to the cost differential (inclusive of SO_2 and NOx damages) between the cleaner and more polluting generation source. The higher the carbon emissions of the dirtier source relative to the cleaner one, the lower the break-even SCC, holding generation and SO_2/NOx cost differences constant. The final column provides the closest SCC value presented in this paper corresponding to the break-even SCC.

New natural gas and wind are competitive over new coal absent any pollution costs, and therefore no SCC is required to make them cost-effective. An SCC between the Working Group's two highest estimates (\$35 and \$65), of \$50, would justify building solar photovoltaic over coal; this is the lowest break-even SCC and can be explained by coal's very high carbon emissions. An SCC of \$215 would justify solar over natural gas. Our

Table 4 Estimated CO_2 emission reductions under polyphase small electric motor standard levels

Regulation level	Cumulative CO_2 emission reduction 2015–2045
1	2.3
2	4.6
3	8.3
4	9.3
4b	15.4
5	18.3
6	19.5
7	21.2

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[35] These figures are for plants built in 2017, and take into account factors that vary widely by technology, such as capacity factors, transmission costs, and operation and maintenance expenses. Tax incentives or subsidies that would lower costs are not included, i.e., these are generation costs before applying any subsidies that would lower cost.

[36] Calculations for a given pollution damage were as follows: \$ damages/kWh = (total annual tons of emissions for unit type × \$ damage/ton)/total number of annual kilowatt hours for a model 600 megawatt (MW) power plant operating at an 85% capacity factor. For example, a model 600 MW coal plant emits 3.6 million tons of CO_2 per year and generates 4,467.6 million KWhs of electricity (1.7 million tons of CO2 for a comparable natural gas plant). An SCC of \$35 thus generates 2.8 cents/kWh in carbon pollution damages for a coal plant, while an SCC of \$65 generates 5.2 cents/kWh in damages. Corresponding to this, the 4 cents/kWh generation cost differential in Table 6 for solar photovoltaic versus coal falls between 2.8 and 5.2 cents/kWh, and the \$50/ton break even SCC between \$35/ton and \$65/ton.

[37] We use the midpoint of damage estimates for SO_2 and NOx provided in the RIA. SO_2 and NOx damages are large for coal and negligible for natural gas; SO_2 damages account for the majority of costs from these two pollutants.

Table 5 Generation costs for new plants constructed in 2017

	Cents/kWh (2007$)
Natural gas	6.3
Wind	9.1
Coal	9.3
Solar photovoltaic	14.5

closest corresponding SCC is the 99th percentile using a 2.5 % discount rate, $221. Wind would require an SCC of $74 to be cost-effective over natural gas. This is slightly above the Working Group's highest SCC ($65), but significantly below our next highest estimate of $107 (95th percentile estimate using a 2.5 % discount rate).

The break-even SCCs presented here are conservative in three respects. First, the SCC grows over time, whereas the SCCs used here are for 2010.[38] Accounting for the growth of SCCs over time would increase the cost of generation (inclusive of carbon damages) with coal or gas for a given starting SCC, reducing the 2010 SCC that corresponds to break even generation costs. Second, technological innovation may continue to drive down costs of wind and solar in the future, further lowering the break-even SCC. Third, we do not account for externalities other than air emissions from the power plants, such as methane emissions from natural gas wells and land disturbance from coal mining.

Discussion

These two regulatory impact analyses suggest that overall emission reductions achieved by a collection of efficiency and air pollution standards could be influenced by the SCC. This appears to be the case with the Working Group's higher SCCs, and even more so with our alternative SCCs (or if the SCC increases for other reasons). Executive orders emphasizing the importance of benefits relative to costs are not legally binding, but regulators may feel more comfortable proposing stricter rules the more they can back them up with strong benefits calculations.

Recent Congressional attacks on the Clean Air Act are instructive: advocates have vigorously defended the Act by pointing to the enormous benefit–cost ratios found in EPA's economic analyses of the statute's implementation, and these ratios are frequently cited in the press.[39] Interestingly, one monetized benefit drives this result: the value of reducing risks to life, as measured by the "value of a statistical life" (VSL).[40] Estimates of the VSL started out very small, but grew substantially over time as they developed in the economics literature.[41] If SCC estimates follow the same trajectory, the long-run consequence of its role in cost–benefit analysis could be significant. Stronger standards might be proposed, and those that are promulgated are likely to be easier to defend against political attacks.

Conclusion

Regulatory standards governing carbon emission reductions may well hinge on the value of the social cost of carbon (SCC). The estimates we report under our different sensitivities span values that are markedly higher than the Working Group's. Had the Working Group used a set of discount rates and discounting methodology considered appropriate for intergenerational costs and benefits, more stringent standards would be justified. The same conclusion applies to our equity weighting results: had the Working Group weighed damages according to income levels, a common practice in the SCC literature, its values would be much higher. Even net benefits calculations using the Working Group's own range of values can justify higher stringency levels, depending upon which of their SCCs are used.

In addition to demonstrating the importance of discounting and equity weighting on the Working Group's estimates, we hope we have provided a useful introduction to the social cost of carbon. Its estimation is a fundamentally interdisciplinary exercise involving multiple ethical and technical challenges; improving upon it thus depends critically upon input from a

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[38] The SCC increases over time because future emissions are expected to produce larger incremental damages as physical and economic systems become more stressed in response to greater climatic change.

[39] Benefits of the 1990 amendments to the Clean Air Act (CAA) are estimated to exceed costs by a ratio of 26 to 1 in 2010, and 30 to 1 in 2020 (EPA 2011).

[40] EPA summarizes this measure as follows: "[W]hen conducting a benefit–cost analysis of new environmental policies, the Agency uses estimates of how much people are willing to pay for small reductions in their risks of dying from adverse health conditions that may be caused by environmental pollution…This is best explained by way of an example. Suppose each person in a sample of 100,000 people were asked how much he or she would be willing to pay for a reduction in their individual risk of dying of 1 in 100,000, or 0.001 %…[if the average willingness to pay for this reduction in risk were $100] [t]hen the total dollar amount… to save one statistical life in a year would be $100 per person × 100,000 people, or $10 million" (http://yosemite.epa.gov/ee/epa/eed.nsf/pages/MortalityRiskValuation.html#whatisvsl).

[41] Early economic theory estimated the value of a life using foregone earnings (i.e., the value of a lost life was equal to the individual's remaining lifetime earnings), which produced estimates far lower than today's that use VSL methodology. EPA currently uses $7.6 million per life. (http://yosemite.epa.gov/ee/epa/eed.nsf/pages/MortalityRiskValuation.html#whatvalue, converted from 2006$ to 2007$).

Table 6 SCCs required to make cleaner generation cost-effective (2007$)

	Cost differential for cleaner source to be cost-effective (cents/kWh), excluding carbon	Break-even 2010 SCC	Closest Working Group (WG) and/or Johnson-Hope (JH) cost-effective SCC
Natural gas versus coal	Not applicable*	Not applicable*	Not applicable*
Wind versus coal	Not applicable*	Not applicable*	Not applicable*
Solar photovoltaic versus coal	4	$50	Between WG 2.5 % ($35) and WG 3 % 95th percentile ($65)
Wind versus natural gas	2.8	$74	Between WG 3 % 95th percentile ($65) and JH 2.5 % 95th percentile ($107)**
Solar photovoltaic versus natural gas	8.2	$215	JH 2.5 % 99th percentile ($221)**

*Both natural gas and wind are more cost-effective than coal without consideration of carbon damages.

**Even though the Working Group uses 2.5 percent as one of its discount rates, we classify this as a JH estimate because the Working Group does not include this value as one that regulatory agencies can use in their impact analyses

broad range of expertise. With the unlikely prospect of comprehensive climate legislation in Congress at present, direct or indirect (e.g., through energy efficiency standards) regulation of greenhouse gases under existing law is likely to be the primary tool used to address climate change in the United States for the foreseeable future, with the SCC taking on an increasingly important role.

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Appendix

The FUND model uses the Ramsey discounting formula to apply regional equity weights to damages based upon whether they occur in poorer versus wealthier regions.

To understand the methodology in more detail, this Appendix describes the discounting equations themselves—both the one used by the Working Group, and the Ramsey formulation we used to apply regional equity weights. We include here a review of some of the concepts discussed in "The social cost of carbon models used by the Working Group" section.

Equation 1 below shows the Working Group's discount rate formula, where δ is the constant discount rate, t the time period, r a given region, and D_{tr} damages in region r in time period t caused by one additional ton of CO_2 emitted today. T is the number of years considered for the analysis.

$$\text{SCC with constant discounting}(\delta) = \sum_r \sum_{t=0}^{T} D_{tr} \left(\tfrac{1}{1+\delta}\right)^t = \sum_{t=0}^{T} \left(\tfrac{1}{1+\delta}\right)^t \sum_r D_{tr} \tag{1}$$

In layman's terms, Eq. 1 discounts all damages by the same discount rate δ, regardless of the region in which they occur, and then sums them over time.

Equation 2 describes Ramsey discounting, without an equity weight applied between regions.

$$\text{SCC with Ramsey discounting without regional equity weights}(\rho, \eta, g_t) = \sum_r \sum_{t=0}^{T} D_{tr} \underbrace{\left(\frac{1}{1+\rho+\eta g_t}\right)^t}_{\text{Ramsey discount factor}} \tag{2}$$

where η is the elasticity of marginal utility, ρ the pure rate of time preference (PRTP), and g_t average per capita world consumption growth between the present and time t.[42] The PRTP is the most controversial parameter, as it captures a tendency to prefer experiencing utility from consumption today rather than delaying it into the future—thus discounting future damages to individuals simply because they have the misfortune of being born later. The parameter η represents the idea that as one's income increases, each additional dollar brings less utility; correspondingly, one dollar's worth of climate damages causes more "disutility" to a poor individual than it does to a wealthier one. The growth term, g_t, correspondingly captures changes in income. If g_t is positive, the discount rate increases; if it is negative, it decreases.

Finally, we apply a regional equity weight to Eq. 2

$$\text{SCC} = \sum_r \underbrace{\left(\frac{C_n}{C_{0r}}\right)^\eta}_{\substack{\text{equity}\\ \text{weight}}} \sum_{t=0}^{T} D_{tr} \underbrace{\left(\frac{1}{1+\rho+\eta g_{tr}}\right)^t}_{\substack{\text{Ramsey discount}\\ \text{factor}}} \tag{3}$$

$$\approx \sum_r \sum_{t=0}^{T} D_{tr} \left(\frac{C_n}{C_{tr}}\right)^\eta \left(\frac{1}{1+\rho}\right)^t$$

where C_n is consumption per capita in time 0 in the region to which other regions' damages are weighted, C_{or} per capita

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[42] More precisely, let g_s be the actual consumption growth rate at time s, then g_t is defined by the following equation $(1+g_t)^{-t} = \prod_{s=0}^{t} (1+g_s)^{-1}$, i.e., g_t is the geometric mean growth from the present to time t.

consumption at time 0 for a given region r for which the equity weight is computed, and C_{tr} per capita consumption at time t in region r. g_{tr} now stands for the average consumption growth between the present and time t in region r (the precise definition follows the same method as outlined in the footnote above).

We set C_n equal to U.S. per capita income, so that the equity weight for impacts in the U.S.A. is 1, i.e., that impacts in the U.S.A. are valued the same way as any other cost or benefit within the U.S.A. would be valued.[43,44]

To estimate a regionally equity weighted SCC corresponding to a given constant consumption discount rate used by the Working Group, we first solved for the value of ρ in Eq. 2 that gave us the same SCC as obtained for a given consumption discount rate δ in Eq. 1, assuming a value of 1 for η and the realized consumption growth rates corresponding to the given EMF-22 socioeconomic scenario for different regions. For each EMF-22 scenario, we obtained a value for ρ, denoted hereafter $\overline{\rho}$. After solving for $\overline{\rho}$, we then substituted that value into Eq. 3, to get the final regionally equity weighted SCCs corresponding to the different consumption discount rates. In effect, we isolate the impact of adding equity weights from the time discounting component of the Working Group's SCCs.

We set η equal to 1 because it was the simplest way to do the calculation, and because it is the most used value in the literature. It is important to note, however, that in this exercise we are not advocating any particular value of η (or ρ); rather, we are demonstrating the importance of imposing regional equity weights on the Working Group's SCC estimates for a given consumption discount rate.

Different values of η would produce different SCCs and corresponding $\overline{\rho}$s, so the equity-weighted estimates presented here should not be interpreted as the only possible values the Working Group would have obtained had it used regional equity weights. In general, damages can increase or decrease as η increases, depending upon how incomes for rich versus poor regions compare relative to one another in a given time period (equity weighting between regions in a given time period), and relative to their starting values ("marginal utility" weighting for a given region over time via the discount rate). The latter effect, however, does not impact our SCCs, as we held that constant by varying ρ (see above). The effect of η can also vary depending upon whether regions are assumed to get benefits from climate change (e.g., through CO_2 fertilization) and the income level of regions obtaining such benefits.

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[43] Ideally, the models would be constructed at a more disaggregated level such that inequalities within countries could also be accounted for. At present, however, the models are not sufficiently developed to do so, and it would be challenging to modify them due to limited inequality data in many parts of the world.

[44] It is important to note that equity weighted results can be presented using different per capita consumption levels for normalization, as long as the costs of mitigation (and any other costs and benefits in the U.S.) are similarly weighted. Regardless of the normalization weight chosen, if it is consistently applied across all costs and benefits the conclusion of a cost–benefit analysis will not change (i.e., the cost–benefit ratio will stay the same). In calculating an SCC for any given region, using that region's per capita income as the normalization weight reduces the likelihood of errors in a cost–benefit analysis. If a social cost of carbon that is equity weighted and normalized with world average per capita consumption is used in a U.S. cost–benefit analysis, one consequently has to equity weight the other costs and benefits the same way, with a weight also less than 1. In practice this would be highly cumbersome, confusing, and prone to error. Alternatively one can pick U.S. per capita income as the normalization for the equity weighting, as was done in Anthoff et al. (2009) and for the FUND results presented in this paper. With this normalization, the equity weight for the U.S. is 1, and the need to equity weight any other costs or benefits in the U.S. to which the benefits of emission reductions might be compared is not necessary, given that a weight of 1 would not change these estimates.

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