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## Article

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Economics: The Open-Access, Open-Assessment E-Journal

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*Suggested Citation:* Dietz, Simon (2012) : The treatment of risk and uncertainty in the US social cost of carbon for regulatory impact analysis, Economics: The Open-Access, Open-Assessment E-Journal, ISSN 1864-6042, Kiel Institute for the World Economy (IfW), Kiel, Vol. 6, Iss. 2012-18, pp. 1-12, <https://doi.org/10.5018/economics-ejournal.ja.2012-18>

This Version is available at:

<https://hdl.handle.net/10419/59036>

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# The Treatment of Risk and Uncertainty in the US Social Cost of Carbon for Regulatory Impact Analysis

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**Abstract** This note considers the treatment of risk and uncertainty in the recently established ‘social cost of carbon’ (SCC) for analysis of federal regulations in the United States. It argues that the analysis of the US Interagency Working Group on Social Cost of Carbon did not go far enough into the tail of low-probability, high-impact scenarios, and, via its approach to discounting, it mis-estimated climate risk, possibly hugely. Given the uncertainty about estimating the SCC, the note concludes by arguing that there is in fact much to commend an approach whereby a quantitative, long-term emissions target is chosen, 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.

Special Issue

[The Social Cost of Carbon](#)

**JEL** Q54

**Keywords** Ambiguity; climate change; discounting; integrated assessment modelling; risk; social cost of carbon; uncertainty

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**Citation** The Treatment of Risk and Uncertainty in the US Social Cost of Carbon for Regulatory Impact Analysis. *Economics: The Open-Access, Open-Assessment E-Journal*, Vol. 6, 2012-18. <http://dx.doi.org/10.5018/economics-ejournal.ja.2012-18>



## 1 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). 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. 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 wilfully ignore some other important issues, such as how to weigh the impacts of US carbon dioxide (CO<sub>2</sub>) 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 & 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.

## 2 The Damage Function and the SCC

The SCC is the present value of the impact of an additional tonne of CO<sub>2</sub> emitted to the atmosphere. In order to estimate it, one needs to use a simulation model connecting emissions of CO<sub>2</sub> 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 distributions 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 CO<sub>2</sub>, 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.<sup>1</sup> 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.

Recent work by, among others, Martin Weitzman (2012) and Frank Ackerman and colleagues (2010) has questioned the prevailing assumptions made about functional form. To take the DICE model as an example (Nordhaus, 2008; Nordhaus & Boyer, 2000), it can easily be shown that the assumption of a quadratic relationship between damages and temperature, together with the modellers’ specific coefficient values, implies that global warming can reach more than 6°C before the equivalent of 10% of global GDP is lost, and 18°C before the

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<sup>1</sup> It might be contended that this criticism is unfair, since, comprising policy-makers, the Working Group is a consumer of modelling, rather than a producer. It is certainly true that the balance of modelling expertise lay with the modellers engaged by the Working Group, rather than with the Working Group itself. Such an imbalance will generally be found whenever integrated assessment modelling is commissioned for use in policy. However, since the Working Group sought to specify modelling choices elsewhere, such as about the climate sensitivity, baseline socio-economic change and discount rate, it is not unreasonable to expect that it might have done the same about the damage function.



equivalent of 50% is lost. Similarly, while the parameters of the damage function in PAGE are modelled as random, damages can reach a maximum of only 10% of global GDP when global warming reaches 5°C (Warren et al., 2006). These predictions should be contrasted with the observation that 5°C warming 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?<sup>2</sup> 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.<sup>3</sup>

Clearly this begs the question of how much higher the SCC might be, if the damage function is steeper. A recent paper by Ackerman and Stanton (2012) attempts to answer it using the DICE model, applying a functional form proposed by Weitzman (2012). 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, 2011).

In its defence, these recent papers using steeper damage functions have appeared (in peer-reviewed journals) after the Working Group performed its

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<sup>2</sup> This is not to deny the potential role of adaptation in reducing climate damages, which is taken into account by all three of the integrated assessment models used by the Working Group. Indeed, uncertainty about adaptation feeds into broader uncertainty about the damage function. Thus models predicting that relatively small damages will accompany large increases in global mean temperature are generally very optimistic about the potential of adaptation to 'cope' with environmental change. My argument is, however, that we should admit within the range of possible outcomes pessimistic scenarios too.

<sup>3</sup> 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.



analysis in 2009-10. Therefore one can to some extent excuse the Working Group for not having explored this issue more thoroughly. It is, however, something that should be revisited as a matter of priority. One would like to see the Working Group, in its next round of analysis, treat the damage function(s) probabilistically in all of the integrated assessment models it uses and moreover include in the relevant probability distributions scenarios where damages rise steeply as temperature increases (at least beyond the 3°C calibration point).

### **3 Discounting, Risks to Welfare, and Uncertainty**

The consequence of such modelling 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 probabilities<sup>4</sup> (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.<sup>5</sup>

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

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<sup>4</sup> These precise probabilities may be objective or subjective.

<sup>5</sup> 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.



calculating a single stream of expected damages, treating this single stream as if it were 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.<sup>6</sup> 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 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

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<sup>6</sup> It is also a reason to place greater weight on climate impacts on poor regions. However, the Working Group's analysis ignored this aspect.



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 summarised in Camerer & 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 (Gilboa, 2009; Klibanoff, Marinacci, & Mukerji, 2005). In the present context, this means that the decision-maker focuses more on models yielding higher estimates of the SCC (see also Millner, Dietz, & 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.

## 4 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 CO<sub>2</sub>. 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 & Fankhauser, 2010). Since recent research has stretched out the upper tail of SCC estimates, this ratio could now be even greater.<sup>7</sup> 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, as explained in Dietz and Fankhauser, 2010). 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

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<sup>7</sup> Using Tol (2008), we set the maximum SCC today to \$654/tCO<sub>2</sub> for our comparison. The maximum SCC in 2010 in Ackerman and Stanton (2012) is \$893/tCO<sub>2</sub>. Unfortunately how the range of estimates of the MAC has evolved over the past few years is not known.



instruments under uncertainty (Stern, 2007). 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, especially in the short run, since the short-run marginal benefit function for a long-lived stock pollutant (e.g. CO<sub>2</sub>) is flat, compared with a short-run marginal cost function that is steep (Pizer, 2002). With a conventional gently-sloping damage function, it has also been found that price instruments are more efficient in the long run. While the long-run marginal benefit function is steeper than its short-run equivalent, it is not steep enough to make quantities more efficient, according to such analyses. However, with a steep damage function eventually the opposite holds (Pizer, 2002), and, as set out above, we should indeed allow for the possibility that the damage function is steep.

This target-driven approach to carbon pricing is now being followed in the UK (Department of Energy and Climate Change (DECC), 2008), after several years of (mixed) experience in using the SCC (beginning with Clarkson & 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.

## 5 Conclusions

It remains to conclude this note with recommendations for where the Working Group should focus its analysis in future. Section 2 argued that the Working Group did not go far enough into the tail of low-probability, high-impact scenarios, because it did not sufficiently include in its analysis the possibility that the damage function linking atmospheric temperature and economic impacts could be 'steep'. Recent contributions to the academic literature have stressed this possibility and have shown that the SCC is much higher as a result. It is therefore recommended that in future the Working Group treats the damage function(s) probabilistically in all the integrated assessment models it uses and moreover that the relevant probability distributions include scenarios where damages rise steeply as temperature increases. Section 3 considered how the analysis of the Working Group handled the difficult issues of discounting, in the face of risk, and uncertainty, in the shape of combining results from different integrated assessment



models. It pointed out a basic mistake in the way the Working Group performed discounting, which must be rectified in future: by imposing an exogenous, constant discount rate in the tradition of simple discounted cash flow analysis, the effect of low-probability, catastrophic consumption losses on the SCC is likely to have been significantly underestimated. It also pointed out the difficulties inherent in combining SCC estimates from different models. While it might seem natural to compute an unweighted multi-model average of the SCC, this in fact runs counter to what the emerging literature on ambiguity aversion recommends. Faced with uncertainty about which of a set of models produces the ‘correct’ forecast, and assuming aversion to this uncertainty (termed ambiguity), a number of leading theories indicate that, in this context, more emphasis should be placed on the model yielding the highest estimate of the SCC. Finally, section 4 suggested that, given the huge difficulties involved in estimating the SCC, the price of carbon for regulatory impact analysis might instead be based on the marginal abatement cost (MAC) of CO<sub>2</sub> necessary to achieve a given quantitative long-run emissions target. The US administration now has such a target, and if the price of carbon for regulatory impact analysis were based on the MAC consistent with this target, then we could have much greater confidence that decisions will be made on federal regulations that put us on a path to meet it.

**Acknowledgement** I am grateful to Antony Millner, Martin Weitzman, two anonymous referees and an editor for commenting on earlier drafts, and to David Anthoff, Charles Griffiths and Chris Hope for answering various questions. All errors and views remain, however, my responsibility. The financial support of the Grantham Foundation for the Protection of the Environment, as well as the Centre for Climate Change Economics and Policy, which is funded by the UK’s Economic and Social Research Council and by Munich Re, is also acknowledged.



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