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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.

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## Introduction

In this note I offer some comments on the recently established 'social cost of carbon' (SCC) for analysis of federal regulations in the United States (Interagency Working Group on Social Cost of Carbon 2010). 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 and Tetlock 2008). Nevertheless, the introduction of an SCC is a potentially significant step in the development of US climate-mitigation policy, especially in the continuing absence of dedicated, overarching mitigation policy instruments whose costs to individuals and firms could more directly enter benefit-cost calculations in other policy areas.

## The damage function and the SCC

The SCC is the present value of the impact of an additional 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 distribution functions for the SCC. Among these random variables, it is particularly noteworthy that the Working Group treated the climate sensitivity, i.e. the change in the global mean temperature in equilibrium accompanying a doubling in the atmospheric stock of 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. 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 (2010) and Frank Ackerman and colleagues (2010) has questioned the prevailing assumptions made about functional form. To take the DICE model as an example (Nordhaus and Boyer 2000; Nordhaus 2008), it can 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 18°C before the equivalent of 50% of global GDP is lost. This seems remarkable, since, for example, such temperatures are likely to test the limits of human physiology (Sherwood and Huber 2010). While the parameters of the damage function in PAGE are modelled as random, such that damages reach up to around 10% of global GDP when global warming reaches 5°C, it has equally been argued that 5°C constitutes an environmental transformation, being a larger change in global mean temperature than exists between the present day and the peak of the last ice age. Surely it is at least

*possible* that climate damages will exceed 10% of global GDP upon 5°C warming? As far as FUND is concerned, Figure 1A of the Interagency Working Group shows that its more complex, sectorally disaggregated approach implies total damages are actually *slowing* as warming passes 5°C, and at 8°C above pre-industrial they are only about 7% of GDP.<sup>2</sup>

Clearly this begs the question of how much higher the SCC might be, if the damage function becomes steeper. A recent paper by Ackerman and Stanton (2011) attempts to answer it using the DICE model, applying a functional form proposed by Weitzman (2010). Furthermore, they also question the damage estimates of the models at low temperatures, drawing on work by Michael Hanemann (2008) that argues damages could also be significantly higher in this realm. Looking at these changes separately and together, they show that the SCC could be several times, even orders of magnitude, higher. This result is in fact corroborated by some recent analysis of my own. Combining steeply increasing damages with a positively skewed distribution on the climate sensitivity parameter, I otherwise replicated the analysis with PAGE for the Stern Review (Stern 2007) to also find that the SCC could be hundreds of dollars higher than previously estimated (Dietz forthcoming).

### **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>3</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)

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<sup>2</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.

<sup>3</sup> These precise probabilities may be objective or subjective.

and/or take different parameter distributions as their inputs (also true of this case), raises the issue of uncertainty.<sup>4</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 calculating a single stream of expected damages, treating this single stream as if it is deterministic, and discounting.

At first glance, this is an elegantly simple approach. Unfortunately it breaks down in the face of the sorts of large risk to future (welfare-equivalent) consumption prospects outlined in the previous section. To see why this is so, recall that, in making the final steps in an integrated assessment model from monetary climate damages to changes in social welfare, the transformation of consumption per capita into individual utility is non-linear, specifically the utility function is concave, because of the assumption that marginal utility is diminishing in rising consumption. In estimating the SCC, diminishing marginal utility plays at least two roles: it is a reason for discounting the future, if the future is forecast to be richer, and it implies risk aversion, and a consequent premium on individual willingness to pay to mitigate climate change, if climate change increases the spread on consumption prospects.<sup>5</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.

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<sup>4</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.

<sup>5</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.

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 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 and Weber 1992). Loosely speaking, this means that they prefer courses of action with known probabilities to those with unknown probabilities. While there are competing models of ambiguity aversion, what a number of them share is the concept that, in the presence of ambiguity aversion, pessimistic models that yield lower estimates of expected utility from a course of action demand more of the decision-maker's attention. In the present context, this means that the decision-maker focuses more on models yielding higher estimates of the SCC (see also Millner, Dietz and Heal 2010). It is important to stress that this weighting does not stem from a prior belief that one model is more likely to be correct in its forecast than another: in fact it will emerge even if the models are given equal weight. Rather, the weighting stems from the decision-maker's preferences. The second assumption is then that the decision-maker is ambiguity-neutral.

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

### **Target-driven prices**

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



The key observation here is that uncertainty about the SCC is currently a great deal larger than uncertainty about the corresponding marginal abatement cost (MAC) of 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 and Fankhauser 2010). Since recent research has stretched out the upper tail of SCC estimates, this ratio could now be even greater.<sup>6</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). Doing so permits greater confidence that the target will be met, while the existence of a long-run quantity target in the first place can be supported by reasoning about the efficiency of price and quantity instruments under uncertainty (Stern 2007). To expand, the comparative efficiency of price and quantity instruments under uncertainty is known to depend in a general setting on the relative slopes of the marginal cost and benefit functions (Weitzman 1974). In the context of carbon abatement, this insight has generally been used to recommend price instruments in the short run, since the short-run marginal benefit function for a long-lived stock pollutant (e.g. CO<sub>2</sub>) is flat, compared with a short-run marginal cost function that is steep (Pizer 1999). However, in the long run, with the existence of possibly catastrophic climate change, the opposite seems to hold: marginal benefits are steeply increasing upon reaching some stock of CO<sub>2</sub>, while marginal costs are fairly flat.

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 and Deyes 2002). The Obama administration has set a target of reducing US greenhouse gas emissions by 80% by 2050 (which admittedly is not legally binding, unlike the UK's corresponding 80% target), so the question should be what price of carbon is

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<sup>6</sup> Using Tol (2007), we set the maximum SCC today to \$654/tCO<sub>2</sub> for our comparison. The maximum SCC in 2010 in Ackerman and Stanton (2011) 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.

required to deliver that target. The more consistent and robust source of that price is currently estimates of the MAC.

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