WORKSHOP PROCEEDINGS

Assessing the Benefits of Avoided Climate Change: Cost-Benefit Analysis and Beyond

The Social Cost of CO_2 and the Optimal Timing of Emissions Reductions under Uncertainty

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Abstract

The social cost of CO_2 is the extra climate change impact that would be caused by the emission of one more tonne of CO_2 into the atmosphere. PAGE2002 is an integrated assessment model that can find the social cost of CO_2. It uses simple equations to capture complex climatic and economic phenomena. This is justified because all aspects of climate change are subject to profound uncertainty. Using the same inputs as in the Stern review, PAGE2002 finds the mean social cost of CO_2 in 2008 to be $120 per tonne of CO_2, growing at about 2 percent per year, with a wide range from $25 to $320, almost independent of the emissions scenario on which the extra tonne of emissions is superimposed. Optimal global emissions fall to 45 percent of their year 2000 levels by 2020, and to 25 percent of their year 2000 levels by 2060. The theoretically correct price on CO_2 is the social cost of CO_2 on the optimal emission path. As the social cost of CO_2 does not vary much with the emissions path, we don't need to be too worried about the exact details of the optimal path when setting a price on CO_2. On the other hand, seemingly technical choices, about equity weights, the exponent of the impact function and the pure time preference rate, have almost as much influence as the more obvious climate sensitivity on policy-relevant results like the social cost of CO_2.

Introduction

There is now a great deal of interest in attacking the problem of climate change by putting a price on emissions of carbon dioxide (CO_2) (see for instance, Gore, 2007, Nordhaus, 2009). The social cost of CO_2 is the extra climate change impact that would be caused by the emission of one more tonne of CO_2 into the atmosphere. The polluter pays principle means that anyone who emits a tonne of CO_2 should be charged the social cost of CO_2 for doing so, either through a tax, or through the purchase of a tradable permit. Finding the social cost of CO_2 requires an integrated assessment model – a model which combines scientific and economic information to produce policy-relevant results.

The PAGE2002 model

PAGE2002 is such an integrated assessment model, estimating the temperature rises and impacts that result from a user-specified emissions scenario. It is the integrated assessment model used by the Stern review in its calculation of impacts and social costs (Stern, 2007). It uses a number of simplified formulas to represent the complex scientific and economic interactions of climate change. A full description of the model can be found in Hope (2006) and Hope (2008). Most of the model's coefficients and data ranges are calibrated to match the projections of the Third Assessment Report of the Intergovernmental Panel on Climate Change (Houghton et al., 2001).

The model includes ten time intervals spanning the 200 years from 2000 to 2200, divides the world into eight regions, and explicitly considers three different greenhouse gases (carbon dioxide, methane, and sulphur hexafluoride) with other gases included as an excess forcing projection.

Three types of impact are calculated:

- economic impacts, which are impacts on marketed output and income, in sectors such as agriculture and energy use, that are directly included in GDP;
- non-economic impacts, which are impacts on things like health and wilderness areas which are not directly included in GDP; and
- discontinuity impacts, which are the increased risks of climate catastrophes, such as the melting of the Greenland or West Antarctic Ice Sheet.

These three types of impacts are measured in economic terms and summed to calculate total impacts. Of course the quality and uncertainty in the estimates are heavily dependent on the ability of economists to make the primary measurements which the PAGE2002 model simulates. This ability is reasonable for the economic impacts, limited for the non-economic impacts, and rudimentary for the discontinuity impacts, which motivates the use of probability distributions throughout the model.

The PAGE2002 model uses relatively simple equations to capture complex climatic and economic phenomena. This is justified because the results approximate those of the most complex climate simulations, as shown by Hope (2006), and because all aspects of climate change are subject to profound uncertainty.

To express the model results in terms of a single ‘best guess’ could be dangerously misleading. Instead, a range of possible outcomes should inform policy. PAGE2002 builds up probability distributions of results by representing 31 key inputs to the impact calculations by probability distributions, making the characterization of uncertainty the central focus, as recommended by Morgan and Dowlatabadi (1996); the most frequently reported results from PAGE are the mean outcomes from 10,000 runs of the model, and the 5 – 95 percent confidence intervals representing the uncertainty in the outputs.

The social cost of CO_2

The top row of table 1 shows the social cost of CO_2 calculated by PAGE2002 with projections of GDP, population and emissions of greenhouse gases taken from IPCC Scenario A2 (Nakicenovic and Swart, 2000) to 2100, and constant thereafter. The pure time preference rate is 0.1 percent per year, and the equity weight is 1, as in the Stern review, meaning that a $1 loss to someone with an income of $1000 per year is counted as ten times as bad as a $1 loss to someone with an income of $10,000 per year. This gives consumption discount rates derived from the Ramsey rule of the order of 1.5 percent per year in annex 1 countries (i.e. industrialized nations like the USA, Germany, and Japan), higher in non-annex 1 countries (i.e. developing countries), and declining over time. This consumption discount rate does not take account of the covariance between climate impacts and consumption that could perhaps make the discount rate lower still.

Table 1. The social cost of CO_2 in 2008, by scenario*

2000 - 2200	**$US(2008)**		
	5 percent	**mean**	**95 percent**
Scenario A2	25	120	320
‘450’ scenario	20	125	370

**Based on 10000 PAGE2002 model runs using 0.1 percent pure time preference rate*

Under the A2 scenario, PAGE2002 projects the mean CO_2 concentration to be about 815 ppm by 2100 and the mean global mean temperature to be 4.1 °C above pre-industrial levels by 2100. The mean social cost of CO_2 in 2008 is $120 per tonne of CO_2, but the range is wide, from $25 to $320. This wide range is a simple consequence of the uncertainties that surround most parts of the climate change issue, both scientific and economic.

The second row of table 1 demonstrates a result that surprises many people: the social cost of CO_2 hardly depends at all on the emissions scenario on which the extra tonne of emissions is superimposed. In the second row, the social cost of CO_2 is calculated for a scenario with the same projections of GDP and population, but with emissions of greenhouse gases aimed at stabilizing the concentration of CO_2 at 450 parts per million (ppm) (Wigley, 2003). The mean social cost of CO_2 in 2008 under this '450' scenario is $125 per tonne of CO_2; this mean value and the range are almost the same as under the business as usual A2 scenario.

The '450' scenario involves aggressive abatement measures, with global emissions of CO_2 35 percent lower in 2050 and 70 percent lower in 2100. As PAGE2002 includes stimulation of natural CO_2 as a bad feedback loop (using the IPCC estimates of less effective uptake of CO_2 by oceans as temperature increases), it actually predicts a mean CO_2 concentration for the '450' scenario that is slightly higher than 450 ppm in 2100, but still substantially lower than the A2 scenario. Mean CO_2 concentration is about 515 ppm by 2100, and mean global mean temperature is 3.1 °C above pre-industrial by 2100.

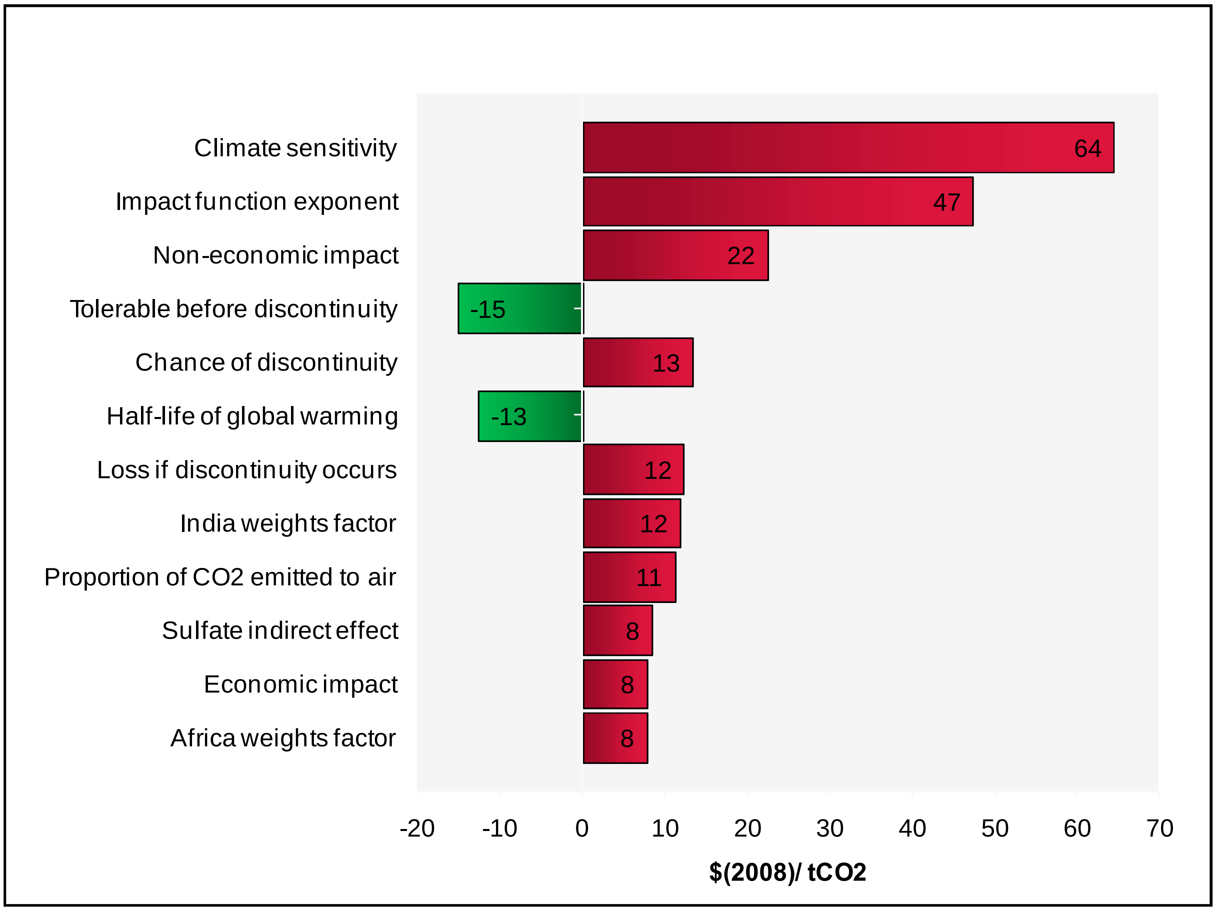
The reason why the social cost of CO_2 does not vary between the scenarios is not straightforward. It is caused by the interplay between the logarithmic relationship between forcing and concentration, which makes one extra ton under the lower concentrations of the '450' scenario cause about twice the temperature rise that it causes under the A2 scenario, and the nonlinear relationship of impacts to temperature which makes one extra degree of temperature rise on top of the lower temperatures of the '450' scenario cause only about half the extra impact it causes under the A2 scenario. These two effects roughly cancel each other out, leaving the mean social cost of CO_2 the same under each scenario. This empirical result is not unique to this particular combination of baseline and abatement target and appears to be robust (Hope, 2006a). The theoretically correct price on CO_2 is the social cost of CO_2 on the optimal emission path. As the social cost of CO_2 does not vary much with the emissions path, we don't need to be too worried about the exact details of the optimal path when setting a price on CO_2.

Major influences on the social cost of CO_2

The social cost of CO_2 may not vary much with the path of emissions, but it is strongly affected by several of the variables in the PAGE2002 model. Figure 1 shows the top 12 influences on the social cost of CO_2 under the A2 scenario. For each input, the bar shows the amount by which the social cost of CO_2 would increase if the input in question increased by one standard deviation.

The three top influences are the climate sensitivity, which is the temperature rise that would occur for a doubling of CO_2 concentration, the impact function exponent, which measures how curved the impact function is with temperature, and the non-economic impact parameter, which measures the non-economic impact for a 2.5 °C temperature rise. All three are positively correlated with the social cost of CO_2. For the climate sensitivity, an

Figure 1. Major influences on the social cost of CO_2 *(Source: PAGE2002 model runs for scenario A2 using 0.1 percent pure time preference rate)*



increase of one standard deviation, which is about 0.75 °C as the climate sensitivity takes a triangular distribution with minimum, most likely and maximum values of 1.5, 2.5 and 5 °C (Houghton et al., 2001), would increase the social cost of CO_2 by $64 per ton. Having this quantified measure of influence enables us to estimate what would happen to the social cost of CO_2 if one of the higher estimates of climate sensitivity that have been produced since the IPCC third assessment report turn out to be correct. The non-economic impact parameter is about three times as influential as the economic impact parameter, largely because the model assumes that a great deal of the economic impacts can be adapted to, at least in rich countries.

Three of the next four influences relate to the discontinuity impact. The temperature rise that can be tolerated before there is any chance of a discontinuity is negatively correlated with the social cost of CO_2, as a rise in this parameter leads to a lower social cost of CO_2. It is a bit surprising that the discontinuity impact should have such a large influence on today's social cost of CO_2, as any discontinuity that might occur is far more likely to happen in the 22nd century than in this one. But the discontinuity is large enough, and the discount rate small enough, that it does indeed emerge as a major influence. The only reason that the discount rate itself does not appear as a major influence is because in these results the pure time preference rate is fixed at the single value of 0.1 percent per year, and the equity weight at the single value of 1, used in the Stern review.

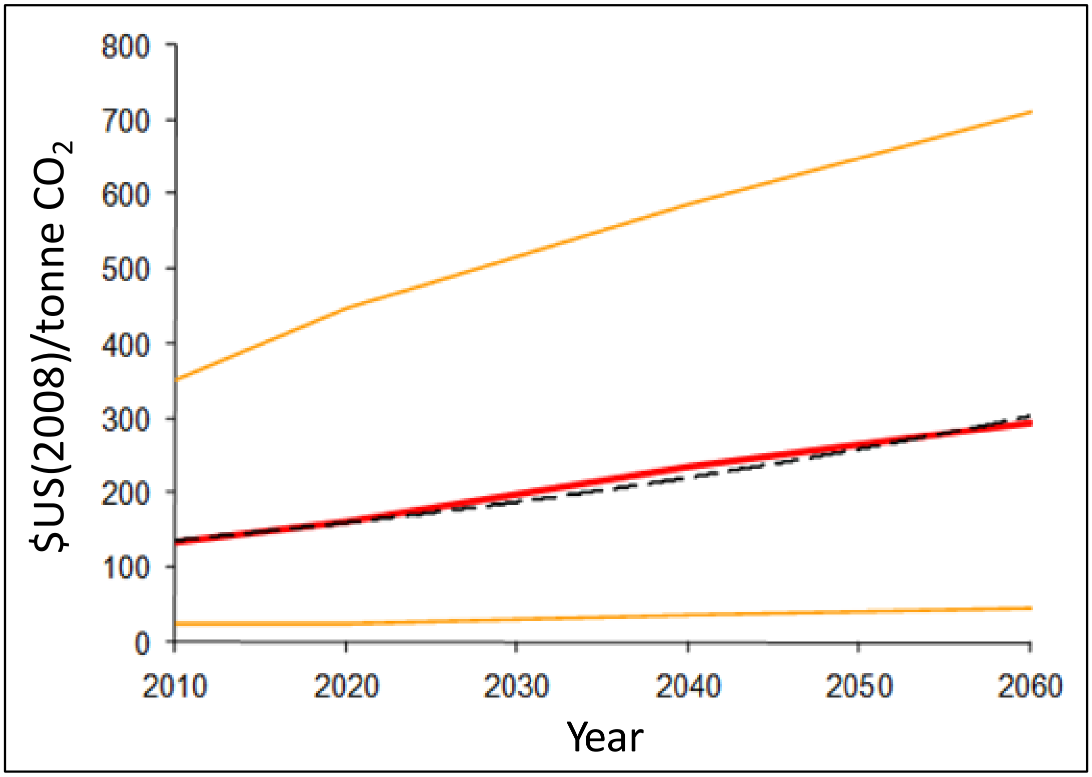
That the major influences divide into six scientific and six economic parameters is another strong argument for the building of integrated assessment models such as PAGE2002. Models that are exclusively scientific, or exclusively economic, would omit parts of the climate change problem which still contain profound uncertainties.

Growth in the social cost of CO_2 over time

Figure 2 shows how the PAGE2002 estimates for the social cost of CO_2 vary with the date that the carbon dioxide is emitted under the A2 scenario. The thicker, red, line shows the mean values, the thinner, orange lines show the 5 percent and 95 percent uncertainty points on the probability distribution. On average, the mean values increase by just under 2 percent per year, as shown by the dashed black line in the figure; by 2040 the mean estimate has risen to about $200 per tonne of CO_2.

The social cost of CO_2 grows as we move closer to the time that the most severe impacts of climate change are likely to occur. The rate of growth is kept down somewhat by the time horizon of 2200 for calculating impacts; with a 0.1 percent pure time preference rate, omitting any impacts after 2200 gives an increasingly large downward bias to estimates of the social cost of CO_2 as we move into the future.

Figure 2. The social cost of CO_2 by calendar year as estimated from PAGE2002 model runs for scenario A2 using 0.1 percent pure rate of time preference.



Optimal emission reductions

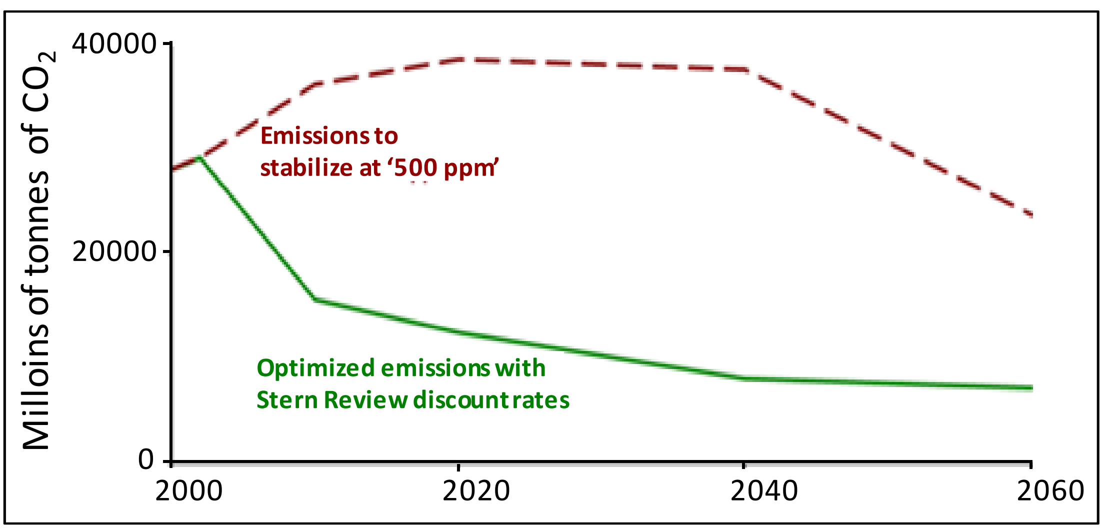
Optimal emissions can be defined as the path of emissions which minimise the mean net present value of the sum of climate change impacts and abatement costs. Figure 3 shows the optimal emissions up to 2060 calculated by the PAGE2002 model, using the Stern review assumptions which give the social cost of CO_2 results reported above.

The Common Poles Image (CPI) scenario is used as the business as usual scenario (den Elzen et al, 2003), rather than the A2 scenario as the initial analysis was performed for the Innovation Modelling Comparison Project which standardised on this BAU scenario, and the GDP, population and non-CO_2 greenhouse gas emissions from this scenario are used throughout the analysis of optimal emissions.

The optimal global emissions fall to 45 percent of their year 2000 levels (a 55 percent emissions reduction) by 2020, and to 25 percent of their year 2000 levels (a 75 percent reduction) by 2060. These emissions give mean CO_2 concentrations in 2100 of 445 ppm, with a 5 to 95 percent range of 415 to 485 ppm, and annual mean global mean temperature in 2100 of 2.6 °C above pre-industrial levels, with a 5 to 95 percent range of 1.5 to 4.1 °C.

For comparison, figure 3 also shows the 500 ppm CO_2 emission path, developed using the MAGICC model (Wigley, 2003). Due to a feedback loop in PAGE2002's carbon cycle that simulates the ocean's decreasing carbon sequestration ability as the temperature rises, PAGE2002's mean expected concentrations in 2100 are higher than the stated value for the scenario by around 70 ppm, with a fairly broad range. Therefore this path is described as '500 ppm', rather than 500 ppm, in figure 3. What is clear is that if the Stern review conclusions are accepted, the optimal emission cutbacks justified by them are much steeper than those which would lead to the stabilization of CO_2 concentrations at 500 ppm or more of CO_2.

Figure 3. Optimal emissions of CO_2 by calendar year as estimated by PAGE2002 model runs from CPI baseline using 0.1 percent rate of pure time preference.



Alternative assumptions and their effect on the social cost of CO_2

To show the effect of making changes to the inputs to the PAGE2002 model, we can try out an alternative set of assumptions and see the changes in the social cost of CO_2 and the major influences on the result. The alternative assumptions reflect some of the advances in understanding and concerns that have been raised since the Stern review's publication. The social cost of CO_2 that results should be understood as an illustration of the PAGE2002 model's ability to use some plausible alternative inputs, but not a fully updated and peer-reviewed calculation.

Pure time preference rate and equity weight

The Stern review's choice of a low 0.1 percent per year pure time preference rate has been a point of contention within the economics community. Many critics of the review favoured higher discount rates (e.g., Nordhaus, 2007; Tol and Yohe, 2006), while the review's authors continued to defend a pure time preference rate close to zero (Dietz et al., 2007). Others[1] point out that 'we do not observe "the" market rate of interest, but rather a multitude of different rates of return to assets having different characteristics' and so observations of market interest rates are of limited use for evaluating long-term public investments like those required to tackle climate change. Rather than trying to resolve this dispute, the alternative assumptions assume a range of possible pure time preference rates of <0.1, 0.5, 1> percent per year (here, and throughout the rest of this paper, the triangular brackets denote a triangular probability distribution with <minimum, most likely, maximum> parameter values). Similarly, the alternative assumptions have a range of equity weights of <0.5, 1, 2>. Combining the maximum values would give a consumption discount rate of about 3 - 4 percent per year, if growth rates in per capita GDP are in the range of 1 – 2 percent per year.

Adaptation

The PAGE2002 defaults, adopted by the Stern Review, assume that substantial, nearly costless adaptation will occur; the reported damage estimates are for damages remaining after that adaptation takes place. Specifically, PAGE assumes that in developing countries, 50 percent of economic damages are eliminated by low-cost adaptation. In OECD countries, the assumption is even stronger: 100 percent of the economic damages resulting from the first 2 degrees of warming, and 90 percent of economic damages above 2 degrees, are eliminated. For non-economic, non-catastrophic damages, adaptation is assumed to remove 25 percent of the impact everywhere. No adaptation is assumed for discontinuity damages.

These adaptation assumptions seem optimistic to some commentators, particularly for the economic sector (Ackerman et al., 2009). So the alternative assumptions have adaptation

[1] See the paper by Ackerman et al. in this volume.

that is only about half as effective: in developing countries, 25 percent of economic damages are eliminated by low-cost adaptation, while in OECD countries, 100 percent of the economic damages resulting from the first 1 degree of warming, and 50 percent of economic damages above 1 degree, are eliminated.

Discontinuity

PAGE2002 assumes that a threshold temperature must be reached before catastrophic events, which would lead to impacts on GDP an order of magnitude higher than 'normal' climate impacts, become possible; once that threshold is crossed, the probability of catastrophe gradually rises along with the temperature. Two of the uncertain parameters are involved here. One is the threshold temperature, with default values of <2, 5, 8> degrees C above pre-industrial in the Stern analysis. A second parameter is the rate at which the probability of catastrophe grows, as the temperature rises past the threshold. The default has the probability of catastrophe increasing by <1, 10, 20> percentage points per degree C above the threshold.

Much of the recent discussion of potential catastrophes, such as the loss of the Greenland or West Antarctic ice sheets, has suggested that they become possible or even likely at temperatures below the default "most likely" threshold of 5 °C of warming (e.g., Rahmstorf, 2007). So the alternative assumptions change the threshold temperature to <2, 3, 4> degrees Celsius, and the growth in the probability of catastrophe to <10, 20, 30> percentage points per degree Celsius above the threshold.

The shape of the damage function

PAGE2002, like most integrated assessment models, assumes economic and non-economic climate damages are a function of temperature, using a simple equation of the form:

$$\text{Damages} = aT^N$$

Here, 'a' is a constant, 'T' is the temperature increase, and 'N' is the exponent governing how fast damages rise. If N = 2, then 4 °C is four times as bad as 2 °C; if N = 3, then 4 °C is eight times as bad, etc.

PAGE2002 treats the exponent N as one of the uncertain parameters that is allowed to vary in the uncertainty analysis, with a default input of <1, 1.3, 3>. Based on recent scientific assessments of climate impacts (Smith et al., 2009), the "most likely" value of 1.3 now appears too low. In the alternative assumptions we set the exponent at <1.5, 2.25, 3>. This alternative keeps the exponent within the same range used in the Stern Review, but weights the higher end of the range more heavily; it assumes that the exponent is most likely to be a little more than 2, the value used in many recent models (e.g., Nordhaus, 2008).

Non-economic impacts and regional weights

The PAGE2002 defaults have non-economic impacts as <0,0.7,1.5> percent of GDP in the focus region (the European Union) for a 2.5 degC rise in temperature above pre-industrial levels, lower in other OECD regions, and higher in most developing countries, except China, with regional multipliers as shown in Table 2.

Some studies have shown that many economic models omit a range of impacts that actually may prove to be important (Watkiss et al., 2006; Ackerman et al., 2009). Commentators have also noted that regional weights giving more importance to impacts in other regions of the world do not necessarily fit with actions taken in other policy areas that affect developing countries (Gardiner, 2004).

Table 2. Default regional weight factors in PAGE2002 as a multiple of EU values
Source: Hope (2006)

Region	Minimum	Mode	Maximum
Eastern Europe & FSU weights factor	-1	-0.25	0.2
USA weights factor	0	0.25	0.5
China weights factor	0	0.1	0.5
India weights factor	1.5	2	4
Africa weights factor	1	1.5	3
Latin America weights factor	1	1.5	3
Other OECD weights factor	0	0.25	0.5

To illustrate these general ideas, the alternative assumptions increase the non-economic impacts to <0.2,1,2> percent of GDP in the focus region and increase the USA regional multiplier to <0.5, 1, 1.5>. However, they decrease all other regional multipliers to one half of their value in table 2.

Results—sensitivity of social cost of CO_2 to alternative assumptions

How do these alternative assumptions affect the social cost of CO_2? Table 3 shows that the mean estimate decreases from $120 per tonne of CO_2, with the default inputs, to $95 per tonne of CO_2 with the alternative assumptions, a drop of about 20 percent. The 5 percent and 95 percent points drop by a similar percentage, so the shape of the probability distribution of the social cost of CO_2 has not changed a great deal. The primary reason for the decrease is the larger average discount rate in the alternative assumptions, with smaller contributions from decreased non-economic impact multipliers in developing countries. These changes outweigh the combined effect of other alternative assumptions that would tend to increase the social cost of CO_2, including less effective adaptation, greater probability and sensitivity to discontinuity, and a steeper damage function. This result illustrates the strong sensitivity of the estimated social cost of CO_2 to the chosen discount rate.

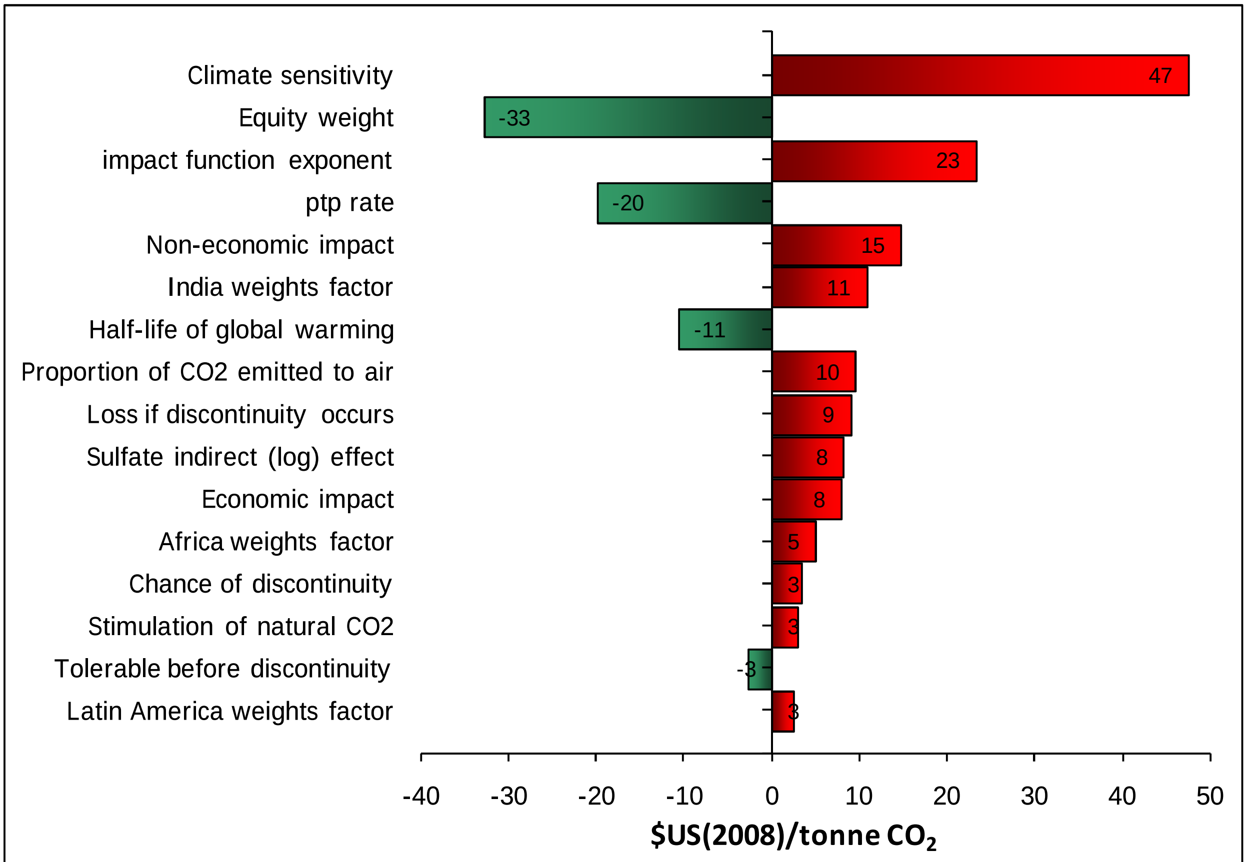
Table 3. The social cost of CO_2 in 2008, by input assumption *(Source: 10000 PAGE2002 model runs for scenario A2)*

2000 - 2200	$US(2008)		
	5 percent	**mean**	**95 percent**
Default assumptions	25	120	320
Alternative assumptions	20	95	250

Figure 4 shows the top influences on the social cost of CO_2 with the alternative assumptions. For each input, the bar shows the amount by which the social cost of CO_2 would increase if the input in question increased by one standard deviation.

- The climate sensitivity is still the top influence; an increase of one standard deviation would now increase the social cost of CO_2 by $47 per ton.
- Now the equity weight becomes the second most important influence and an increase of one standard deviation would decrease the social cost of CO_2 by about $35 per ton. Recall that in the original results, the discount rate was fixed at the single value of 0.1 percent per year, and the equity weight at the single value of 1, used in the Stern review, so they did not appear as influences in figure 1. Figure 4 shows that a higher equity weight leads to a lower social cost of CO_2. This might seem counter-intuitive, but it comes about because of the logical link between equity weights and discount rates; as the equity weight goes from 0.5 to 2, the consumption discount rate rises according to Ramsey's rule (consumption discount rate = pure time preference rate + equity weight x growth in GDP per capita), and the drop in present values that results far outweighs the increase in the valuation of impacts in poor countries that a higher equity weight brings.
- The impact function exponent is now the third most influential input, down from $47 to $23 for a one standard deviation rise. This drop is at least partly because the range of the exponent is now smaller (i.e. one standard deviation is now a smaller change in the parameter).
- The pure time preference rate is the fourth most important parameter. A higher pure time preference rate leads to a lower social cost of CO_2 as impacts in the future are discounted more.
- The non-economic impact parameter is now only about twice as influential as the economic impact parameter, because we have now assumed that adaptation will be less effective at reducing the economic impacts.
- The inputs relating to the discontinuity impact are now less important than with the default inputs, despite the probability of a discontinuity being higher with the alternative assumptions. For instance, the influence of the chance of a discontinuity has decreased from $13 to $3. This is because the higher mean discount rates under the alternative assumptions make impacts that occur in the far future less important.

Figure 4. Major influences on the social cost of CO_2 with alternative assumptions in PAGE 2002.



Conclusions & Recommendations

The results with these alternative assumptions demonstrate the flexibility of the PAGE2002 model, and the importance of using a model to lay bare the interactions between the different parts of the climate change problem, and provide the best evidence we have to inform climate change policy.

The best evidence must include an assessment of the risks and uncertainties as well as most likely or mean results. With our present knowledge, the social cost of CO_2 has a range of at least an order of magnitude; this has implications, suggesting that flexibility and detection of surprises will be important components of a good policy towards climate change.

The details matter. Seemingly technical choices, about equity weights, the exponent of the impact function and the pure time preference rate, have almost as much influence as the more obvious climate sensitivity on policy-relevant results like the social cost of CO_2.

Acknowledgement

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