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How Sensitive are the Social Costs of Greenhouse Gases to Discounting and Distributional effects?

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Abstract

Since 1982 hundreds of estimates of the social costs of greenhouse gases (most commonly carbon dioxide) have been produced in many different studies, by different researchers, using different models. The development of this area of research has been characterized by deep controversies between the scientists working in the field, mainly about the treatment of distributional issues and the related the choice of discount rate, and until now no consensus about these matters has been reached.

In this paper these key assumptions, among others, are examined. Special attention is also paid to uncertainty and the probability distribution of the social cost of greenhouse gases. The discussion is based on a set of integrated assessment model runs, using the PAGE2002 model. Many results show graphically how the social costs of greenhouse gases depend on different parameter values. One key result is that the estimates of the social costs of greenhouse gases are highly uncertain, and that proper treatment of risk is essential.

Key words; Social cost of greenhouse gases, Social cost of carbon, Discounting, Equity weighing

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1 Introduction

Although the phenomenon of global warming has been known for many decades (the magnitude of the effect was first estimated in 1896 by Arrhenius[1]), it was not until 1982 that the first estimate of the social cost of carbon dioxide emissions ($SCCO_2$) was made[2]. This area of research is a young discipline. The first estimates of $SCCO_2$ were very schematic, omitting many important factors such as non-market effects (like health and environmental effects), uncertain effects (like the risk of extreme weather)[3] and adaptation. Since then hundreds of estimates have been produced in many different studies, by different researchers, using different models. There has been strong progress in the sophistication and comprehensiveness of the models during this time, but there are still deficits to tackle and omitted factors to include. Two examples are the impacts of violent conflicts and biodiversity losses.[4] Also in the economic modeling part inclusion of relative prices has been shown to have a potential huge effect on SCC estimates, but this treatment is not included in the standard models.[5] On the social valuation side, risk aversion between different potential scenarios is usually not included.

The development of this area of research has also been characterized by deep differences and controversies between the scientists working in the field. Especially the Stern review started some very hot discussions. The Stern Review obtained much higher SCC estimates than the mainstream literature at this time, largely due to a different treatment of ethics in combination with a more sophisticated treatment of uncertainty. [6]

The background to the new ethical approach taken in the Stern Review was that many economists (e.g. Booth, 1994) and philosophers (e.g. Rawls 1972) had already concluded that a strict cost benefit analysis (CBA) is not acceptable from an ethical point of view and that it is not enough that the winners could compensate the losers, rather, satisfactory compensation must actually be paid which, for various reasons may be complicated, expensive and sometimes impossible.[7]

Another related question that one can ask is: assuming the developing countries are the losers, how should the money to transfer to the developing countries be raised? Budget constraints are already a problem for the developed countries' governments. Should this be done by raising income taxes? In which way is this less harmful to the economy than greenhouse gas taxes? It might be possible to optimize the level of greenhouse gas taxes, so that the governmental incomes from this could be used for compensation.

Tol (2008) argued that it is inconsistent to use equity weighting in CBA of climate change, if it is not also used in national appraisals.[8] His point is reasonable, but one may still not agree. This is because the greenhouse effect is an international problem. The people of Bangladesh have not voted on how Great Britain should value their damages. The intra-national inequality can be handled by each country itself (at least if there is a functioning democracy), but not the international one. If there

[1] Arrhenius (1896), *On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground*
[2] Tol (2008), *The Social Cost of Carbon. Trends, Outliers and Catastrophes*
[3] Watkiss & Downing (2008), *The social cost of carbon: Valuation estimates and their use in UK policy, p 8*
[4] Tol (2008), *Why Worry About Climate Change? A Research Agenda*
[5] Sterner & Persson (2007), *An even Sterner review*
[6] Dietz et al (2007), *Right for the Right Reasons A final rejoinder on the Stern Review*, p 230
[7] Azar & Sterner (1996), *Discounting and distributional considerations in the context of global warming*
[8] Tol (2008), *Why Worry About Climate Change? A Research Agenda*

were a world parliament or a compensation system approved by the world's poor, the case would be different. In that case equity weighting would be inadequate from an efficiency point of view (see Harberger, 1978), but because that is not the reality of today, equity weights may be necessary.

If we assume that the elasticity of marginal utility (η) is close to 1 (as was argued in the Stern Review), it is reasonable to think that the proper η to use in equity weighting should be in the range 0.5-1. This is to account for the fact that some compensation can be performed, and probably also will, but not perfectly. This can at least be true inter-regionally, even though it is more complicated in the inter-temporal case. For this reason a higher value might be suitable in the inter-temporal case (which would lead to a lower $SCCO_2$ value).

Overall maybe 0.8-0.9 is a good value for η, if we assume, along with Stern, that 1 is the true average elasticity of marginal utility. The more pessimistic we are about compensation processes the higher the value should be, and the more optimistic we are the lower the value should be. This is because in a system where compensation was optimal no equity weighing should be used, in order to maximize efficiency.

It could be argued that in a democratic society people's preferences should be used and not any philosopher's opinion, and hence that discount rates should be set as observed market rates.[9] But we think that in this case, optimally, one should ask the people what social time preference should be used in this specific case, and not to observe how they selfishly act in practice. But this kind of assessment is of course very hard in practice.

The fact that the discount rate is higher for investments may be due to the risk of losing the whole capital, or that it becomes more or less worthless. If you on the other hand don't choose to make the investment, and it later, after some of the uncertainty is revealed, appears that the investment is more profitable than originally thought, one can mostly do the investment at that point in time instead. So if you invest you risk losing the capital, and if you don't invest you don't risk anything but the profit during the time period. Therefore investors want a premium in return for their risk taking.

For private citizens the reluctance of delaying consumption may be due to the risk that each respective individual may be dead in one year. The risk that the whole humanity will be dead in one year is much less than the risk that one specific person will be. Therefore it makes perfect sense that the social pure rate of time preference is much less than each individual's one (when she tries to totally selfishly maximize her own utility).

Except from this, most individuals' incomes tend to increase throughout life, and this more than the growth in society. This is because children usually don't have incomes (or very small ones), and that salaries tend to increase throughout individuals' careers. As a conclusion each individual's discount rate may, to a big part, be due to the Ramsey rule[10], but with higher values for PRTP and η, than in

[9] It has been told on many web pages that Varian and Tol have taken this stance, eg http://en.wikipedia.org/wiki/Stern_Review. We have not been able to verify this statement against any original source, though. Our stance in the question remains the same, though, independently Tol and Varian have really made this statement or not.

[10] One way of dealing with discounting is to use the Ramsey rule for discounting; $r = \delta + \eta g$ (where r is the discount rate, δ is the pure rate of time preference (PRTP), η is the elasticity of marginal utility and g is the growth rate). In this case there is still the problem of finding the pure rate of time preference. Stern argued

the social case. Also irrational motives such as impatience can play a part, which there is no ethical reason to use in the social case.

Another reason why market rates are not proper to use is because there is no single market rate. The market rate is situation specific and varies with society, time and perceived risk.[11] In the case of global warming, the risk is in the other direction from in the most usual case (investment), so that a high discount rate will reduce the influence of risk instead of taking it into account. It is therefore much better to model the risk (and eventual risk aversion) separately instead of trying to incorporate it into the discount rate.

2 Methods

For the purpose of this study a range of simulations with the PAGE2002 model have been performed, testing how the $SCCO_2$ result from the model is influenced by different assumptions and different parameter values for some of the most important parameters. All simulations were run with 10,000 iterations, so that each simulation resulted in 10,000 estimates of $SCCO_2$, from which different statistical measures can be used, for example center values, where the mean is the most important one and considered as the estimate of the whole simulation set.

Some measures were tested with different scenarios. The three schemes most commonly referred to are the *Default discount scheme*, the *Stern discount scheme* and the *Modified Stern discount scheme*.

PAGE2002 uses the Ramsey rule for discounting; $r = \delta + \eta g$. In the *Default discount scheme* the PAGE2002 default parameter values are used, including a PRTP drawn from a triangular probability distribution ranging from 0.1 % to 2 % with a mode of 1 % (mean ≈ 1.03) and an elasticity of utility, η, ranging from 0.5 to 2 with a mode of 1 (mean ≈ 1.17). In the *Stern discount scheme*, the *PRTP*, δ is set to 0.1 and the η is set to 1, as in the Stern review. In the *Modified Stern discount scheme* the fact that some compensation will be possible and probably also realized, as was argued in the introduction, is reflected in a modal η = 0.85 instead of 1. An uncertainty interval has then been added around these two parameters, making the *PRTP* range 0.01 to 1 with a mode of 0.1 (resulting in a mean of 0.37) and η ranging from 0.5 to 1.5 with a mode of 0.85 (resulting in a mean of 0.95). The parameter values of the three discount schemes are presented in *Table 3.1*:

Discount schemes	Default	Stern	Modified Stern
Pure rate of time preference, δ (%/y)	Triangle(0.1;1;2)	0.1	Triangle(0.01;0.1;1)
Elasticity of marginal utility, η	Triangle(0.5;1;2)	1	Triangle(0.5;0.85;1.5)

Table 1: Three different discount schemes used in this study. Triangle(*min*; *mode*; *max*) means a triangular probability distribution with a minimum equal to *min*, a mode value equal to *mode* and a maximum value equal to *max*.

that the only rational and ethical reason for this term is the annual risk that the human race would be extinct independently of the global warming. This conclusion led to a comparably very low PRTP of 0.1 % per year. [10]

[11] Nordhaus (2007), A review of *The Stern Review on the Economics of Climate Change*

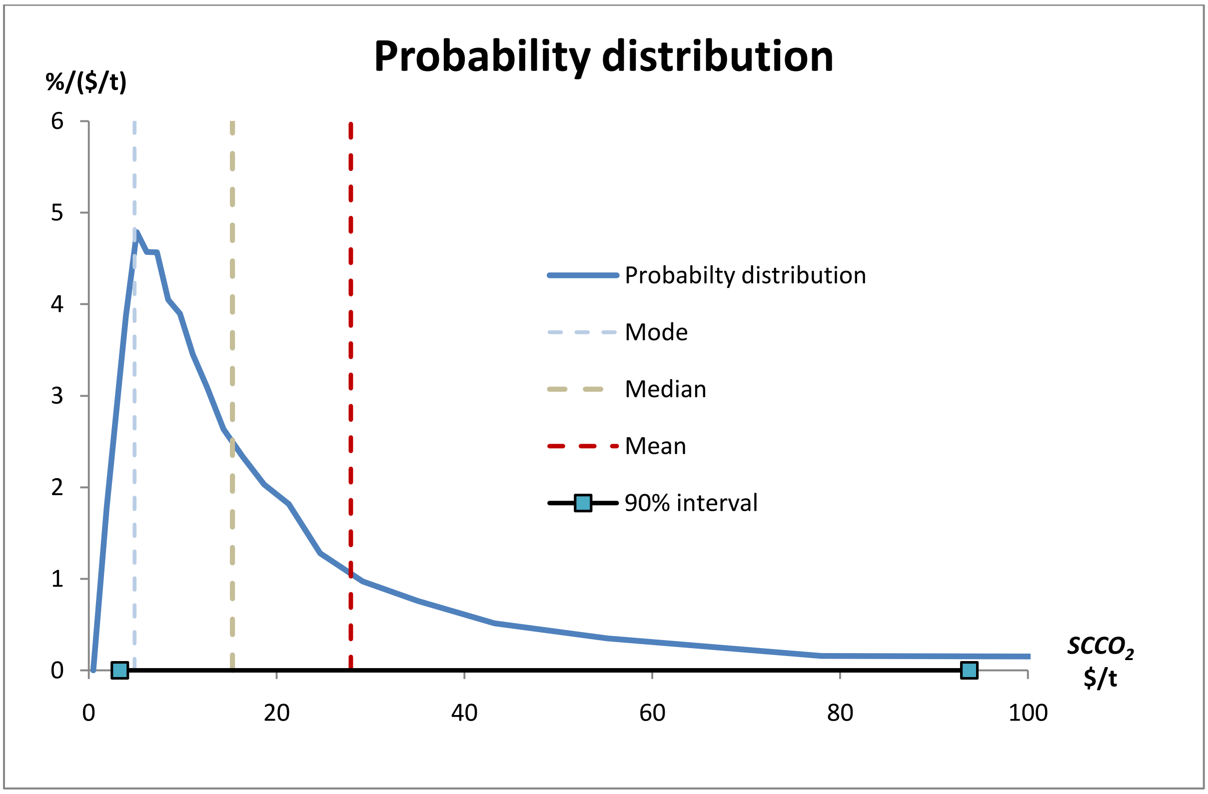
The influence of the per capita GDP growth rate is not tested and hence the *g* is always set as in the original PAGE2002 (different projections in different regions and time periods (S A2)[12]).

The $SCCO_2$ year is 2010 if nothing else is said and all values are in year 2000 monetary value.

3 Results

3.1 Statistical investigation of the PAGE2002 simulation outputs

Firstly the social cost of CO_2 under the default discount scheme is investigated. The results from a simulation of 10,000 iterations are represented in two probability diagrams, with different scales on the horizontal axis. In the probability distribution diagrams, the area under the graph, in each $1interval, represents how many percent of simulation iterations that resulted in a $SCCO_2$ value placed in that interval.[13] These diagrams also somewhat loosely represent the statistical probability that the true, underlying value of the $SCCO_2$ is located in each interval (according to the model). See figure 1 and 2:



[12] Hope, (2006), *The Marginal Impact of CO2 from PAGE2002: An Integrated Assessment Model Incorporating the IPCC's Five Reasons for Concern*

[13] The diagram is constructed from 5% percentile intervals. This was done in the following manner. The height was calculated for each interval by dividing 5% with the width (in terms of SCCO2) of the interval. The height was then placed in the middle of each interval.

Figure 1: Probability density of the output. The view is zoomed in on the area where the probability density is concentrated.

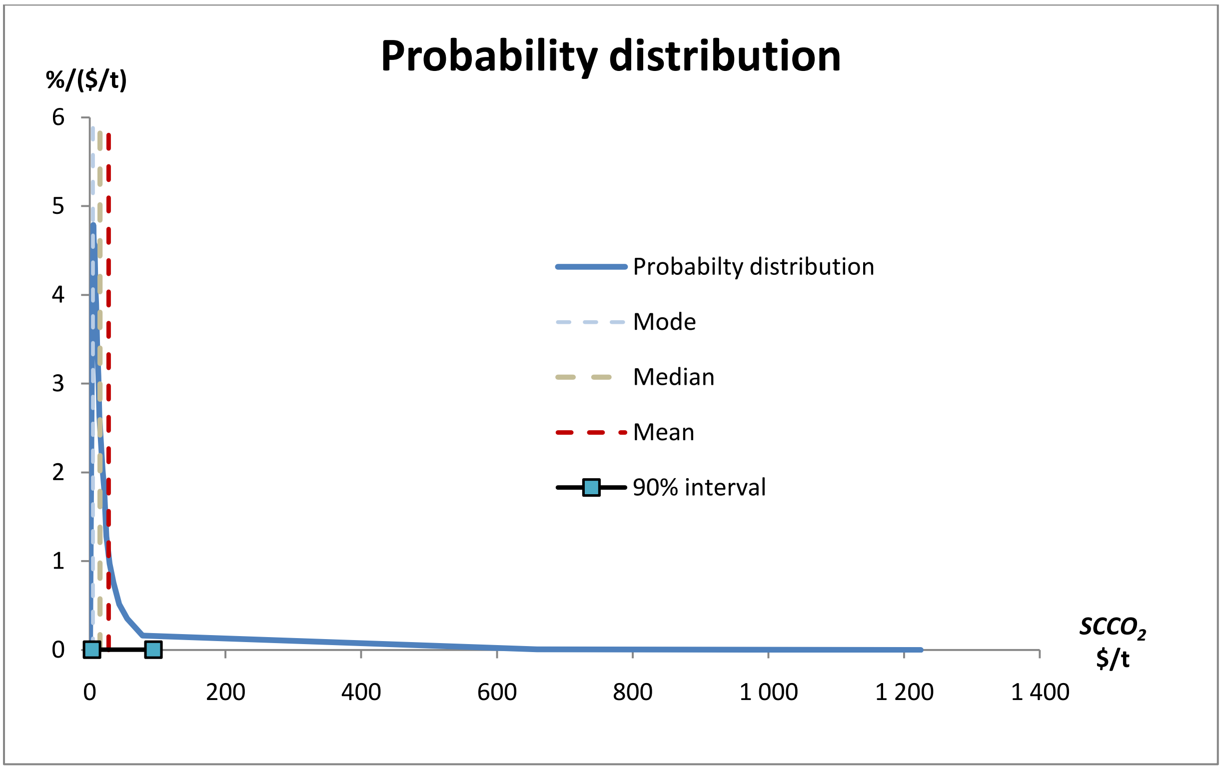


Figure 2: Probability density of the output. The diagram shows the whole range obtained for one particular 10 000 iterations simulation run. (The highest value varies between different simulations, because of the fact that the each iteration output is stochastic. The mean value is stable, though, for 10 000 iterations.)

The probability density in concentrated between 0 and the mean, and the density outside the 95% percentile is very small. Also the tail is very long but thin. According to the @risk software, the lognormal distribution is the standard distribution that best fits the output data[14].

Figures 3 and 4 show how much every interval contributes to the mean estimate. This is done by multiplying the probability density with the estimate value at each estimated point. In other words, in the "Contribution to the mean" diagrams, the area in each $1 interval represents how many percentage points of the mean estimate originates from that interval.

[14] http://www.palisade.com/risk/

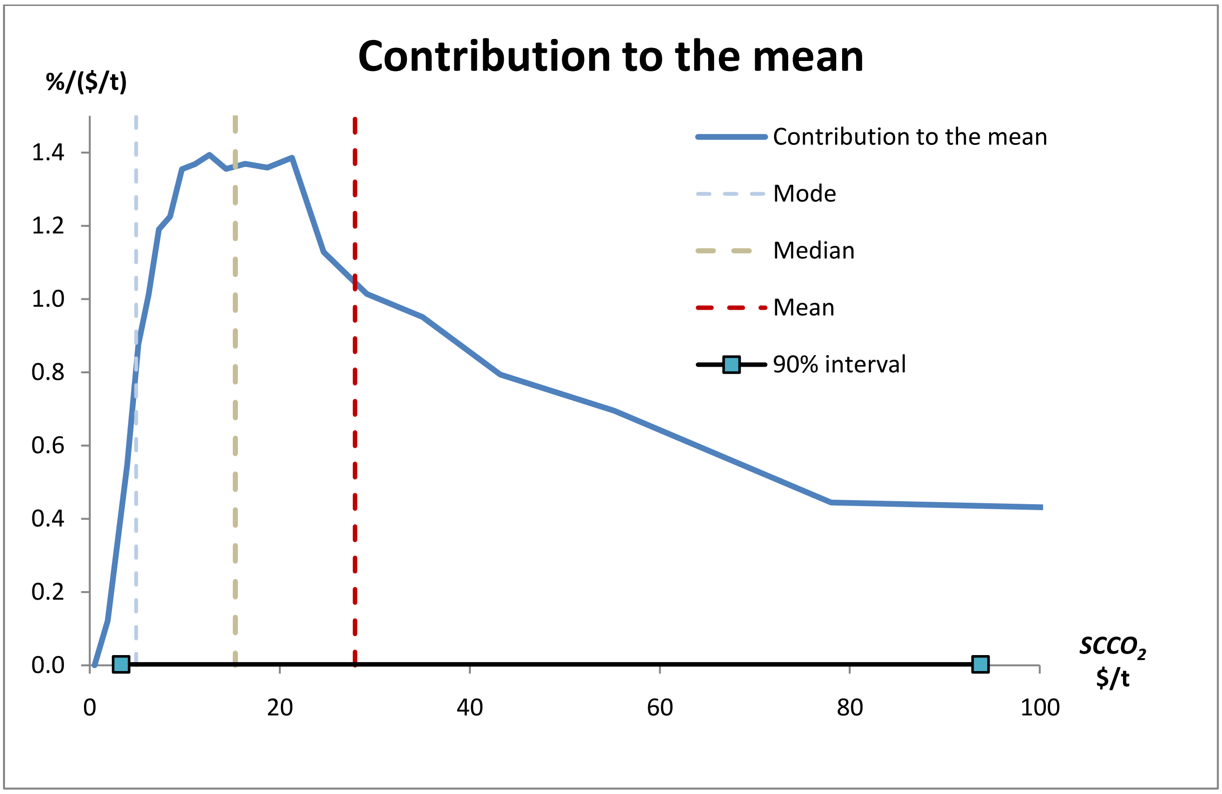


Figure 3: Contribution to the mean from different output intervals. The view is zoomed in on the area where the probability density is concentrated.

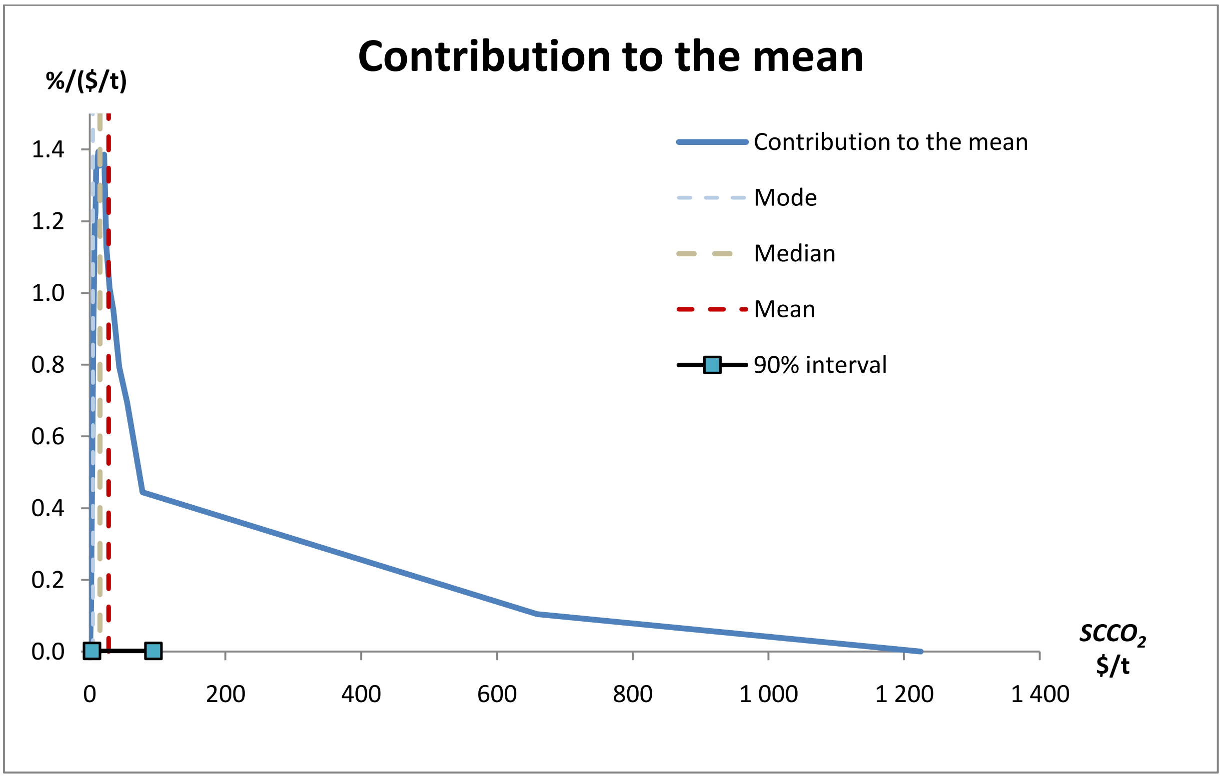


Figure 4: Contribution to the mean from different output intervals. The diagram shows the whole range obtained for one particular 10 000 iterations run.

The contrast between these two types of diagrams is revealing. Although the long tail outside of the 90% confidence interval is very unlikely, it accounts for the most of the contribution to the mean estimate, because of the extremely high damages, if they do occur. Observe that this is not a weakness of the model; this is a strength of this model, representing the $SCCO_2$ problem correctly, with its vast uncertainties. This pinpoints the fatal weakness of a deterministic approach. $SCCO_2$ is not primarily about the very high risk of modest damages, but about the very small risk of a catastrophe.[15]

The results above shows graphically what has already been concluded by Watkiss and Downing in 2008; $SCCO_2$ estimates span at least three orders of magnitude, reflecting uncertainties in climate change and choices of key parameters/variables[16].

This is also consistent with the findings in a sensitivity analysis of Antoff, Tol and Yohe from 2009. In this they presented the results from a sensitivity analysis on two crucial parameters: the rate of pure time preference, and the rate of risk aversion. This analysis showed that the $SCCO_2$ lies anywhere in between 0 and \$33,000/tCO_2.

These results all emphasize the importance of using the mean (or some kind of weighted average) as the measure, rather than the median, or even worse, the mode. The mean is the only measure that estimates the expected utility, and puts a weight on all values. The median will only be dependent on a small number of estimates, and totally ignore the values of the higher and lower estimates.

In *Table 2* below some statistics from the simulation results are summarized:

Statistical measure	*Mode*	*Median*	*Mean*	*Std Deviation*	*Skewness*	*Kurtosis*
Value	5	15	28	*40*	*7*	*107*

Table 2: Statistical properties of the PAGE2002 default $SCCO_2$ estimate outputs. Unit: \$/tCO_2.

3.2 Growth of the social cost of different climate gases over time

Different greenhouse gases are modeled separately in PAGE2002, allowing for the evaluation of their social cost separately. The three greenhouse gases; carbon dioxide, methane and sulfur hexafluoride are investigated through separate simulations in this study. Simulations were run with two different discount schemes and the year of emission varying from 2000 to 2080 (there are 7 different analysis years in this interval tested). In total 14 simulations were run for each climate gas. For each gas three diagrams and one table present the result from these simulations under separate headings for each gas.

3.2.1 Carbon dioxide

The results for the social cost of carbon dioxide (CO_2) are shown in the *Figure 5*:

[15] Weitzman, (2007), *A Review of the Stern Review on the Economics of Climate Change*
[16] Watkiss & Downing (2008), *The social cost of carbon: Valuation estimates and their use in UK policy*

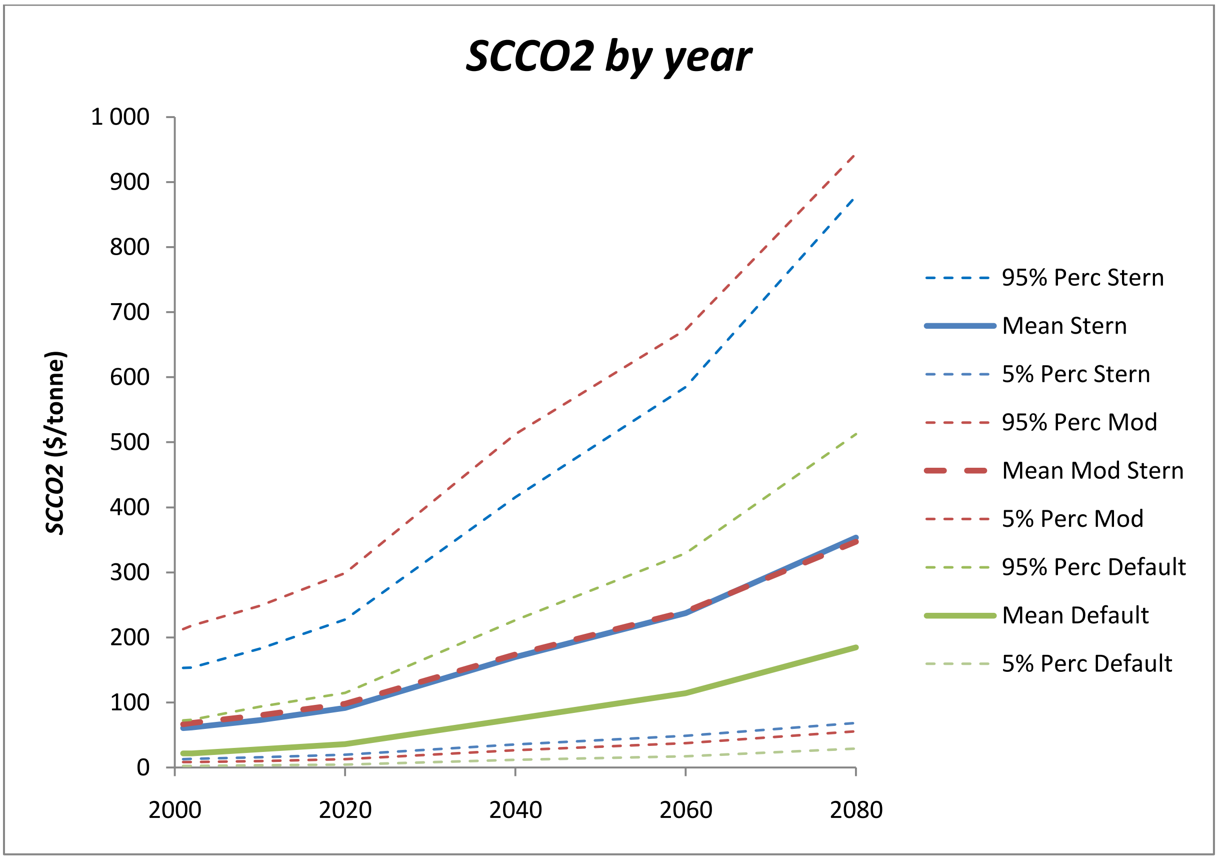


Figure 5: $SCCO_2$ estimates dependent on calculation year, using the PAGE 2002 default discount scheme, the Stern discount scheme and the Modified Stern discount scheme respectively

One can clearly see from all the results that the $SCCO_2$ is growing over time, in an approximately exponential fashion. The mean annual growth rate of the mean value is 2.7%[17] over the 80 year period for the default discount rate scheme. The mean growth rate of the mean value is 2.2% for the Stern scheme and 2.1% for the Modified Stern scheme. Also the curves for the *Stern* discount scheme and the *Default* discount schemes look similar, but with different magnitude. A question one can ask is: 'Why are the Stern and modified Stern means essentially the same, but the ranges different?' It is pretty natural that the modified Stern scheme has larger range, because a range has been added in the discount parameters, which are deterministic in the Stern scheme. Also the mean estimates are about 10 % higher in the modified scheme in the beginning of the period (but not in 2080), but the scale of the diagram makes that hard to see.

3.2.2 Methane

The results of the social cost of methane (CH_4) are show in
Figure 6.

[17] g=1/80*ln(x_{2080}/x_{2000}) where x= $SCCO_2$

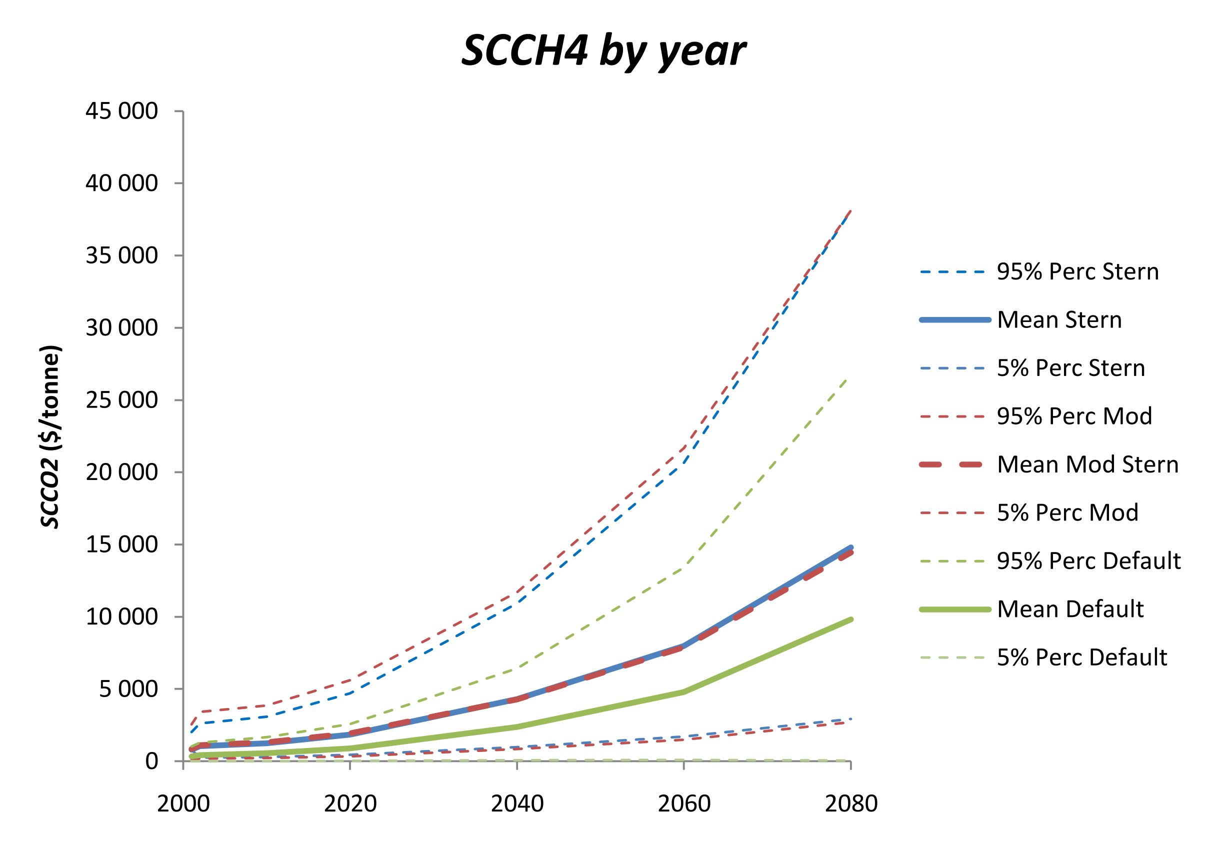


Figure 6: $SCCH_4$ estimates dependent on calculation year, using Default, Stern discount schemes and the Modified Stern discount scheme

The social cost of methane has a much steeper growth curve than Carbon dioxide, with annual growth rates of the mean value of 4.2% for the whole period. The growth rate is 3.7% for the Stern case and 3.5% for the Modified Stern scheme. This is because methane has much shorter atmospheric life time than carbon dioxide, around a decade, so that the negative impacts are only felt for a short time after being emitted. Because the biggest impacts of global warming will occur further away in the future, the social cost of methane emitted at that time is much higher. This means that the social cost of methane cannot be estimated by a linear amplification of the $SCCO_2$ with the ratio of their GWP (global warming potential)[18], but must be modeled explicitly. This is also because the GWP of methane varies greatly with the length of time considered (due to the very short atmospheric life time). Our results show that the ratio of the mean social cost between CO2 and CH4 varies between 13 (Stern and Modified Stern at year 2001) and 53 (Default at year 2080).

One additional conclusion one can draw from the above results is that the higher the discount rate is, the higher is also the growth rate of the social cost of greenhouse gases. This is natural, because the more we discount, the greater is the gap between the value we put on the damages (occurring in the future) today compared to the value we put on them tomorrow.

[18] IPCC (2001), *Climate Change 2001: The Scientific Basis*

3.2.3 Sulfur hexafluoride

The results for the social cost of sulfur hexafluoride (SF_6) are show below in *Figure 7.*

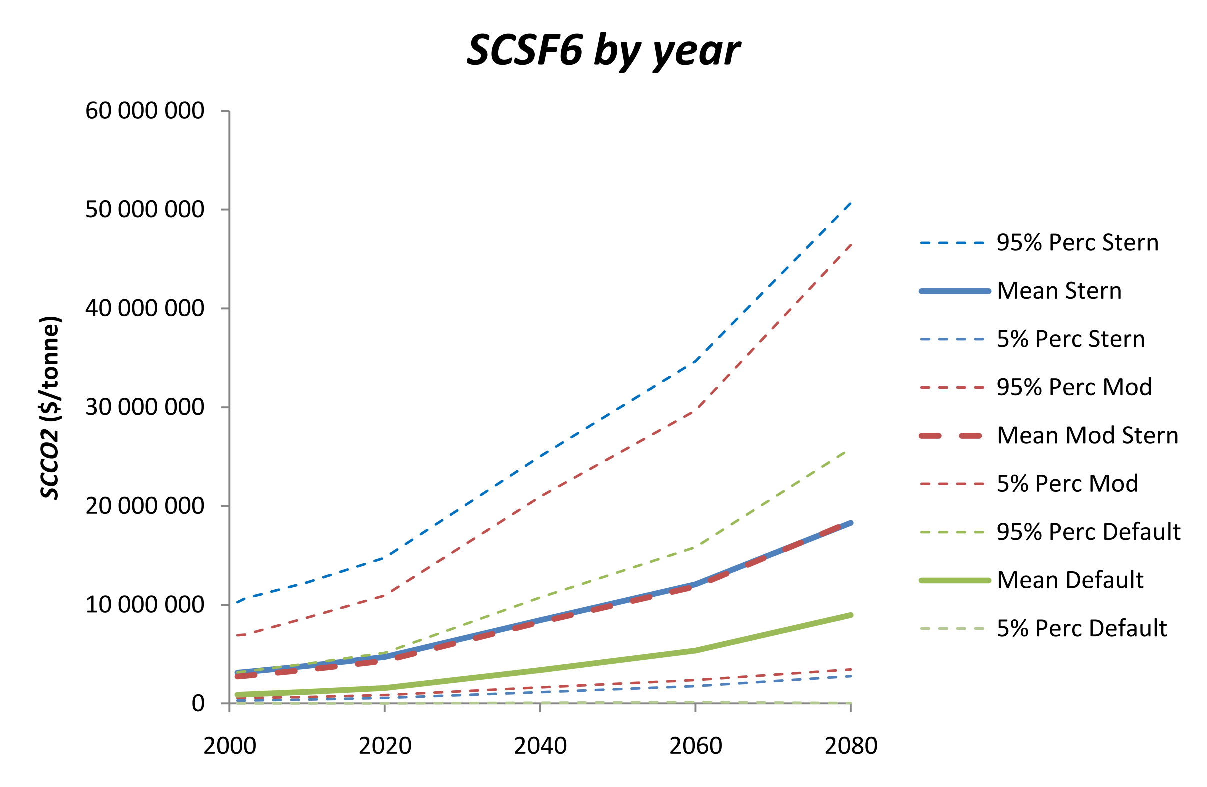


Figure 7: $SCSF_6$ estimates dependent on calculation year, both scenarios

The shapes of the curves are very similar to the ones for carbon dioxide, due to the very long atmospheric life time of SF6. The implication of this is that the social cost of SF_6 may be approximated by a linear multiplication of the $SCCO_2$. Our results show that the ratio of the mean social cost between CO2 and SF6 varies between 41 000 (Default in year 2001) and 53 000 (Modified Stern in year 2080). If one would like to use a single value as an approximation then one may therefore multiply the SCCO2 by for example 45 000 to get the social cost of SF6.

3.4 How equity weighting is handled

For a thorough discussion (and analysis) of equity weighting in the context of social cost of greenhouse gases, see Antoff et al 2009.

In PAGE2002 the equity weighting is performed in an ad hoc way following the method used in Eyre et al (see technical annex). In this study the effect of this is tested against *no* equity weighting and *flat* equity weighting, both for the default parameter values in PAGE2002 and for the parameter values used in the Stern review.

The term flat weighting refers to weighting which is independent of time and space. This is in this case done by not using the Ramsey rule for discounting. Instead first an equity weighting is performed over all regions during all times simultaneously, comparing different regions during different time periods to each other, so that the weight is only dependent on income (the result is also scaled so that the GDP in the starting year is correct). After that discounting is performed, using only the pure rate of time preference. The results are shown in the *Table 3* below:

Type of equity weighting	*Without equity weighting*	*Original weighting*	*Flat weighting*
Default	21	28	34
Stern	57	73	93

Table 3: Mean $SCCO_2$ for three different kinds of equity assessments. Unit: $/t$CO_2$.

The effect of equity weighting (compared to no equity weighting) is considerable but not extreme, neither using the *Default discount* nor the *Stern discount scheme*. The difference between the default way of handling equity weighting and the new (flat) way is in the same order of magnitude as the difference between the *No equity weighting* and the *Original weighting* scenarios, approximately doubling the effect of equity weighting.

3.5 The impact of calculation period

The default time horizon for the calculations in the PAGE2002 model is the year 2200. The impact of the length of calculation period is investigated by comparing the default scenario with a scenario where the calculation period is prolonged to the year 3000. This is done by simply extrapolating all the results from the last calculating period in the default scenario only changing the discount factors, by adding five new periods with identical outputs. The impact of calculation period is tested for the *Default discount scheme*, *Stern discount scheme* and the *Modified Stern discount scheme*. Also two low discount scenarios are tested, one low but reasonable discount scheme with $\delta = 0.05$ and $\eta = 0.5$ (referred to as Low discount) and one minimum discount scenario with $\delta = 0.1$ (same as in Stern) and $\eta = 0$. Below (in *Table 4*) a summary of the simulation runs on the impacts of prolonged time horizon is shown:

Time horizon	δ	η	*Default* ($/t$CO_2$)	*Prolonged* ($/t$CO_2$)	*Ratio*
Default	Triangle(0.1;1;2)	Triangle(0.5;1;2)	28	29	1,04
Stern	0.1	1	74	76	1,03
Modified Stern	Triangle(0.01;0.1;1)	Triangle(0.5;0.85;1.5)	81	86	1,06
Low discount	0.05	0.5	454	588	1,30
Min discount	0.1	0	3 900	27 836	7,14

Table 4: SCCO$_2$ with default time horizon and with a prolonged time horizon respectively. *Ratio* is the unit free ratio between the *Prolonged* value and the *Default* value.

As can be seen, the impact of a prolonged calculation period is very small for both the *Default* discount scheme and the *Stern* discount scheme, because of the discounting. This means that the default calculation period in PAGE2002 is sufficiently long for this range of discount parameters. Also if the discount rate is higher than this, the calculation period should be sufficient, because the impacts in the far future are more heavily discounted, and therefore even more closely valued to zero. With the *Modified Stern* discount scheme the impact of the prolonged calculation period is a little bit bigger, but not much (with a ratio of 1.06).

In the low discount case differences are considerable, with a ratio of 1.30, making the default PAGE2002 settings regarding the time horizon insufficient for this set of discount parameters. The impact of prolonged calculation period using this *Minimum discounting scheme* is dramatic, with the mean *SCCO2* rising nine times, implying that if we would choose this set of parameters, the default time horizon is insufficient.

Most models usually have one fixed time horizon. This is chosen to be appropriate for the default discount rate of each model, but these results shows that if the discount rate is radically decreased, the result may by heavily truncated by the default choice of time horizon. The time horizon could be varied as a function of discount rate, so that no significant truncation is made. Objections can be made about that this could lead to time horizons that are too long. But it is better to have a smooth, continuous function, because it makes no sense that one year will have a considerable value and the next one no value at all. The PAGE model is constructed so that the time horizon is chosen by the user, as long as no more than 10 analysis years are calculated in total. So it is not impossible for this idea to be implemented without rewriting the model.

3.6 The influence of probability distributions

In the default version of PAGE2002 all important parameters are set as triangular probability distributions. Is such a simplified distribution sufficient? Here we change the distribution to an unbounded distribution like the normal distribution, for some of the most important parameters, in such a way that the standard deviation and the mean for each input parameter value are unchanged. A comparison is made for both the default scenario and for the Stern discount scheme. See *Table 5*:

Distribution	Default discount scheme 5%	Mean	95%	s	Stern discount scheme 5%	Mean	95%	s
Triangular	2	22	74	30	11	59	135	50
New (unbounded) distribution	2	21	72	33	13	59	142	50

Table 5: $SCCO_2$ with two different probability distribution schemes (rows). *Triangular* denotes the original PAGE2002 triangular distribution. *New (unbounded) distribution* denotes an unbounded distribution with the same mean and standard deviations as in the original triangular one. In the cases where it can make sense to have a range from minus infinity to plus infinity this distribution is chosen to be the normal distributions. In cases where it makes sense to have values restricted to positive numbers, such a distribution is chosen. The columns headed *5%* and *95%* percent denote the percentiles respectively. The columns headed *s* denotes the sample standard deviation from the simulated results (10 000 iterations).

The results show that the mean and the standard deviation of the output SCCO2 are practically unchanged (especially in the Stern case where the discount parameters do not have any distribution). This implies that the triangular distribution is a good enough approximation for this purpose.

3.7 The influence of the most important parameter values

Previous investigations have shown that the *PRTP*, η, the equilibrium warming for a doubling of CO_2 and the non-economic impact are amongst the most influential parameters in the default PAGE2002 model[19]. We test the influence of each of these parameters in turn, by setting all other parameters to their default distributions and varying the parameter in question. The results with comments are shown below.

[19] Hope, 2006, *The Marginal Impact of CO2 from PAGE2002:An Integrated Assessment Model Incorporating the IPCC's Five Reasons for Concern*

3.7.1 Pure rate of time preference

See *Figure 8*:

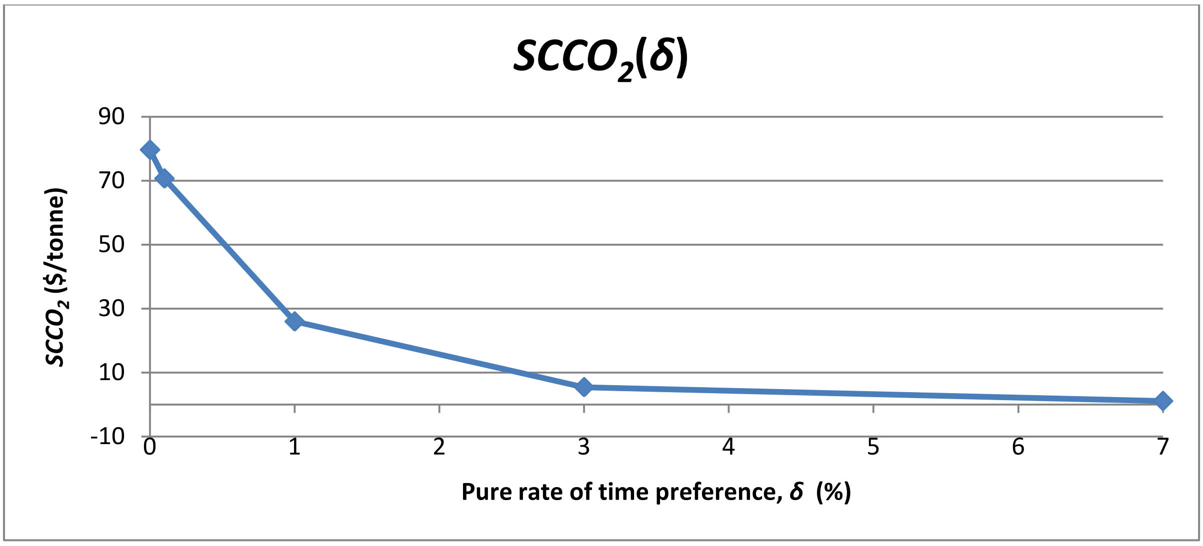


Figure 8: How the $SCCO_2$ mean estimate varies dependent on PRTP

The variation of $SCCO_2$ with different values of PRTP clearly shows a negative relationship looking approximately negative exponential in shape. This is consistent with the logical assumption that the relationship is negative, as a high PRTP more heavily discounts the future damages.

3.7.2 Elasticity of marginal utility

See *Figure 9*:

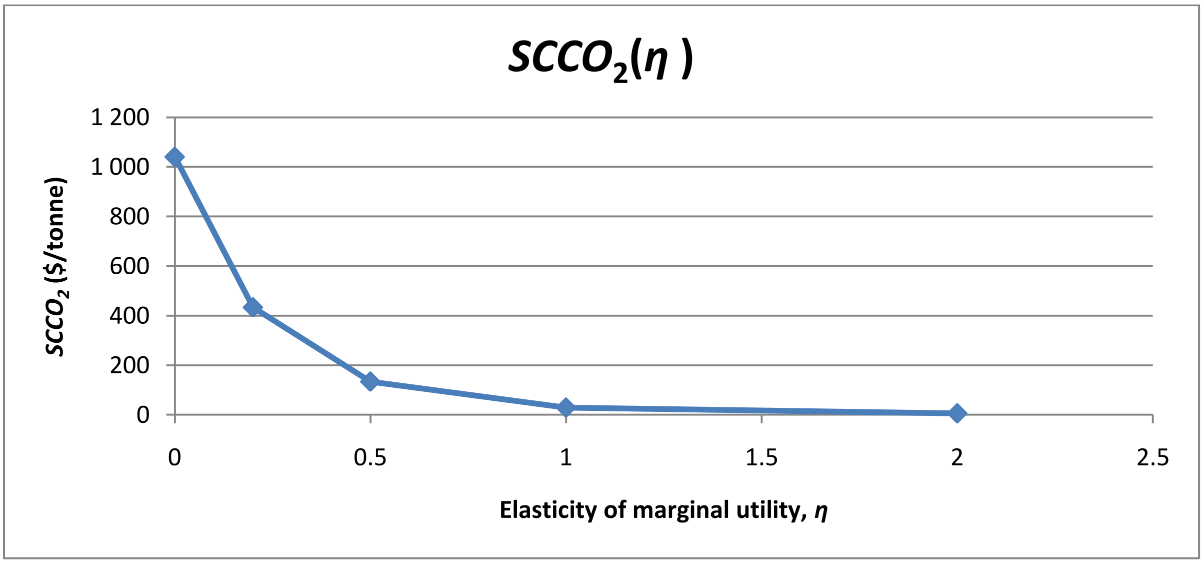


Figure 9: How the $SCCO_2$ mean estimate varies dependent on elasticity of marginal utility

More surprisingly is maybe the negative relationship between *$SCCO_2$* and η. This means that the more we value the impact on poor people compared to rich people, the less we value the damages caused by global warming. This is caused by the expected growth in per capita GDP outweighing the fact that poorer regions will be hit harder than richer regions. Through the Ramsey rule, $r = \delta + \eta g$ (where r is the discount rate, δ is the rate of pure preference, η is the elasticity of marginal utility and g is the per capita GDP growth rate), a higher η increases the discount rate (as concluded by Hope in 2008[20]). An important factor can also be that the growth in PAGE2002 is assumed to be much higher in the developing countries, so that the per capita regional GDP is actually much more equal when the impacts of climate change are realized.

Another reason might be that the damages may be higher in absolute terms in the developed countries. Equity weighting not only increases the value of the impacts in the poorer countries, but also decreases the values of the impacts in the richer countries.

3.7.3 Climate sensitivity

See *Figure 10*:

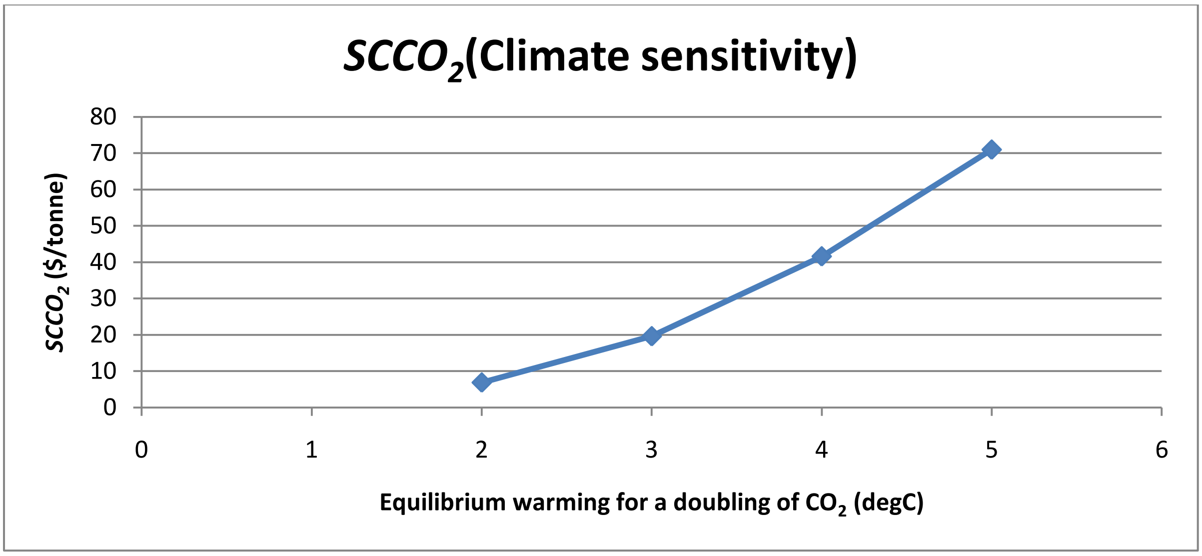


Figure 10: How the $SCCO_2$ mean estimate varies dependent on the equilibrium warming for a doubling of CO_2

The relation between $SCCO_2$ and the (unknown) climate sensitivity also looks exponential, but as expected, positive, making higher levels of warming cause more damages.

[20] Hope (2008), *Discount rates, equity weights and the social cost of carbon*

3.7.4 Non-economic impact

See *Figure 11*:

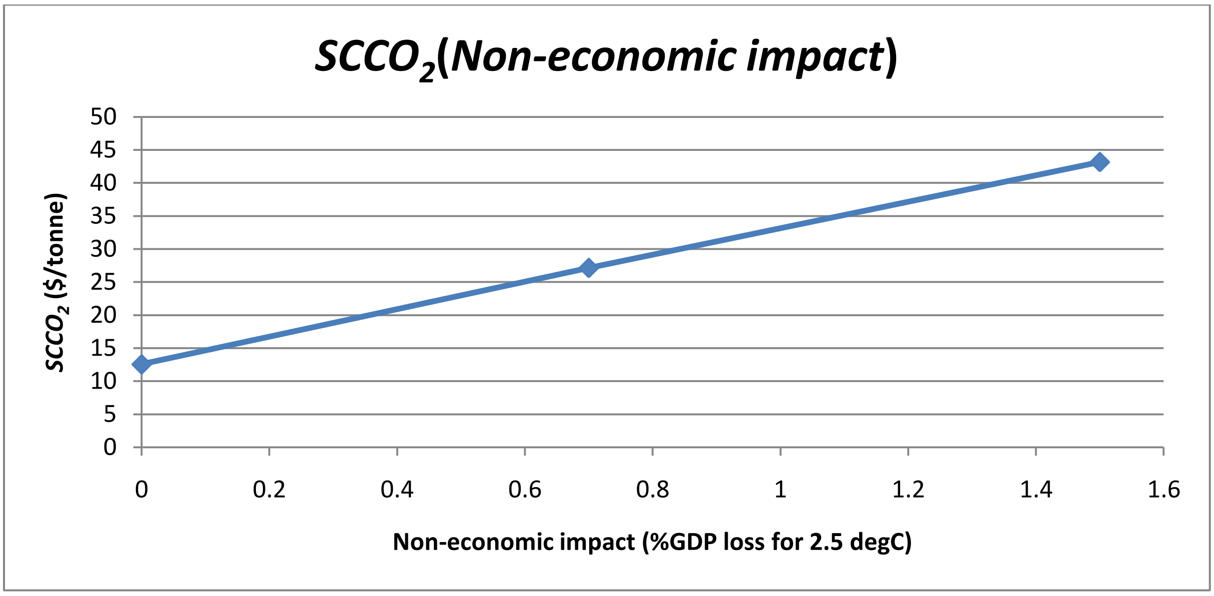


Figure 11: How the $SCCO_2$ mean estimate varies dependent on the non-economic impact share of the total GDP

The influence of the *Non-economic impact* parameter is positive and seems to be linear in the investigated range.

4 Comments

The results in this paper show how much the SCCO2 estimates vary.

The lack of confidence in the current estimates should not lead to a call for the rejection of this discipline and of the use of SCCO2. An uncertain estimate is better than no estimate at all, as long as one remembers that the mean value is just a very uncertain best guess, not something that is written in stone. In a paper from 2008 Barker criticizes utilitarianism and CBA in the context of climate change.[21] One may agree with some of his points, that many CBAs (and estimates of SCC) have been performed in a very oversimplified and unethical manner. Even so, we disagree that utilitarianism and CBA are the wrong methods; it is rather that these methods need continual improvement, so that as much as possible is correctly incorporated and represented.

One important point is that SCC has no correct value, but is highly dependent on the parameter values and ethical considerations that are inputs to the models. Until now, these valuation considerations have mostly been performed by the scientists and modelers themselves. A more reasonable appraisal would be to ask democratically appointed politicians to make the value decision inputs to the models. This could be done by asking simplified questions such as, “How much more should poor people’s impacts be weighted than rich people’s impacts” or “Is it reasonable that we weight $1 to the generation 100 years from now as 10% of our own weight? Should we weight the future generation more or less than this?”. The answers can then be translated into input parameters. This is because this kind of economics is philosophical and political. Researchers do not seem to find a consensus about these matters, which is natural. When it comes to values, it is natural that people have different opinions, and the fact that there have been great controversies in this area of science is a sign of soundness. It is in the discussion and questioning that the development is created. But from this point of view it is also reasonable that these differences are sorted out through the democratic system. In this case it would also be important to not only to ask the politicians currently in power, but rather the whole parliament of a country or institution in question.

[21] Barker (2008), *The economics of avoiding dangerous climate change. An editorial essay on The Stern Review*

Technical annex

In PAGE2002 equity is accounted for in the following manner: Firstly equity weights are applied for each region based on the mean GDP/capita in each time period, independently of other time periods, so that the inter temporal equity at this stage is ignored . Inter-temporal equity is accounted for in a separate next step, where discounting is applied using the Ramsey rule. This is done for each region separately, based on each region's expected economic growth path. This manner of dealing with equity has some mathematical weaknesses, putting unfairly low weight on poorer but fast growing economies' wealth in the future, as will be shown by a simple illustrative example below.

We imagine that there are only two regions in the world, both of the same size, *Region A* and *Region B*; *Region A* is much richer, but *Region B* has a much faster growth. The table below shows the incomes for the two regions for a base year (*Year 1*) and a year in the future (*Year 2*). The mean income for each year is also calculated. For simplicity elasticity of utility = 1 and PRTP = 0 are assumed.

GDP/cap	Year 1	Year 2
Region A	150	150
Region B	50	150
mean	100	150

Based on the mean for each time period, equity weights are calculated in the following way (if the elasticity of utility is 1):

$$w_{R_Y} = \frac{(GDP/cap)_{R_Y}}{(GDP/cap)_{(mean)_Y}}$$

Where $(GDP/cap)_{R_Y}$ is the GDP/cap in the specific region *R*, in the specific year *Y* and $(GDP/cap(mean)Y$ is the mean GDP/cap of both regions in the specific year, *Y*.

This will result in the following weights:

Equity weights	Year 1	Year 2
Region A	0.67	1
Region B	2	1

If we assume that the PRTP is 0 then the discount factors for each region in each period will be calculated as follows:

$$DF_{R_Y} = \frac{(GDP/cap)_{R_1}}{(GDP/cap)_{R_Y}}$$

Where $(GDP/cap)_{R_Y}$ is the GDP/cap in the specific region *R*, in *Year 1* and $(GDP/cap)_{R_2}$is the GDP/cap in the specific region *R* in the specific year *Y*. This will result in the following discount factors:

Discount factors	Year 1	Year 2
Region A	1	1
Region B	1	0.33

The total weight applied to \$1 impact in each region is $TW_{R_Y} = w_{R_Y} \cdot DF_{R_Y}$

This will result in the following total factors:

Tot weight	Year 1	Year 2
Region A	0.667	1.000
Region B	2.000	0.333

Which in turn will lead to a $TW_{R_Y} \cdot \; GDP/cap$ as following:

GDP/cap*Tot weight	Year 1	Year 2
Region A	100.00	150.00
Region B	100.00	50.00

If the weighting would have been carried out in the theoretically correct way (weighting only dependent on income and independent of time and place) all of the last values should have been exactly the same for a PTRP of zero. We can see that the weight in *Region B* in *Year 2* is strongly underestimated, whereas the weight in *Region A* in *Year 2* is overestimated. This modeling problem is even more serious as the impacts of global warming typically occur in the far future and especially in regions corresponding to Region B in the example. There is therefore a risk that this way of performing equity weighting is underestimating the impacts of global warming.

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