Calculating the Social Cost of Carbon

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Abstract
The paper[1] discusses the determination of the social cost of carbon (SCC) using the PAGE2002 model used in the Stern Review. The SCC depends sensitively on assumptions about future economic development, the range and likelihood of economic and social damage arising from climate change at future dates and the discount rate to apply to that damage. The paper critically examines the choice of pure time preference and the weight to place on damage experienced by other countries in the distant future. Key conclusions are that the SCC rises at about 2.4% p.a. and the range of plausible estimates for the SCC is wide. The SCC is sensitive to a number of factors, significantly the equilibrium temperature rise for a doubling of CO_2 concentration, the pure rate of time preference, the non-economic impact, the inequality weighting parameter and the half-life of global warming. Within the model the SCC appears surprisingly insensitive to the emissions scenario for reasons that are explained. The paper points out that methane and SF6 are also powerful GHGs whose impact can be estimated within the model.

Key words
Climate change, social impacts, carbon price, rate of pure time preference

JEL classification
Q54, Q58, Q52

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[1] **Forthcoming in *Delivering a Low Carbon Electricity System: Technologies, Economics and Policy* Editors: Michael Grubb, Tooraj Jamasb and Michael G. Pollitt (*University of Cambridge)* Cambridge University Press.**

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Abstract

The paper discusses the determination of the social cost of carbon (SCC) using the PAGE2002 model used in the Stern Review. The SCC depends sensitively on assumptions about future economic development, the range and likelihood of economic and social damage arising from climate change at future dates and the discount rate to apply to that damage. The paper critically examines the choice of pure time preference and the weight to place on damage experienced by other countries in the distant future. Key conclusions are that the SCC rises at about 2.4% p.a. and the range of plausible estimates for the SCC is wide. The SCC is sensitive to a number of factors, significantly the equilibrium temperature rise for a doubling of CO_2 concentration, the pure rate of time preference, the non-economic impact, the inequality weighting parameter and the half-life of global warming. Within the model the SCC appears surprisingly insensitive to the emissions scenario for reasons that are explained. The paper points out that methane and SF6 are also powerful GHGs whose impact can be estimated within the model.

1 Introduction

Fossil-fuel electricity generation accounted for 74% of total electricity in Britain in 2005, 62% in the OECD, and 66% in the world (in 2003). Burning fossil fuels releases carbon dioxide, CO_2, which, as the main greenhouse gas is the major contributor to future climate change. Greenhouse gases (GHGs) are, in technical economic language, a global stock pollutant that is a non-excludable pure public bad. That is, emissions today add to the stock of atmospheric GHGs that only decays slowly, and which affect everyone, regardless of their location and the source of the emission, whether or not they are willing to pay to avoid the resulting cost. Unless properly priced they will be released in excessive amounts. Carbon pricing would then be a way of confronting those emitting GHGs with the social cost they impose. "Companies that face a price for carbon will be incentivised to reduce their emissions, either through energy efficiency improvements, investing in new technology, or switching to the use of less carbon-intensive sources of energy." (DTI *Energy Review Report 2006,* p27).

Most technologies for delivering low or zero carbon electricity are not competitive at current electricity prices without either a carbon price or some other subsidy. Projections of how economies like the UK might move towards a low-carbon configuration imply that over the next 40 years a large fraction of the least-cost decarbonisation could come from the electricity supply industry, so a proper carbon price for generation is critical. Carbon is currently priced in the European Emission Trading System, but its future post 2012 is still in doubt. Generation investment has a life-time of 20-60 years, and so its profitability will depend heavily on views about likely future electricity and carbon prices. This paper assesses how carbon should be priced, and more fundamentally, how to assess the benefits of moving to a low-carbon economy, so that one can better judge whether the extra costs of low-carbon electricity are worthwhile.

The fundamental concept is the social cost of carbon that measures the present discounted value of the additional social costs (or the marginal social damage) that an extra tonne of carbon released now would impose on the current and future society. This immediately raises four questions: what is society and social value, how should we measure the social cost when it occurs, what rate of discount should we apply to these costs, and how should we take account of the considerable uncertainty about the future damage and costs?

Climate scientists attempt to model the effects of releasing greenhouse gases over the next few decades on concentrations of these gases and the consequential impacts on climate by region, specifically temperature distributions over time and space, sea-levels, storm frequency and other damaging impacts. In order to translate these impacts into costs that can be compared with the costs of reducing emissions, one needs an Integrated Assessment Model that estimates the economic impact of the climate impacts, aggregates these impacts across regions and over time to give a present value that can be compared with the investment costs of mitigating climate change. The *Stern Review* (Stern, 2006) provides two ways of making this comparison – it computes the social cost of carbon released as GHGs and it estimates the damage done by climate change compared against a world in which GHG emissions had no adverse effects. The specific way in which it measures these damages is in terms of their Balanced Growth Equivalent (BGE), a concept that appropriately goes back to Mirrlees and Stern (1972).

Both concepts of the cost of climate change depend on science, economic modelling and ethics, as is made very clear in the *Stern Review* and explained below. This is not the place to discuss the climate science, but the economic modelling and especially the ethical assumptions needed to value impacts are critical to the magnitudes of both damage measures and warrant some further discussion. The BGE has certainly caught the headlines with the dramatic claim that the impacts of climate change could be equivalent to 5%-20% of world GDP while the costs of mitigation might only be 1%, implying a large benefit cost-ratio for mitigation. However it is not a particularly useful guide to policy, and is not further discussed here (rather elliptical details are provided in the *Stern Review* at Box 6.3 at page 161).

The 5%-20% number is higher than many previous estimates for three sets of reasons. First, most preceding estimations of costs used the results from the third assessment report of IPCC, and Stern included more up-to-date scientific evidence. The subsequently released fourth assessment report of IPCC confirmed this approach. Second, many cost estimates only considered direct economic impacts, but the *Stern Review* attempted to include all of the IPCC's five reasons for concern about projected climate change impacts (risks to unique and threatened ecosystems, risks from extreme climate events, distribution of impacts, aggregate impacts, and risks from future large-scale discontinuities) (IPCC, 2001a, p5). Third, the *Stern Review* used endogenous discounting and lower rates of pure time preference (0.1%) than many other authors.

As the *Stern Review* relies heavily on the PAGE2002 Integrated Assessment Model (IAM) this is also a suitable place to provide a brief description of the model, and to illustrate the way in which the damage costs are derived, and their sensitivity to different ethical and statistical assumptions.

The *Stern Review* reviewed various IAMs before selecting the PAGE2002 model, and argued that "A model of the monetary cost of climate change ideally should provide:

- Cost simulations across the widest range of possible impacts, taking into account the risks of the more damaging impacts that new scientific evidence suggests are possible.
- A theoretical framework that is fit for the purpose of analysing changes to economies and societies that are large, uncertain, unevenly distributed and that occur over a very long period of time.

… *The model we use – the PAGE2002 IAM – can take account of the range of risks by allowing outcomes to vary probabilistically across many model runs, with the probabilities calibrated to the latest scientific quantitative evidence on particular risks.*" (Stern, 2006, p152, emphasis in original).

2 The PAGE2002 model

Integrated assessment models incorporate knowledge from more than one field of study, with the purpose of informing climate change policy. The first version of the PAGE (***P**olicy **A**nalysis of the **G**reenhouse **E**ffect*) integrated assessment model was produced in 1991 for the European Commission. The latest version, and the one used in the *Stern Review,* was updated in 2002 to PAGE2002. It is able to include all five of the IPCC's five reasons for concern about climate change, by virtue of its sectoral and regional structure, and its aggregation of impacts into a global net present value.

The main structural changes to the earlier versions of PAGE incorporated in PAGE2002 are the introduction of a third greenhouse gas and, crucially for the *Stern Review*, the incorporation of possible future large-scale discontinuities into the impact calculations of the model. Default parameter values have also been updated to reflect changes since the IPCC Second Assessment Report in 1995. PAGE2002 contains equations that model:

- Emissions of the primary greenhouse gases, CO_2 and methane, including changes in natural emissions stimulated by the changing climate. PAGE2002 allows the explicit modelling of a third gas whose forcing is linear in concentration (which is the way in which various trace GHGs contribute to global warming), and models other greenhouse gases such as N_2O and (H)CFCs as a time-varying addition to background radiative forcing.
- The greenhouse effect. PAGE2002 keeps track of the accumulation of anthropogenic emissions of greenhouse gases in the atmosphere, and the increased radiative forcing that results, using a logarithmic relationship between concentration and forcing for CO_2, a square root form for methane, and a linear form for the third gas (included to allow the social cost of trace gases to be estimated).

- Cooling from sulphate aerosols. The direct and indirect reductions in radiative forcing are separately modelled.
- Regional temperature effects. For the eight world regions in PAGE2002, the equilibrium and realised temperature changes are computed from the difference between greenhouse warming and regional sulphate aerosol cooling, and the slow response as excess heat is transferred from the atmosphere to land and ocean. Sulphate cooling is greatest in the more industrialised regions, and tends to decrease over time due to sulphur controls to prevent acid rain and negative health effects.
- Nonlinearity and transience in the damage caused by global warming. Climatic change impacts in each analysis year are modelled as a polynomial function of the regional temperature increase in that year above a time-varying tolerable level of temperature change, $(T\text{-}T_{tol})^n$, where n is an uncertain input parameter normally in the range from one to three. Impacts are aggregated over time using time-varying discount rates.
- Regional economic growth tracking each region's GDP and GDP per capita over time. Impacts are evaluated in terms of an annual percentage loss of GDP in each region, for a maximum of two sectors; defined in this application as economic impacts and non-economic (environmental and social) impacts .
- Adaptation to climate change. Investment in adaptive measures (e.g. the building of sea walls; development of drought resistant crops) can increase the tolerable level of temperature change before economic losses occur and also reduce the intensity of both non-economic and economic impacts.
- The possibility of a future large-scale discontinuity. This is modelled as a linearly increasing probability of a discontinuity that substantially reduces gross world product occurring as the global mean temperature rises above a threshold.

ThePAGE2002 model (hereafter abbreviated to the PAGE 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 in Hope (2006), and because all aspects of climate change are subject to profound uncertainty. The full set of equations and default parameter values in PAGE are included in Hope (2006). Most parameter values are taken directly from the IPCC Third Assessment Reports (IPCC, 2001a,b).

The outputs of PAGE include estimates of the impacts of climate change across the regions of the world and over time, how these impacts change if measures are taken to cut back the emissions of greenhouse gases, or adapt to changes in climate, and what the costs of the abatement or adaptation measures might be.

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. PAGE builds up probability distributions of results by representing 31 key inputs to the SCC calculations by probability distributions, making the characterisation of uncertainty the central focus, as recommended by Morgan and Dowlatabadi (1996).

Figures 1 and 2 show the climate change impacts calculated by the PAGE model to 2200 on the IPCC's scenario A2 for the OECD, China, India (including the rest of South Asia), and the Rest of the World (ROW). The projections of GDP per capita in the A2 scenario at PPP exchange rates are shown on a logarithmic scale so that lines of constant slope have a constant growth rate. Note the different vertical scales in the two graphs. In both figures the graph "no CC" shows the evolution of per capita income assuming no climate change impacts, while the graphs labelled "mean" show the evolution of per capita income under the mean climate change impact, and those marked 95% shows the 95% worst case (i.e. 95% of possible paths have less severe impacts than this).

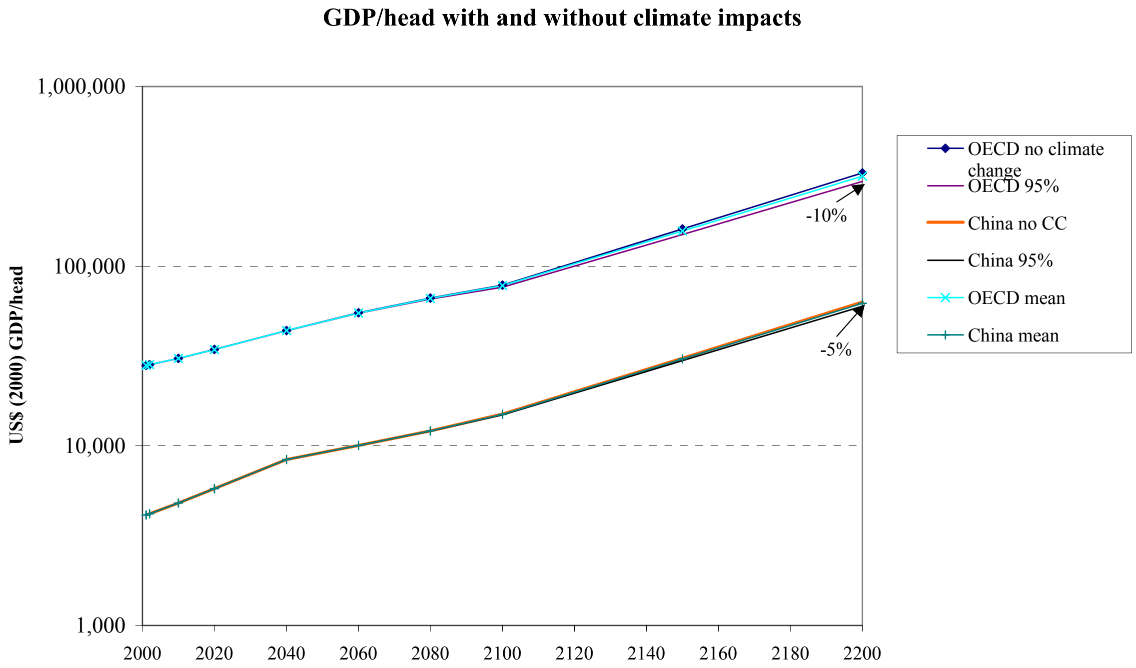

Figure 1. Evolution of GDP/head with and without climate change - OECD and China

Figure 2 shows the evolution of per capita income for India and the Rest of the World (ROW).[2] The ROW per capita income assuming no climate change (CC) grows on average at 1.5% p.a. reaching the dizzy heights of $100,000 by 2200. The numbers at the right-hand side of the graphs show the decrease in terminal GDP/head relative to the no climate change impact. Thus for India the impact of climate change in the 95% case causes a 69% fall compared to its level without any climate change impact, i.e. there is a 5% chance that Indian income in 2200 will be more than 69% below the no climate change reference path (but still over five times as rich as in 2001) and a 50% chance that it will be 27% below. For RoW, there is a 5% chance that income in 2200 will be more than 40% below the no climate change reference path but still over 13 times richer than in 2001. Thus in both cases these countries would still be considerably richer than now even in the extreme case. In Figure 1 the percentage changes are too small to see easily but the arrows show the 95% case - for OECD

[2] ROW is all countries other than OECD, India, and China

in 2200 the impact is only 10% of the no impact level (and more than ten times as rich as in 2001) and for China is only 5% (and over 14 times as rich).

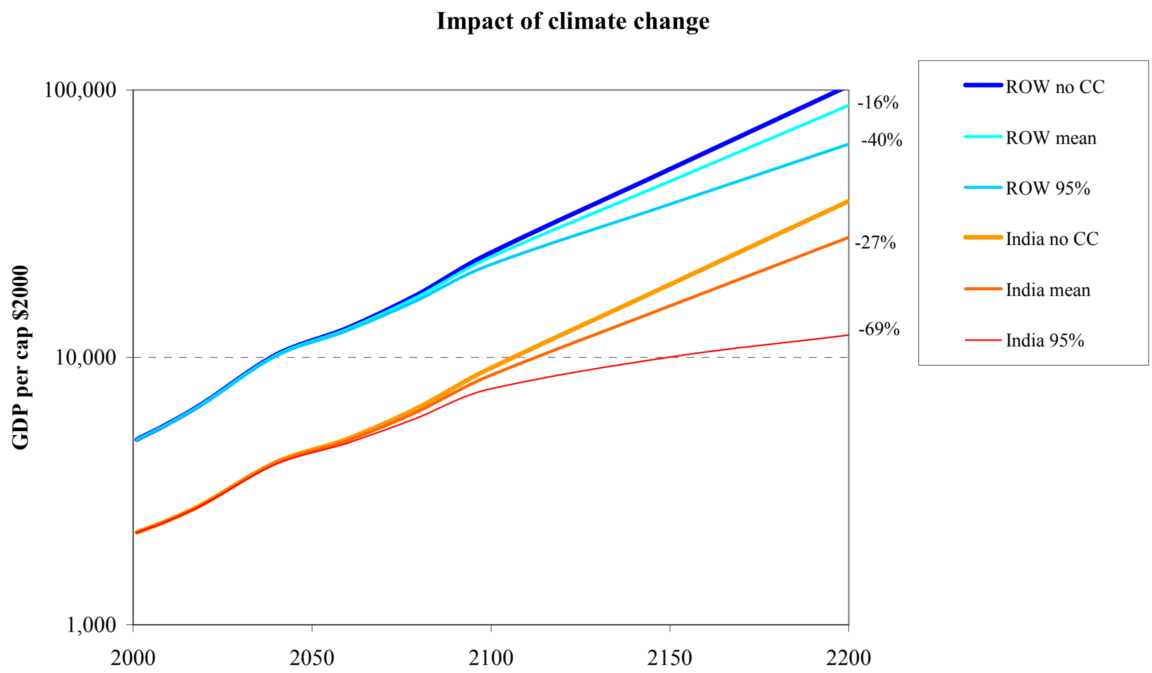

Figure 2 Impact of climate change on India and the rest of the world

The PAGE model provides one-half of the story on climate change, for it captures the impacts of climate change across time and regions, and, as we shall see below, values them to derive an estimate of the damage caused by climate change. Figure 2 shows that these impacts are delayed in time and concentrated on relatively poorer countries. Action to mitigate climate change will need to be taken in the near future and in countries that appear to be relatively sheltered from the full impact of climate change, as figure 1 shows. The other half of the cost-benefit analysis is therefore to compare the costs of mitigation with the benefits of reducing the damage of climate change, and this paper discusses some of the issues involved in making that balance. The critical element is to derive a price of carbon that will allow investors and consumers to make appropriate and decentralised decisions that collectively will deliver the right balance of mitigation and climate change.

As the *Stern Review* and other commentators have noted, the costs of mitigating climate change appear modest when compared with future decreases in income: "In summary, analyses that take into account the full ranges of both impacts and possible outcomes - that is, that employ the basic economics of risk - suggest that Business and Usual (BAU) climate change will reduce welfare by an amount equivalent to a reduction in consumption per head of between 5 and 20%. … ***Resource cost estimates suggest that an upper bound for the expected annual cost of emissions reductions consistent with a trajectory leading to stabilisation at 550ppm CO_2 is likely to be around 1% of GDP by 2050."*** (Stern, 2006, pages x and xiii, emphasis in original). While this suggests that the benefit-cost ratio of mitigation is highly attractive at between 5 and 20, the benefit estimates derive from a particular aggregation across countries and over long periods of time, while the costs will be incurred initially largely in developed countries like the UK and in the next few decades. How this might be done is developed at greater length in Grubb and Newbery (2007) where the choice of instruments is discussed. The rest of this paper is directed to describing how the climate damage estimates are derived and how they can be translated into a carbon price.

3 Measuring the damage of greenhouse gas emissions

If we are to measure the damage of GHG emissions we need to be able to value the impacts of the consequential climate changes. This is complicated for several reasons, but the idea is relatively straightforward – what compensation (in money that can be used to buy other goods and services) would individuals require to make them as content with climate change as without? This immediately raises obvious problems – we are not sure what the physical consequences will be, and even if we were, we do not know how different future individuals would make the valuation (i.e. reveal what compensation would be just adequate), and (this is where the ethics comes in) how to balance these future monetary amounts needed to compensate future individuals (mostly as yet unborn) against expenditures by different people now to mitigate these impacts.

Nor can we leave the choice to the market, because, as noted above, GHGs are non-excludable public bads, and reducing GHG emissions is a pure public good (where "pure" means non-excludable). Pure public goods require collective agreement on what action to take, and that involves balancing costs or payments now for future benefits to others, most of whom are not here to speak up for their shared common interest in our actions. We may be able to reach considerable agreement that we would like to pass on a better world (or at least not a worse world) to our descendants and those with whom we share an immediate gene pool.[3] We might therefore be willing to make some financial sacrifices now to benefit these descendants provided others (interested in their own relations) would do so as well in a collective agreement. The *Stern Review* goes considerably beyond this rather loose selfish gene approach to take on board the full ethical content of a particular specification of classic utilitarian welfare economics. In doing so it follows a tradition of often controversial arguments for equity weighting in general, and a specific form of that weighting (see appendix).[4]

Utilitarianism evaluates outcomes in terms of their consequences to individuals while welfare economics assumes that these consequences can (to an operational extent) be

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[3] Thus the famous British scientist, J.B.S. Haldane, is credited with saying that he would give his life to save more than two drowning brothers or more than eight drowning cousins, on the argument that if he were only concerned with passing on his genes to succeeding generations, as each brother shares half his genes and each cousin only one eighth, in expected terms his genes would survive better provided the trades were sufficiently advantageous. It is thus not necessary (on the selfish gene model at least) for everyone to have children to be concerned for future generations.

[4] see e.g. Eyre et al, (1997), Fankhauser et al, (1997); (1998); Clarkson and Deyes, (2002).

measured in terms of consumption (or more broadly, well-being which includes health, wealth and happiness to the extent that it can be measured by the same yardstick of money used to value material consumption). The ethics enters by supposing that consumption accruing to different individuals can be compared and aggregated using a Social Welfare Function (SWF), $W(U^1(\boldsymbol{c}_1),...U^h(\boldsymbol{c}_h)...U^n(\boldsymbol{c}_n))$, where $\boldsymbol{c}_h$ is the vector of consumption goods received by household h, and $U^h(\ )$ is a measure of utility of that household (which will typically depend on the number and age of household members and the internal distribution of goods between them).

The maintained assumption in the *Stern Review* (and the British Government's *The Green Book: Appraisal and Evaluation in Central Government,* HMT 2003 and many of the references in footnote 2) is that the consumption bundle, $\boldsymbol{c}_h$, can be measured by consumption expenditure per equivalent adult at market prices, c_h, and that the Social Welfare at some particular moment but including everyone on the planet takes the very specific additive form

$$W(U^1(c_1),...U^h(c_h),...U^n(c_n)) = \sum_{h=1}^{n} U^h(c_h) = \sum_{h=1}^{n} \frac{c_h^{1-\nu}}{\nu - 1}, \quad \nu \neq 1, \qquad (1)$$
$$= \sum_{h=1} \log c_h, \quad \nu = 1.$$

where ν is Atkinson's (1970) coefficient of inequality aversion, analogous to the coefficient of relative risk aversion. One attraction of this iso-elastic form (ν is the elasticity of marginal utility, which is constant)[5] is that it provides a single parameter to describe attitudes to inequality. Thus $\nu = 0$ corresponds to a complete disregard for inequality, where society is solely concerned with total consumption and not its distribution. Higher values of ν attach increasing importance to redistributive goals. The social weight attached to consumption of person i is then $\beta_i = c_i^{-\nu}$. If, as in the *Stern Review* and the *Green Book*, one makes the further assumption that $\nu = 1$, the utility function is logarithmic, $U(c_h) = log c_h$, (sometimes referred to as the Nash-Bernouilli utility function). In that case someone receiving half the average consumption level would count as twice as deserving in receiving an extra £1 in grant allocation as the average person – socially we would consider it as equally desirable to give £1 to this poorer person as £2 to the average. If $\nu = 2$ then the social weight of the poorer person would be $(½)^{-2} = 4$ times as high as the average.

Where do these ethical ideas (and particular parameter values for the coefficient of inequality aversion, in this case $\nu = 1$) come from? One not very ethically convincing argument is that many perceptions (loudness of sounds, visual acuity, etc) are logarithmic, so that a doubling of sound has an equal impact whether quiet or loud (and is measured in decibels, a logarithmic scale). If pain and pleasure are logarithmic, then perhaps the individual utility function should also be logarithmic. In the climate change debate, the ethical issue shows up sharply in whether to attach equity weights to future damages or not. Here, the two extremes are to count a $ worth of damage to a US citizen (per capita GDP

[5] Stern uses the notation η for the elasticity of marginal utility.

$41,400 at Purchasing Power Parity in 2004) and one in Bangladesh (per capita GDP $2,011 at PPP) as equal, or to weight them by the social marginal utility of consumption. If we take the Stern and *Green Book* weighting then each person's gain or loss is given by the inverse of their consumption. On this basis damage to the Bangladesh economy would be weighted nearly 21 times as heavily per citizen affected as damage to the US economy. If it so happened that damage to each were in proportion to their income the effect would be to weight the damage as the same per head regardless of location in the world, which would have an appealing ethical simplicity.

As far as damage is concerned, a large part is likely to be the impact on human well-being, particularly the quality of life, where the approach of health economists of measuring benefits by Quality Adjusted Life Years (QALYs) gained, has immediate appeal. These are likely to be closely related to per capita GDP, so a Bangladeshi QALY might have a monetary value only 5% (at PPP exchange rates) of an American QALY. Weighting these by the inverse consumption per head would once again give an equal social weight to a Bangladeshi QALY as in the US.[6] (Other elements of damage, e.g. to crops, property from flooding, hurricanes, etc, may also be roughly proportional to GDP, so this argument may extend more broadly.) Another way to appreciate the force of Stern's ethical assumption is that the social cost of reducing the consumption of a person in a rich country by 10% is valued equal to the social benefit of increasing the consumption of a person in a poor country by 10% now. Thus as the US has 21 times the per capita consumption of Bangladesh (at Purchasing Power Parity exchange rates), incurring a cost of $21 in the US to deliver a benefit of more than $1 in Bangladesh would register a net social gain on this calculus.

3.1 The social cost of carbon

The social cost of carbon (SCC) measures the present discounted value of the additional social costs (or the marginal social damage) that an extra tonne of carbon released now would impose on the current and future society. Other GHGs can be similarly valued and their social costs similarly expressed as a price per tonne. The PAGE model is set up to compute the social costs of carbon and other GHGs.

We noted above that estimating the SCC raises a number of related questions: what is social value and how should we measure the social cost when it occurs? In addition, we need to decide what rate of discount to apply to these future utility levels. A component of this discount rate, the rate of pure time preference, δ, measures the weight to attach to future levels of well-being solely because they are enjoyed later in time.[7] Some ethicists (notably Frank Ramsey, who developed the intertemporal theory of optimal investment) argued that to discount at any positive rate was solely because of a failure of imaginative sympathy, while others have argued that there is a non-zero risk of extinction of life as we know it (from asteroids, super volcanoes, or global nuclear war) and hence that $\delta > 0$. The number is critical when dealing with long time periods as with climate change. The *Green Book* takes a value

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[6] The argument that lives lost in Bangladesh are no less valuable than those lost in the US was persuasive in early debates, and is an attractive feature of the Nash-Bernouilli form.

of δ = 1.5% while the *Stern Review* takes the point estimate of δ = 0.1%. The implication of Stern's assumption that welfare is a logarithmic function of per capita consumption and that the rate of pure time preference is 0.1% is that the social cost of reducing the consumption of a person in any country by 10% (rich or poor) now is valued equal to the social benefit of increasing the consumption of a person in any country (rich or poor) by 11% in a 100 years' time.[8] Thus if per capita consumption were to grow at 1.5% p.a. for 100 years, future generations would be 4.43 times richer than current generations, and a $1 spent now would be more than compensated by avoiding a loss of $4.9 in 100 years, even though the future generations are much richer.

Finally, we need a method that can take account of the considerable uncertainty about the future damage and costs. This last point is handled by Stern's utilitarian ethics embodied in equation (1), combined with weighting each possibly future outcome with a measure of its likelihood. The cost of a significantly adverse outcome is measured by the lower utility caused by a lower level of future consumption (or well-being) of agent *h* at time *t* in state of the world *s*: c^h_{ts}, while the weight to attach to state *s* is the probability of that state occurring, p_s. Putting this all together, the valuation of a trajectory of future levels of consumption is

$$W = \int_0^{\infty} \sum_{h=1}^{h=n} E \frac{(c^h_{ts})^{1-\nu}}{1-\nu} e^{-\delta t} dt, \qquad (2)$$

where δ is the rate of pure time preference, the sum is over all (equivalised for age) individuals *h* living at time *t*. *E* is the expectations operator, so that $E\,(c^h_{ts})^{1-\nu}$ is $\Sigma_s\, p_{ts}(c^h_{ts})^{1-\nu}$, where p_{ts} is the probability of state *s* occurring at date *t*. Taking account of the range of possible future levels of well-being profoundly affects the cost, as can be readily demonstrated. Suppose we follow Stern and take ν = 1, so that the utility function is logarithmic. Suppose also that there is a 95% chance of consumption levels being 105, and a 5% chance of consumption being 5, so that the expected level of consumption is 100. However, the expected level of utility is 4.5 which is equivalent to a (certain) level of consumption of 90, and in terms of welfare risk has imposed a 10% reduction in the expected standard of living compared to the welfare associated with the expected point estimate of 100. If the two possible outcomes are 110 with *p* = 90% and 10 with *p* = 10%, the loss of welfare is 13.5%. Risk is costly in a way that can be quantified (once the utility function is specified).[9]

There is an obvious attraction in combining attitudes to risk and attitudes to inequality in the same utility function, and the coefficient of inequality aversion, ν, in (1) and (2) is formally identical to Arrow's coefficient of relative risk aversion, which is often invoked to determine such critical parameters as the equity risk premium in discounting models, as discussed further below. They both relate to balancing the pain of suffering a loss or lower consumption level with the joy of a windfall gain or higher consumption level. Indeed, it is often

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[7] Stern uses the notation ρ for the rate of pure time preference.

[8] 1.001^{100} =1.105 is the value of $1 invested at 0.1% for 100 years so an increase of 10% now is as valuable as an increase of 11.05% in 100 years' time.

[9] $0.95*\log_e(105) + 0.05*\log_e(5) = 4.5$ and $\exp(4.5) = 90$. $0.9*\log_e(110) + 0.1*\log_e(10) = 4.46$ and $\exp(4.46) = 86.5$.

argued that observing risky choices would allow us to infer the utility function, but most estimates suggest an implausibly high aversion to risk, measured by ν.[10]

However, the concept of risk aversion attempts to describe a single person contemplating risky choices, where the person experiencing the gain or loss is the same as the one making the decision. Social risk aversion relates to social decisions (i.e. made by a policy maker) contemplating either good or bad outcomes for others affected by the decision. Inequality aversion is a further step in which decision makers contemplate actions which differentially affect the rich or poor, or, taking an even further step, contemplate transferring resources from the rich to the poor. Arguably each extra step requires a somewhat stronger ethical position, or would require more discussion among the population affected. We come back to the issue whether we are likely to be as concerned about outcomes to our possible genetically related descendants as to complete future strangers, and, more to the point, whether we need to be if each country takes collectively supportive actions.

Finally, and this may be less obvious but is an immediate consequence of equation (2), attitudes to inequality (as well as the rate of pure time preference) affect the rate at which we discount the future. A simple example demonstrates this. Suppose that over long future periods of time we expect the rate of growth of per capita consumption to be g (which for Britain over the past half century has averaged 2% p.a.). If we consider the person of average consumption at date t, $\bar{c}_t = \bar{c}_0 e^{gt}$, the associated weight to attach to marginal changes in well-being at date t is $\beta_t = \bar{c}_0^{-\nu} e^{-\nu gt}$ and the value now is $\beta_t e^{-\delta t} = (\bar{c}_0)^{-\nu} e^{-\nu gt} e^{-\delta t}$ which is falling at rate $i = \delta + \nu g$. This is the effective rate at which small changes in future standards of living (caused, for example, by the release of an extra Gigatonne of carbon now) should be discounted back to give a present value, essential to estimating the social cost of carbon. In social cost-benefit analysis it is known as the Consumption Rate of Interest, CRI, as it measures the trade-off between *consumption* now and consumption in the future. It should be contrasted with the Investment Rate of Interest, IRI, which relates the rate at which investible funds now generate re-investible profits in the future (and which might be distributed for consumption then). We shall return to the difference between these below.

If we think that high rates of growth which lead to high future standards of living, should not *therefore* be given much weight, then this can be achieved by a higher discount rate, which might argue for a higher value for inequality aversion, ν. In that case we automatically argue (in this particularly utilitarian framework) for a high weight to be placed on the poor now and less on adverse outcomes for future richer generations. Exploring the consequences of treating these various outcomes separately seems advisable.

The rate of pure time preference is a similarly powerful and contentious parameter that merits further discussion. For example, the *Stern Review* uses PAGE to project the world

[10] There are many explanations, of which one of the more plausible is that hard wiring in the brain has been selected to survive the kinds of risk encountered in the ancestral environments where humans evolved. Such instinctive responses are not necessarily well-suited to more nuanced rational calculations of expected utility (Laland and Brown, 2002, p162)

with and without climate impacts until 2200, and thereafter assumes that whatever damage climate change has done (as a percentage reduction in GDP below the no-climate impact reference) will continue thereafter. Thus if in 2200 climate change has caused a 13.8% reduction in GDP relative to no climate change, then average per capita world GDP is assumed to continue to grow at 1.3% p.a. (with no further population growth) but 13.8% below the no-climate change path. Yohe (2006) calculates that 55% of the present discounted value of the impact will occur after 2200 (when the model predictions cease) if the rate of pure time preference, δ, is 0.1%, but only 19% if the rate is 1% (and only 8% at 2%). A large part of the disagreement about the benefits of climate change mitigation arises from different views about this parameter (and about the "right" way to discount the future more generally).

Perhaps the most persuasive argument for Stern's *conclusions* about the social cost of climate change, if not the logic of the argument, comes from Weitzman's (2007) review of the *Stern Review*. He notes that a not unreasonable consensus view on the rate of pure time preference δ might be 2%, of the elasticity of marginal utility v might be 2, and the rate of growth g, might be 2%, suggesting a discount rate of 6%, leading to a valuation of damage 100 years' hence only 1% as high as Stern's estimates. However, Weitzman notes that this fails to do justice to the possible variability of future growth rates, and that the correct discount rate when the rate of growth is variable is not the simple expectation of $\delta+vg$, but that one should take expectations of discount factors, which gives a much lower average discount rate, considerably closer to the Stern value of 1.4%. The advantage of the PAGE model as used in the Stern review is that by applying the discount factor associated with each outcome and working with probability distributions of outcomes, as in equation (2), risk is correctly treated.

Weitzman also notes that the risk-free interest rate, the return to equity (risky) investment, the rate of growth and the variability of the rate of growth are, using similar logic to deriving the discount rate as $\delta+vg$, closely related. If the growth rate is normally distributed as $N(g, \sigma^2)$ then Weitzman shows that the equity risk premium (the difference between the risk-free rate and the return to equity) should be $v\sigma^2$. If the standard deviation of the growth rate, σ = 2%, and the other parameters are taken as Weitzman's consensus values (all 2's), then the average return to equity would be 6% and the risk free rate would be 5.9%. If climate damage is proportional to GDP then the equity return is the correct discount rate, but the observed equity risk premium in the market place is closer to 5-6% than the 0.1% implied by the theory – hence the dual puzzles: the observed equity risk premium is apparently too high and/or the observed risk free rate is too low.

Weitzman's resolution of these puzzles is to observe that observationally one cannot reject the hypothesis that the tails of the distribution of risky outcomes (growth rates, equity returns, etc) are "thicker" than the normal distribution, and over long periods of time, because the tails of the normal distribution fall off faster than a negative exponential, discounting makes extreme events carry little present weight. Fatter tails do not have this property and they can grow faster than any discount rate given a long enough period of time, meaning that future very uncertain events (like extreme climate damage) can carry a far greater current weight than would be implied by simple equity discounting as illustrated above. Put another way, future climate damage may be perceived to be very costly today not because our rate of pure time preference is very low, nor because our inequality aversion (or the elastiticity of marginal utility) is rather low, nor because our growth predictions are rather cautious (Stern assumes g = 1.3%), but because we attach greater subjective weight to a possibly extremely unlikely but very bad future outcome. Weitzman thus argues that Stern has the right answer (the damage may be 5 or more times as high as the cost of avoiding the damage) for the wrong reasons. Put in the context of the benefit-cost analysis of mitigating climate change, the high value of action now reflects the value of insurance against unlikely future disaster, where the probability and scale of that disaster are both unknown.

3.2 Calculating the social cost of carbon using the PAGE model

The PAGE model calculates the social cost of carbon (SCC) by finding the difference in the discounted economic cost of climate change impacts between two emission scenarios that are identical except for the emission of an extra one billion tonnes of carbon as CO_2 in 2001 for one of the scenarios. The difference in impacts is divided by one billion to obtain the SCC. The calculation is repeated with twice the difference in emissions to check that rounding errors for this small amount of extra emissions are not significant. The uncertainty in the SCC is captured by running the model 1000 times, selecting different values for about 30 inputs from probability distributions. These probability distributions are triangular, and thus completely described by the minimum value, the value for the peak of the triangle, and the maximum value, expressed here as [minimum, most likely, maximum]. With wide enough ranges for the parameters, they can include the fat tails that have exercised those like Weitzman when attempting to reconcile rational responses to risk with observed behaviour, and this degree of uncertainty is a considerable improvement over simpler deterministic models.

The units in which damage is measured are in the first instance changes in GDP ($2000 at PPP) by region and time. These are then equity weighted, so that for region r at date t the total impact is the change in GDP multiplied by $\beta_{rt} = (c_{rt}/c_{Wt})^{-\nu}$, where c_{Wt} is average world per capita consumption at date t. The equity weighted damage is then discounted at the time and regional varying consumption rate of interest ($\delta + \nu g_{rt}$, equivalent to multiplying β_{rt} by $(c_{rt}/c_{r0})^{-\nu} e^{-\delta t}$) and integrated over the period from now until 2200.[11] If eventually regions converge in their per capita growth rates, then the Appendix shows that there is a reasonably simple relationship between the unweighted cost of carbon, CC, and the equity-weighted SCC, SCC:

[11] This is a rather hybrid approach to equity weighting, as Anthoff et al (2006) argue. They propose using world average per capita consumption at date 0 as the numeraire, c_{W0}, so that the equity weight to apply for region r at date t is $\beta_{rt} = (c_{rt}/c_{W0})^{-\nu}$. This is then discounted by the rate of pure time preference, δ. If one chooses any other numeraire (e.g. EU per capita income, c_{EU0}) then the resulting SCC can be expressed relative to that numeraire by multiplying by $(c_{EU0}/c_{W0})^{\nu}$. This can make quite a difference. Thus if $\nu = 1$ (the logarithmic and Stern case), as the world PPP income per head is $9,500 and the EU is $29,600 the result would need to be multiplied by 3.2, (CIA World Factbook, at https://www.cia.gov/cia/publications/factbook/rankorder/2004rank.html).

$$\frac{CC}{SCC} = \frac{Cov(D_r, Y_{r0})/Y_{W0} + D}{Cov(D_r, n_r) + D}, \tag{3}$$

where D_r is the present value of climate change damage in region r expressed each year as a fraction of region r's GDP of that year, and discounted at a suitable discount rate (δ +(ν-1)g), Y_{r0} is region r's GDP now, Y_{W0} is current world GDP, n_r is r's the share of world population and D is the average of the D_r's. If populous countries (those with high values of n_r) have higher than average damage impacts on future GDP, but smaller than average GDP's now, then $Cov(D_r, Y_{r0})$ will be negative and $Cov(D_r, n_r)$ will be positive, making the ratio less than 1 and hence making the unweighted cost of carbon less than the equity-weighted SCC.

Using scientific and economic inputs taken mainly from the IPCC's 2001 *Third Assessment Report*, and taking (as point estimates) the 2003 *Green Book* assumptions on the social rate of time preference δ = 1.5%, and ν = 1 (the logarithmic case which is also the Stern assumption), the mean PAGE estimate for the SCC under the A2 scenario is \$66/tC (tonne of carbon = \$18/tCO_2) emitted in 2001, in year 2000 dollars, with a 5-95% range of \$13 – 185/tC (\$3.5-50/tCO_2). If the average rate of per capita growth until 2200 is 1.5%, this corresponds to a CRI of 3%. We see immediately just how broad the range of plausible estimates is, even with these fixed assumptions for discount rates and equity weights.

Allowing discount rates and equity weights to vary in PAGE gives slightly different results. With pure time preference rates δ of [1%, 2%, 3%] per year, and an equity weight parameter ν of [0.5, 1.0, 1.5], the mean PAGE estimate for the SCC becomes \$43/tC (\$12/tCO_2) emitted in 2001, with a 5-95% range of \$10 – 130/tC (\$3-35/tCO_2). The figures are lower because the central value for the pure time preference rate, 2% per year, gives a slightly higher discount rate than the Treasury *Green Book*, and so the impacts that occur in the far future have less weight. The mean CRI would be 3.5% with a range from 1.75% to 5.25%.

Ignoring equity weighting altogether, but taking the discount rate [2%, 3%, 4%], the mean SCC is \$51/tC (\$14/tCO_2) with a range from \$10 to \$150/tC (\$3-41/tCO_2). Other authors have similarly explored the sensitivity of the SCC to equity weights. Clarkson and Deyes (2002) update various estimates to 2001 and find that Eyre et al (1999) with no equity weighting the SCC is \$53/tC \$14/tCO_2) at δ = 3%, very close to the PAGE mean estimate above for δ = [2%, 3%, 4%] and not far from the mean value of \$66/tC (\$18/tCO_2) with equity weighting and a CRI of 3%.

The *Stern Review* takes point estimates δ = 0.1%, and ν = 1 and, after updating PAGE to take account of more recent climate science that updates the IPCC 2001 models, arrives at a mean estimate of \$85/tCO_2, (\$312/tC). The difference between the *Stern Review* results and the estimates presented here is almost entirely due to the low value of δ; applying a value of δ = 0.1% to the estimates in this paper gives a mean SCC of \$330/tC (\$90/tCO_2), with a 5-95% range of \$65 – 870/tC (\$18-237/tCO_2).

The extreme sensitivity of the SCC (or the benefit-cost ratio of mitigating climate change) has been remarked on by other authors, including most recently Weitzman (2007),as discussed above. Cline (1992) argued for a very low discount rate and produced high damage estimates. Clarkson and Deyes (2002, table 1) cite Eyre et. al.'s (1999) estimate for the equity weighted SCC with δ = 1% of \$244/tC (\$66/tCO_2), and at δ = 3% \$110 (\$30/tCO_2). Ackerman and Finlayson (2006) observes that in the DICE model of Nordhaus and Boyer (2000), which fully recognises the seriousness of climate change, nevertheless finds that "the optimal carbon price is less than \$6 per ton in 1995 (\$1.6/tCO_2), and less than \$10 per ton in 2005 (\$3/tCO_2), rising very gradually to only \$140 per ton in 2195 (\$38/tCO_2)" (at \$1995). They demonstrate that "a dramatically different policy recommendation results from just three plausible modifications to the model, involving the discount rate, the description of climate dynamics, and the benefits of moderate warming." Combining all three effects and setting δ at zero increases the carbon price from \$6/tC to \$197/tC (\$54/tCO_2) rising at just over ½% p.a. to \$579/tC (\$159/tCO_2) in 2195.

The dramatic effect of apparently reasonable changes on the magnitude of the results may explain the disputes between climate scientists and economists over the past decade. Climate scientists effectively adopt very low discount rates when assessing future damages in a global system with very slow response times, while economists tend to discount future effects strongly, as the required rate of return for investments is typically rather high (8-15%). Once economists and climate scientists agree on how to treat the future and aggregate regional impacts the disagreement almost entirely disappears.

The interim conclusion is that the SCC (and the price) of carbon are very sensitive to a range of factors including the weights placed on future impacts and on impacts in other, poorer countries and are therefore likely to be revised over time. Policy decisions therefore need to take account of this uncertainty, which typically means investing now to allow future decisions to be changed at lower cost, by, for example, enabling fossil-fired generation plant to be retrofitted with carbon capture. High values of the SCC can be defended either by assuming that we are willing to express significant social concern for distant future generations (low rate of pure time preference), or, in the spirit of Weitzman's review of the *Stern Review*, by assuming that the implied actions now, which are costly but not that costly (1-2% of GDP) should be considered as an insurance premium to avoid a possibly very low chance of very serious future damage. By definition, unpredictable events are impossible to model with any confidence, and the high SCC is warning us to take adequate steps now to reduce the risks of extreme, if unlikely, future disaster.

3.3 Growth of the SCC over time

Figure 3 shows how the PAGE estimates for the SCC vary with the date that the carbon dioxide is emitted. The values increase by about 2.4% per year; by 2060 the mean estimate has risen to \$265/tC (\$72/tCO_2). They increase for the simple reason that as we get closer to the time when we expect the most severe impacts of climate change to occur, then the extra impact from putting another tonne into the atmosphere gets higher.

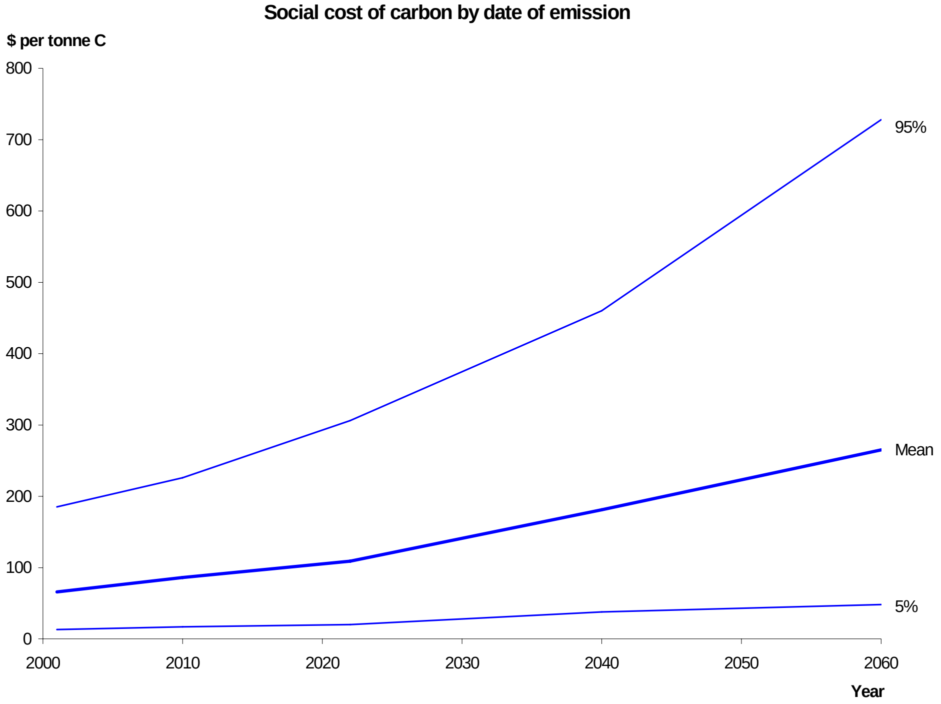
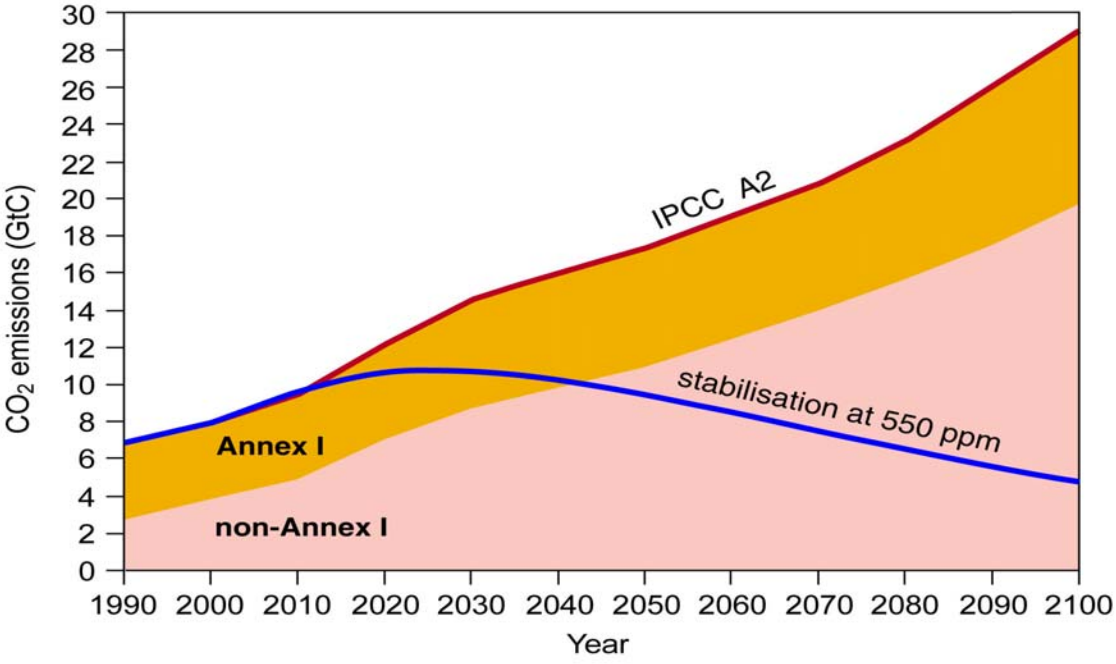


Figure 3 Social cost of carbon over time for δ = 1.5%, and ν = 1

3.4 Invariance of the SCC with emission scenario

All of these results assume the extra tonne of carbon is emitted on top of an unconstrained emission path, scenario A2 from the IPCC Special Report on Emission Scenarios (SRES), shown in figure 4.

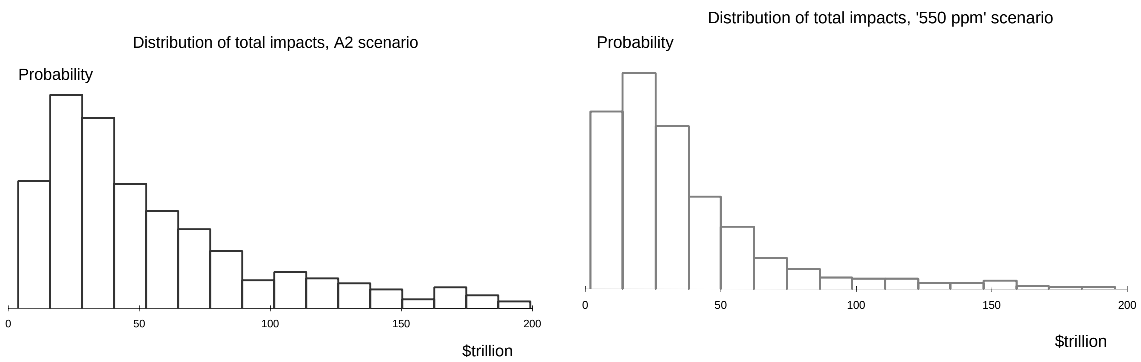


Source: IPCC and Stern (2006)

Figure 4 Evolution of emissions under IPCC A2 and to stabilise at 550 ppm

Under this scenario, PAGE projects the mean CO_2 concentration to be about 815ppm by 2100 (1140ppm by 2150, 1450ppm by 2200), the mean temperature to be 4.1 degC above pre-industrial by 2100, and the mean climate change impacts to be $(2000) 73 trillion, based on a time horizon of 2200 and discounted back to give a net present value. The probability distribution of impacts is shown in the first panel of Figure 5 (a small number of runs that gave impacts above $200 trillion are not shown on the graph, but are included in the mean impacts of $73 trillion).

If climate change is taken seriously, it is unlikely that emissions will be allowed to follow this unconstrained path. One constrained emission path that has been proposed aims to keep the atmospheric carbon dioxide concentration below 550 ppm, double the pre-industrial level, as also shown in figure 4. Because of the stimulation of natural CO_2 included in PAGE, the scenario does not actually stabilise CO_2 concentrations at 550ppm. Mean CO_2 concentration is about 594ppm by 2100 (635ppm by 2150, 670ppm by 2200), mean temperature is 3.4 degC above pre-industrial by 2100, and the mean NPV of climate change impacts is $42 trillion (down from $73 trillion in A2, mainly because of the big difference in temperature after 2100). The probability distribution of impacts from this scenario is shown in the second panel of Figure 5.

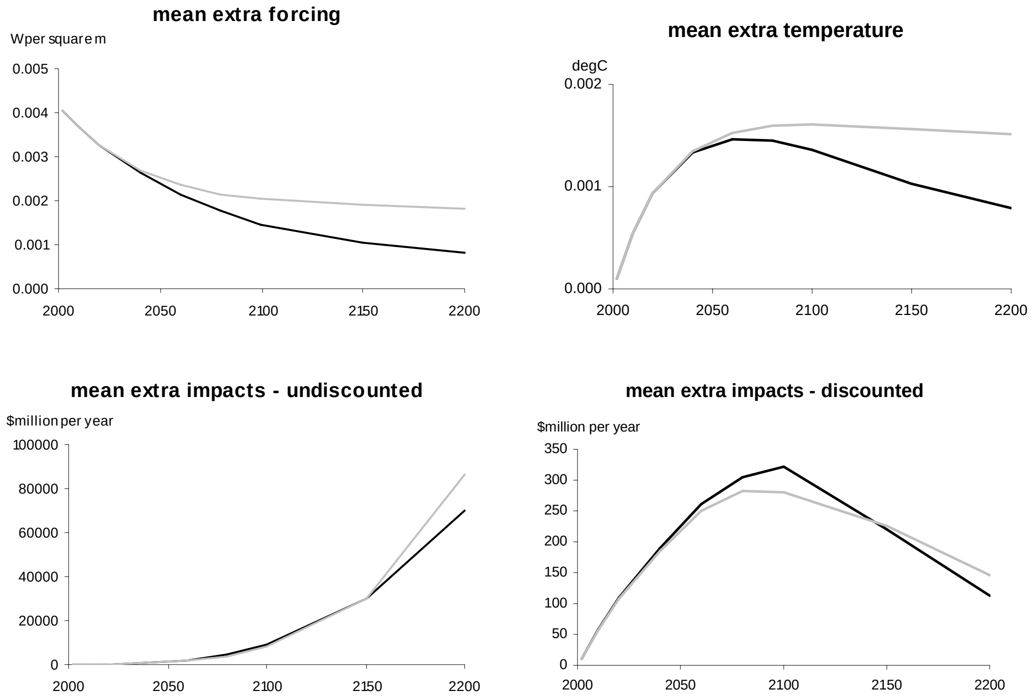


Source: PAGE2002 model runs

Figure 5 Probability distribution of climate change impacts from two scenarios

The social cost of carbon does not vary between the baseline A2 scenario and the '550 ppm' scenario; its mean value is $(2000) 43/tC under both scenarios, with a 5-95% range of $10 to $130/tC, reflecting several non-linearities in the chain of causality between emissions and discounted impacts that tend to offset each other. This finding is rather counter-intuitive and is a strong argument for using an integrated assessment model, as neither a scientific nor an economic model would likely pick it up.

The reason why this is true is not straightforward. It is caused by the interplay between the logarithmic relationship between radiative forcing (i.e. the global warming effect) and concentration (which will tend to make one extra tonne under the A2 scenario cause less impacts), the non-linear relationship of impacts to temperature (which will tend to make one extra tonne under the A2 scenario cause more impacts), and discounting (which will tend to make early impacts more costly than late impacts). This is shown in the four panels of figure 6, in which the darker line represents the mean results from the A2 scenario, and the lighter one the mean results from the '550 ppm' scenario; each panel shows the mean effect of a billion extra tonnes of carbon emitted as CO_2 in 2001.



Source: PAGE2002 model runs

Figure 6 Mean effect of 1Gt CO_2 on forcing, temperature, undiscounted impacts and discounted impacts by year.

Forcing:

The first panel shows that 1 Gt extra CO_2 (1 Gt = billion tonnes) causes more extra forcing under the '550 ppm' scenario than under the A2 scenario. The extra forcing decays away over time both because the total CO_2 concentration rises and because most of the extra CO_2 eventually disappears from the atmosphere.

Temperature:

The second panel shows how this carries through into the extra temperature change from 1Gt extra CO_2 emitted in 2001. The extra forcing takes time to have an effect on temperature, because of the thermal inertia of the Earth. The effect is still greater in the '550 ppm' scenario than in scenario A2, but the temperatures only really begin to diverge after 2060.

Undiscounted impacts:

The next panel shows how this carries through into the extra impacts. Up to about 2040 the extra temperature rise is very similar in the two scenarios, and the impacts anyway are small. From 2040 to 2100, the extra temperature rise in the A2 scenario causes slightly more extra impacts than the larger extra temperature rise in the '550 ppm' scenario, because it is superimposed upon a larger total temperature rise (a mean of 4.1º C above pre-industrial in 2100) in the A2 scenario than in the '550 ppm' scenario (a mean of 3.4º C above pre-industrial in 2100). By 2200, this relationship has reversed, and the larger extra temperature rise in the '550 ppm' scenario has the greater extra impact, mainly because even under the '550 ppm' scenario, global temperatures by 2200 are in the range where a large-scale discontinuity, such as the melting of the West Antarctic Ice Sheet, becomes a possibility.

Discounted impacts:
The final panel shows the extra impacts discounted back to the base year 2000. The peak contributions to the SCC come around the years 2080 to 2100. The SCC is found for each scenario by integrating the values under this curve, and dividing by one billion. The larger values for scenario A2 from 2040 to 2100 and for the '550 ppm' scenario in 2200 approximately cancel each other out.

This final panel also shows that a time horizon of 2200 is barely sufficient to capture all the contributions to the SCC with the discount rates used (a pure time preference rate with a mean value of 2% per year, and a range of 1 – 3% per year). Contributions to the SCC from beyond 2200, which are not captured in PAGE, would continue to be slightly higher for the '550ppm' than the A2 scenario.

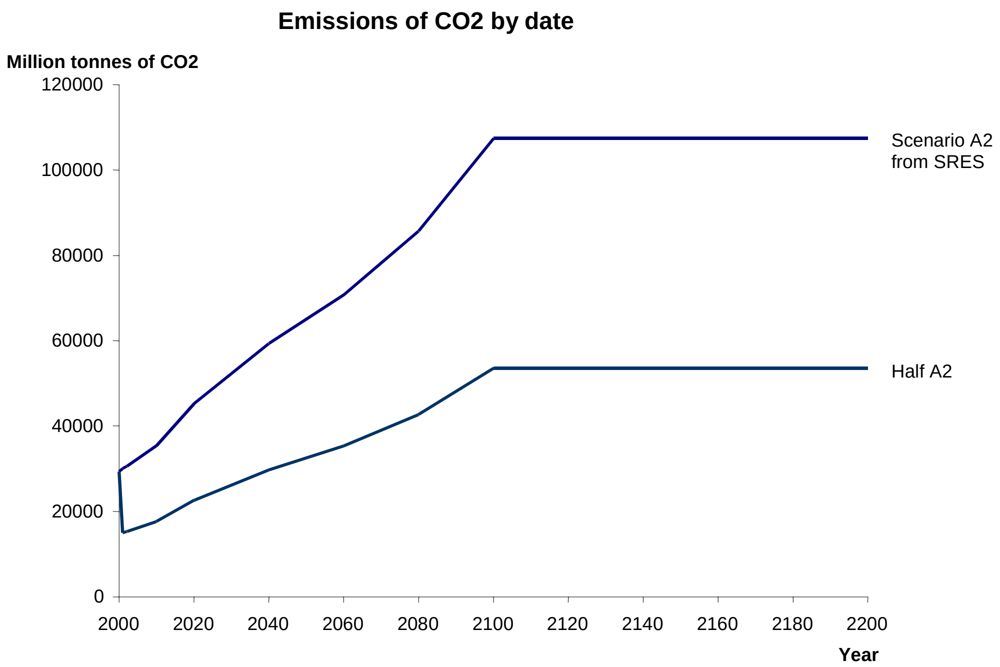


Figure 7 Time path of emissions modelled

The SCC appears to be insensitive to the exact emissions scenario, within quite a wide range. There has been some concern expressed about the accuracy of the emission scenarios from the IPCC Special Report on Emission Scenarios (SRES). All of the results from PAGE that use an unconstrained emission path are based upon scenario A2 from the SRES. What is the effect of making an extreme assumption about the inaccuracy of scenario A2, namely that global emissions of all greenhouse gases and sulphates in all future years are only half the values assumed in Scenario A2 from the SRES? The emissions of CO_2 that result are shown in figure 7; note that they are below the year 2000 emissions until 2040.

How does this extreme assumption affect the concentration, radiative forcing, temperature and impacts in future years? Figure 8 shows the mean values from the PAGE model for these variables by date, expressed as a proportion of the mean values from running PAGE with the A2 scenario from the SRES. The emissions are at 50% of the A2 values throughout, as this is the assumption that we are making.

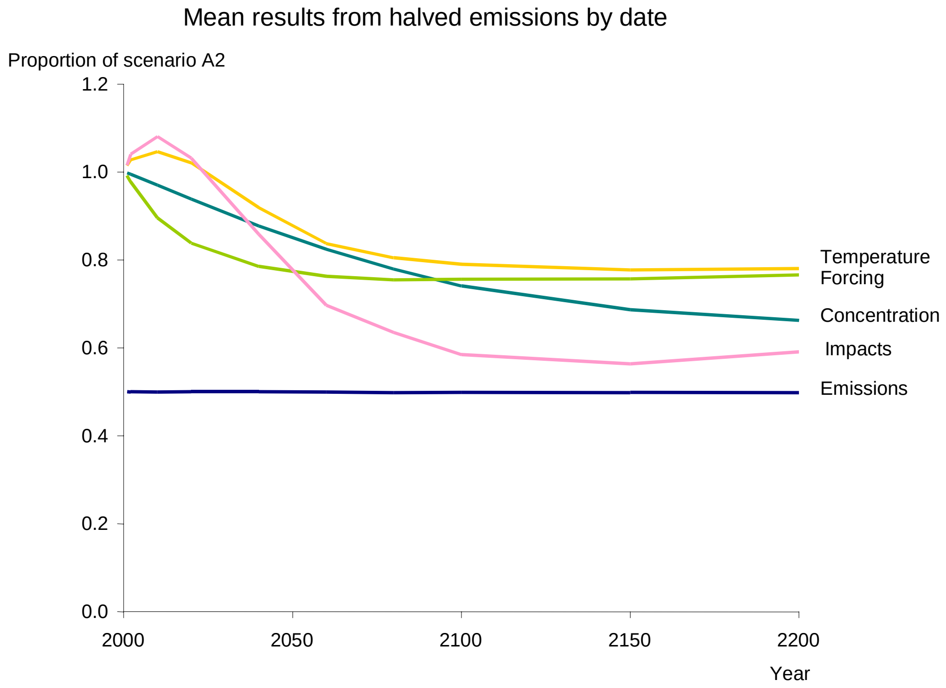


Figure 8 Impact of halving emissions relative to A2 scenario

The concentration of CO_2 in the atmosphere is 88% of the A2 value in 2040, and stays above 66% of the A2 value all the way through to 2200. This is because past emissions stay in the atmosphere for many decades, and so it takes a long time for the lower future emissions to have an effect.

The radiative forcing from the greenhouse gases is 79% of the A2 value in 2040, and never drops below 75% of the A2 value. It is below the CO2 concentration line for most of the next century because the radiative effects of the shorter-lived greenhouse gases such as methane disappear from the atmosphere much more quickly than CO2.

The global mean temperature is actually higher than the A2 value until 2020, as the short-term influence of the lower sulphates outweighs the longer- term influence of the greenhouse gases. Sulphates cool the atmosphere, so if there are less of them, the global mean temperature will be higher. By 2040 the global mean temperature increase is 92% of the A2 value (1.34°C rather than 1.46°C above pre-industrial levels), and it never drops below 78% of the A2 value (6.15°C rather than 7.88°C in 2200).

The impacts of climate change are likewise higher than in the A2 scenario until 2020, and are 86% of the A2 value in 2040. By 2150 they have dropped to 56% of the A2 value, and by 2200 to 59% of the A2 value as impacts are more than a linear function of temperature.

The net result of all this can be seen in the mean total impacts aggregated over time and discounted back to the present day, which are shown in the table below. The mean value of $45 trillion is 59% of the A2 mean value of $76 trillion Of more immediate policy relevance is the social cost of carbon, which is the benefit of reducing today's emissions of carbon by one tonne. As the table shows, the mean value for the social cost of carbon is essentially identical to the A2 value.

Table 1 Mean values of impacts and social cost of carbon, by scenario

	A2 from SRES	**Half A2**
Total climate change impacts	$76 trillion	$45 trillion
Social cost of carbon	$43/tC ($12/tCO_2)	$43/tC ($12/tCO_2)

4 Major influences on the social cost of carbon

If the emission path does not affect the SCC, what does? Figure 9 shows the major influences calculated by PAGE; the longer the line, the larger the influence. That the major influences divide into six scientific and seven economic parameters is another strong argument for the building of integrated assessment models such as PAGE. Models that are exclusively scientific, or exclusively economic, would omit parts of the climate change problem that still contain profound uncertainties.

The two top influences are the climate sensitivity, which is the temperature rise that would occur for a doubling of carbon dioxide concentration, and the pure time preference rate. The climate sensitivity is positively correlated with the SCC, so a rise leads to a higher SCC; the pure time preference rate is negatively correlated with the SCC, so a fall leads to a higher SCC, and so on. We can now see that it is not surprising that the Stern review found such a high value for the mean social cost of carbon; their value for the second most important parameter, the pure time preference rate, was much lower, at 0.1% per year.

As an example of the changes that new scientific information can bring, the journal *Nature* has recently published a new likelihood-weighted probability distribution for the climate sensitivity, with a mean value of 3.6º C, and a 5-95% range of 2.4º to 5.4º C. Using these values for the climate sensitivity in PAGE, instead of the 1.5º to 5.0º C range given by the IPCC, increases the mean value of the SCC from $43 to $68 per tonne of carbon emitted in 2001, with a 5-95% range of $11 - 202.

Using the distribution from Stainforth et al (2005), which has a most likely value of 3º C, and a long tail extending to high values over 8º C, increases the PAGE mean value of the SCC to $90 per tonne of carbon, with a 5-95% range of $10 - 220.

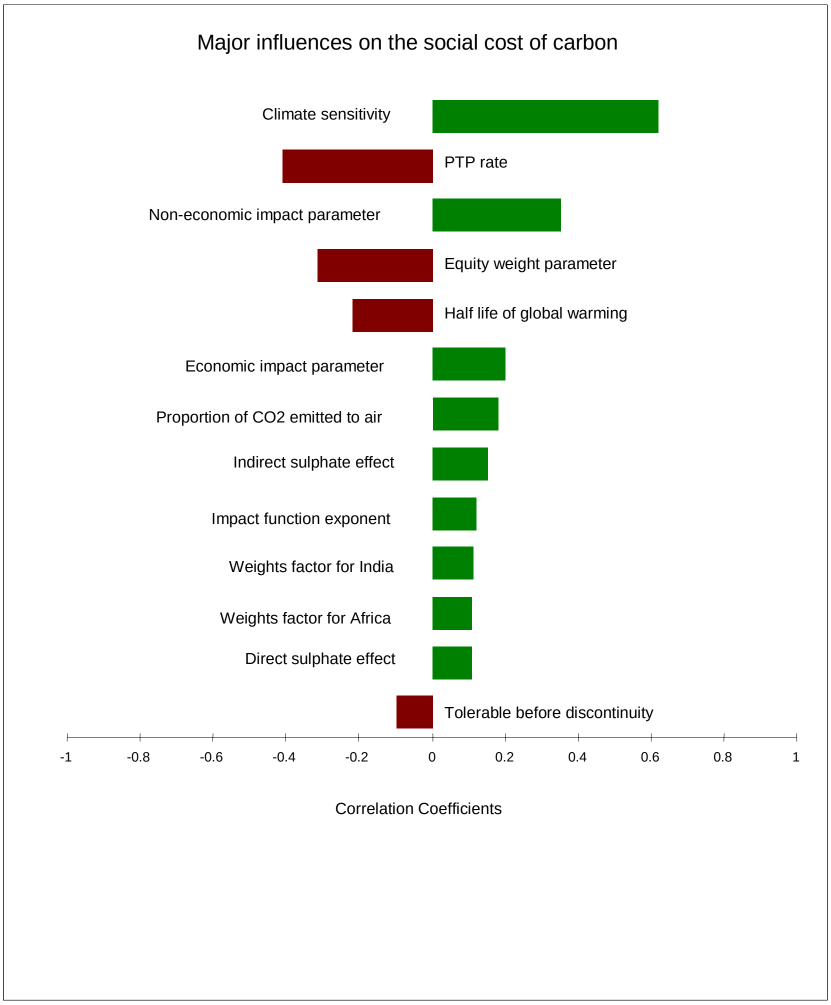


Figure 9 Sensitivity of SCC to parameters

Note: PTP = Pure time preference

5. Social cost of other greenhouse gases

The PAGE model includes a range of greenhouse gases, not just carbon dioxide, and can calculate the social cost of each of them. Using the original assumptions (point estimates δ = 1.5%, and ν = 1 giving a SCC of \$66/t CO_2), the mean PAGE estimate for the social cost of methane is \$280 per tonne emitted in 2001, with a 5-95% range of \$80 – 750. The carbon equivalent of methane now is thus 4.24, i.e. 1 tonne methane is 4.24tC or 15.5/tCO_2. In the future, the social cost of methane increases faster than carbon dioxide, by 3.6% per year. This is because of the short atmospheric lifetime of methane; any extra methane emitted today will have disappeared from the atmosphere before the most severe climate change impacts occur, but emissions that occur later will not. The PAGE estimate for the social cost of SF6 is \$800,000 per tonne emitted in 2001, with a 5-95% range of \$160,000 – 2,100,000, so 1 tonne SF6 = 12,121tC = 44,444/tCO_2.

It is interesting to compare these results with the other preferred method of Global Warming Potentials. DEFRA (2006) explains the thinking behind them: "To compare the relative climate effects of greenhouse gases, it is necessary to assess their contribution to changes in the net downward infra-red radiation flux at the tropopause (the top of the lower atmosphere) over a period of time. Ultimately the best way to do this is by comparing different emission scenarios in climate models, but a simple working method has been derived for use by Parties to the UNFCCC. This provides the relative contribution of a unit emission of each gas, relative to the effect of a unit emission of carbon dioxide integrated over a fixed time period. A 100-year time horizon has been chosen by the Convention in view of the relatively long time scale for addressing climate change. The factor is known as a global warming potential (GWP)."

DEFRA (2006) lists the GWPs for methane and SF8 as 21 and 23,900 respectively in terms of CO_2. This means that 1 tonne of methane emitted to the atmosphere has 21 times the warming potential over 100 years of 1 tonne of CO_2. These figures are the 1995 GWP values. Whilst the Global Warming Potentials have since been updated, the Kyoto Protocol states that "global warming potentials used by Parties [to the Protocol] should be those provided by the Intergovernmental Panel on Climate Change in its Second Assessment Report" (DEFRA, 2004). More recent 100 year GWP values in the IPCC's *Third Assessment Report* (IPCC, 2001b) are 23 for methane and 22,200 for SF6. Thus compared to the present day PAGE estimates, the GWP of methane is overstated and SF6 significantly understated, illustrating the challenge for international political processes to update their processes as better methods become available.

6. Conclusions

What is the right price of carbon if we are to persuade countries to confront those releasing GHGs with a carbon price? Clearly the price should be the same for all countries to achieve a reduction in emissions at least cost, but equally clearly, the SCC with different countries taking their own standards of living as numeraire will all be different. Second, if consumption transfers to India (GDP/head of \$PPP 3,400) counts as 8.7 times as valuable now as consumption transfers to the EU (GDP/head of \$PPP 29,600), would it not be better to make such transfers now as well as over the next 150 years via GHG reductions? Third, if the marginal cost of avoiding damaging climate change is less than the estimate of the SCC, should not the price of carbon be set by the intersection of supply (of climate change mitigation) and demand (for damage avoidance, measured by the SCC)? The answer to this last question is that it certainly should be, but the PAGE model demonstrates that there is good reason to believe the carbon price for a tonne of CO_2 superimposed on an intertemporal optimal path of emissions will not be very different from the price for one superimposed on scenario A2 as calculated in this paper.

This is related to another deep question in intertemporal welfare economics, for the implied consumption rate of interest (CRI, which is what is being used to discount future carbon damage) in the *Stern Review* is of the order of 1.3-1.6% (per capita growth rate in the long-run is about 1.3-1.5% and the CRI so $i = \delta + vg$). The Investment Rate of Return, IRI, is surely much higher than this, perhaps of the order of 5-8% (depending on the treatment of risk) and nuclear generation is likely to be cost-effective with a modest carbon price in this range. If the IRI > CRI, which rate should be used for investing in climate change mitigation? The answer is that if the IRI > CRI, then there must be some constraint preventing the authorities selecting projects (or guiding such decisions) from raising the rate of investment to bring the two rates into equality. That is akin to asking why the price of carbon is not set to balance both the supply and demand for mitigation.

Finally, as there is no global tax jurisdiction or emissions trading system setting a single carbon price to maximise global welfare, presumably the best we can do is imagine a coalition of the willing reaching an agreement on what price of carbon is in everyone's best interests. How does the SCC as computed relate to such a bargaining solution? For efficient climate change mitigation, the price of carbon should be the same everywhere, but the cash value of the damage done to each country will depend on its income level. Suppose that poorer countries have no higher electricity intensity (kWh/$GDP) than richer countries, and suppose that at a carbon price p each country reduces its CO_2 emissions from electricity generation in the same proportion to total generation and hence to GDP, so that country i reduces emissions by μY_{i0} tonnes CO_2. The extra cost to each country will also likely be proportional to the amount of low-carbon electricity that displaces high-carbon electricity, and hence also proportional to its GDP, say $\kappa_i Y_{i0}$. The total global emissions reduction will thus be similarly proportional to global GDP, μY_{W0} and each country will benefit in PDV cash terms by $\mu Y_{W0} D_i Y_i$ where D_i is the ratio of the NPV of the damage that one tonne of CO_2 released now will do to current GDP in country i. The country level benefit-cost ratio will be $\mu Y_{W0} D_i / \kappa_i$. Provided that D_i / κ_i does not increase with income, poorer countries should find such a uniform price as acceptable as richer countries. As poorer countries may have higher values of future damage to their GDP than richer countries, D_i may be higher in poorer countries, encouraging such countries to join a carbon pricing club, but to the extent that they discount the future more heavily, D_i will be lower, making current sacrifices less attractive.

What this uniform price should be is less clear. Fortunately, we have argued above (and the model supports the algebraic claim) that the unweighted or cash value of the SCC, although less than the equity-weighted value using global per capita consumption as the numeraire, it is not that different, and perhaps that is also closer to the price (path) of carbon that would ensure that the optimum climate change mitigation path is followed (optimal in balancing costs and benefits). At present these questions are not readily answered, and one must interpret any calculated *price* of carbon with caution.

Even if the SCC (with some suitable numeraire) provides some guidance for setting the carbon price (or determining the quantity of tradable permits to issue, adjusting quantities to drive the traded price towards the correct carbon price), the estimates from PAGE and other integrated assessment models are only as complete as the scientific and economic information that goes into the model. PAGE does make an attempt to cover all five reasons for concern about climate change identified by the IPCC, including a rudimentary treatment of large-scale discontinuities such as the melting of the West Antarctic ice sheet. It does not include the security implications of any large-scale migration caused by climate change. From an economic perspective it therefore only offers a lower bound to the damage cost, and policy that aims for the best guess rather than a 'scientifically' determined lower bound should take a higher social cost of carbon.

The main purpose in this paper is not to promote any one estimate of the social cost of greenhouse gases. As we have shown, although the social cost of carbon is insensitive to the emission scenario on which an extra tonne of carbon is superimposed, it is influenced by many factors, which are still subject to great uncertainty, and the same is true of the social costs of other greenhouse gases.

Rather, we have tried to demonstrate that integrated assessment models such as PAGE can perform a useful service by taking the best information from the detailed scientific and economic research, and revealing its policy implications. They can also highlight just how much we still have to learn about the economic implications of climate change, and enable different views on economic and scientific parameters, such as discount rates, equity weights and climate sensitivity, to be rigorously explored. To quote from the *Stern Review* "We would therefore point to numbers for the 'business as usual' social cost of carbon well above (perhaps a factor of three times) the Tol mean of \$29/tCO_2 and the 'lower central' estimate of around \$13/tCO_2 in the recent study for DEFRA (Watkiss et al. (2005))… Nevertheless, we are keenly aware of the sensitivity of estimates to the assumptions that are made. Closer examination of this issue – and a narrowing of the range of estimates, if possible – is a high priority for research." (Stern, 2006, p287).[12]

We have seen that the SCC is very sensitive to the treatment of impacts in the distant future (i.e. the discount rate), and the valuation of the more severe impacts on poorer regions (through the equity weights) as well as on the climate science. In addition, what is needed for policy purposes is a carbon price, which is not necessarily the same as the social cost of carbon. The relationship between the two concepts, and the design of a process to elicit a carbon price that can be widely (ideally globally) adhered to, is another and more practically pressing problem. The aim of this paper has been to lay out the various factors that bear on these issues, which are taken up in Grubb and Newbery (2007) which addresses the choice of instruments to guide the economy towards a low-carbon future.

[12] Box 13.1 of the *Stern Review* summarises other estimates of the SCC, citing a study by Downing et al (2005) for DEFRA, which observed that estimates in the literature range from £0-1000/tC, (£0-273/tCO_2) and suggested a lower benchmark of £35/tC (£9.5=\$12.5/tCO_2) (all at 2000 prices). Tol's (2005) survey found a median value of \$14/tC (\$3.8/tCO_2) and the 95th percentile at \$350/tC, (\$95/tCO_2) comparable to that of the *Stern Review* (Stern, 2006, p288). The IPCC has yet to publicly report on its latest findings, but has issued a Summary for Policymakers in which it says "Peer-reviewed estimates of the SCC for 2005 have an average value of US\$43 per tonne of carbon (tC) (i.e., US\$12 per tonne of carbon dioxide) but the range around this mean is large. For example, in a survey of 100 estimates, the values ran from US\$-10 per tonne of carbon (US\$-3 per tonne of carbon dioxide) up to US\$350/tC (US\$95 per tonne of carbon dioxide)."

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