The Stern Review and other economic analyses of climate change — a sensitivity analysis

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The Stern Review commanded worldwide attention through its central message that strong early action on climate change is warranted on economic grounds. In part, this was based on a comparison of damage costs from climate change equivalent to 5 to 20 per cent of global GDP each year now and forever, with costs of action of 1 per cent each year. The Stern Review's damage cost estimates were obtained using an integrated assessment model, the same approach used in many other economic analyses of climate change. The Stern Review's conclusions, however, differ from the findings of other integrated assessment modelling, which typically call for a 'policy ramp' — modest early action ramping up to stronger action in the future. Compared with recommendations for optimal policy from integrated assessment models, the Stern Review advocates more abatement effort now and throughout the rest of the century.

Analysis undertaken using the DICE model suggests that the Stern Review's results are dependent on its choice of scenario to project future greenhouse gas emissions and its estimates of the relationship between temperature increase and damages. Both these 'flatten' the policy ramp somewhat, increasing optimal abatement now and reducing optimal abatement in the second half of the century. That said, the Stern Review's departure from the policy ramp result appears to be driven primarily by the choice of low discount rates.

Key Words

Economics of climate change, integrated assessment, discount rate, Stern Review, DICE model

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Introduction

The Stern Review: The Economics of Climate Change, produced under the direction of the UK Cabinet Office and the UK Treasury, was released in October 2006. The Review was headed by Sir Nicholas Stern who, at the time, was Head of the Government Economic Service and Adviser to the British Government on the economics of climate change.

The Stern Review covers a range of economic issues relating to climate change, including the need for global collective action and policy responses for mitigation and adaptation. Its key message is that there is a need to respond to climate change strongly and immediately:

> There is still time to avoid the worst impacts of climate change, if we take strong action now. (Stern 2006, p. xv)

This message is based, in part, on the Stern Review's comparison of the costs of inaction and action on climate change. The comparison is summarised thus:

> Using the results from formal economic models, the Review estimates that if we don't act, the overall costs and risks of climate change will be equivalent to losing at least 5% of global GDP each year, now and forever. If a wider range of risks and impacts is taken into account, the estimates of damage could rise to 20% of GDP or more.
>
> In contrast, the costs of action — reducing greenhouse gas emissions to avoid the worst impacts of climate change — can be limited to around 1% of global GDP each year. (Stern 2006, p. xv)

The comparison of damage costs equivalent to 5 to 20 per cent of GDP with mitigation costs of 1 per cent of GDP makes a compelling case for action. However, the findings of the Stern Review are at odds with other economic assessments, which endorse a 'policy ramp' approach, involving relatively modest greenhouse gas (GHG) emission reductions in the near term, with measures intensifying over time (Nordhaus 2006b; Kelly and Kolstad 1999).

This paper seeks to investigate why the Stern Review's use of economic modelling arrives at such a different policy prescription to other economic modelling. Economic modelling is not the only evidence cited by the Review to support strong early action — as emphasised by Dietz et al. (2007) — but it is the focus of this paper because it is an integral part of the story that can be readily compared with estimates from other economic assessments.

The comparison between the Stern Review and other economic assessments is in two parts. First, the Review's policy prescription is compared with the results from other economic models. Second, one of these models (the DICE model) is used to investigate reasons for the differences between the Review and other economic assessments.

To begin, a brief summary of key aspects of the Review's economic modelling is provided as a background for the analysis later in the paper.

Economic modelling in the Stern Review

The Stern Review's policy prescription was informed by economic modelling. An optimisation modelling exercise was not undertaken for the Review; rather an abatement objective was formulated in a heuristic fashion, by weighing up estimates of the impacts of climate change against estimates of mitigation costs. Impacts of climate change and mitigation costs were estimated using separate methodologies, discussed below.

Impacts of climate change

The damage cost estimates of 5–20 per cent of GDP were derived using PAGE2002, an Integrated Assessment Model (IAM). The use of an IAM is consistent with previous economic analyses (see Kelly and Kolstad (1999), Goodess et al. (2003) and Weyant et al. (1996) for summaries). IAMs simulate the key human and natural processes believed to be driving climate change and estimate the socio-economic impacts.

Treatment of uncertainty

For the Stern Review, the PAGE2002 model addressed uncertainty inherent in the range of possible impacts using a ‘Monte Carlo’ simulation. Each scenario was run 1000 times and, for each run, parameters were chosen at random from the ranges given in the climate change literature. The Monte Carlo simulation yields a probability distribution of damage cost estimates. This probability distribution can be used to give a point estimate that accounts for uncertainty, attitudes to risk and time preferences.

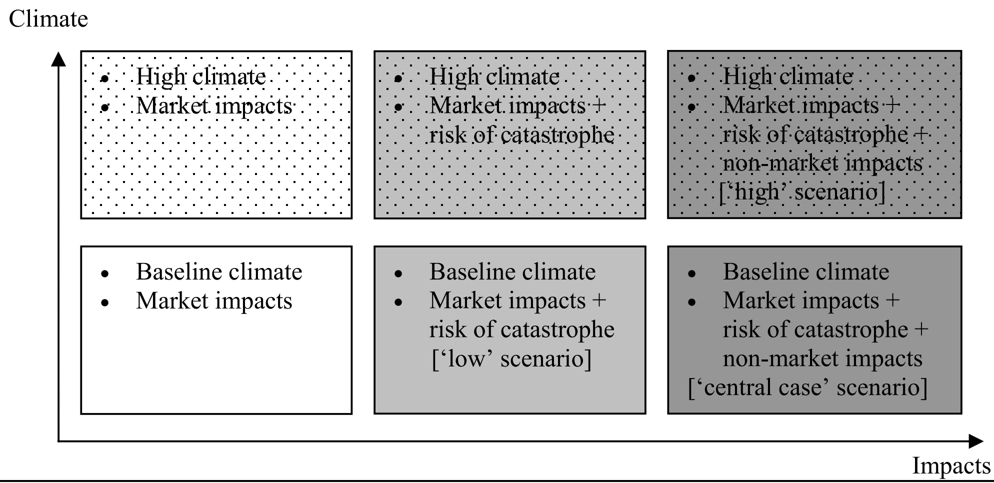
Scenarios

The Stern Review used PAGE2002 to estimate damage costs out to 2200, for two different climate change scenarios (baseline and high climate) and three different sets of impact categories (figure 1).

The baseline climate change scenario was based on the ‘A2’ scenario from the Intergovernmental Panel on Climate Change’s (IPCC’s) Special Report on Emissions

Scenarios (SRES).[2] The Stern Review's high climate scenario assumes a higher climate sensitivity than the baseline scenario, on the basis of recent evidence suggesting that amplifying feedbacks could be important.

Figure 1 **Matrix of climate scenarios and impact categories**



Source: Stern (2007).

The three sets of impact categories (figure 1) are made up of various combinations of :

- market impacts — the effects of climate change that impact on market sectors of the economy
- non-market impacts — direct effects of climate change on human health and the environment for which no market price exists
- the risk of catastrophic events — losses from abrupt or discontinuous changes that could occur as a consequence of higher levels of warming.

The 'central case' scenario in the Stern Review — baseline climate and all impact categories — is used in this paper as the basis for comparison with other economic analyses.

2 The 'A2' scenario is one of six illustrative marker scenarios in the SRES (IPCC 2000).

The damage function

In PAGE2002, damage costs from market and non-market impacts are calculated as GDP losses that are an ‘uncertain power function of temperature rise’ (Warren et al. 2006, p. 30). Damages are calculated separately for each of the eight world regions distinguished by the model, according to (1) below.[3]

$$Damages \propto \left(\frac{T_R}{2.5}\right)^{\gamma} \quad (1)$$

Where T_R = regional temperature increase; γ = damage exponent.

The damage exponent is an uncertain variable, which is varied between 1 and 3 (based on Peck and Teisberg 1992) for each Monte Carlo simulation.

Damages from catastrophes are estimated separately, based on the probability of a catastrophe increasing with temperature. Above some temperature threshold, the potential for a catastrophic event is introduced and, as temperatures increase further, the probability of a catastrophe increases, as do the associated economic losses.

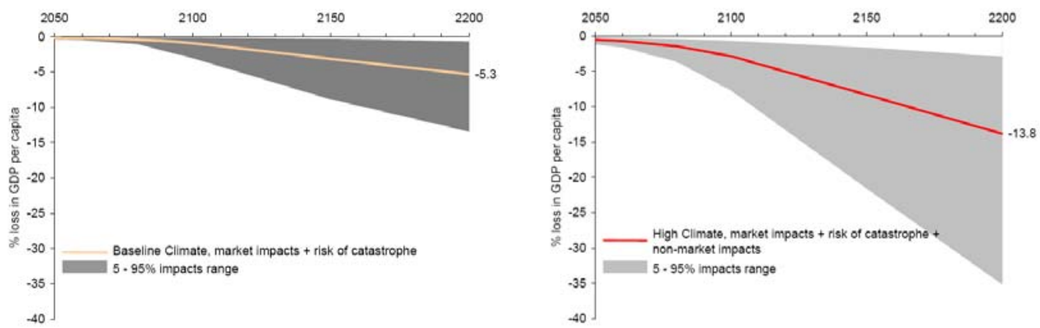
Aggregating costs over time

The PAGE2002 modelling undertaken for the Stern Review yields estimates of damage costs over time (figure 2). The ‘central case’ scenario yields a mean estimate of damage costs of 11.3 per cent of GDP in 2200.

3 Adaptation to reduce damages also varies by region, with more adaptation in developed countries.

Figure 2 **Damage costs**

Panel [a] low scenario | Panel [b] high scenario



Source: Stern (2007).

The Stern Review used the damage cost estimates over time from PAGE2002 to estimate that the damage costs of climate change are equivalent to 5–20 per cent of GDP each year, now and forever. Under the central case, the costs of climate change are estimated to be equivalent to a loss of 10.9 per cent of GDP each year.

Converting time paths of uncertain damages to point estimates requires consideration of:

- uncertainty
- attitudes to risk
- time preferences.

The Review also had to consider the likely damages from climate change post-2200 and the weighting of damages across regions.

Of the judgements made in the Stern Review to convert damage costs over time into point estimates, the time preference inherent in the Review's choice of discount rates has been noted as the key divergence from other economic studies (Dasgupta 2006; Nordhaus 2006b; Weitzman 2007).

Discount rates

Within the welfare economics approach adopted by the Review, an increment of future consumption is typically held to be worth less (that is, have less utility) than an increment of current consumption for two reasons. The Review states:

> First, if consumption grows, people are better off in the future than they are now and an extra unit of consumption is generally taken to be worth less, the richer people are. Second, it is sometimes suggested that people prefer to have good things earlier rather than later – 'pure time preference' – based presumably in some part on an assessment of the chances of being alive to enjoy consumption later and in some part 'impatience'. (Stern 2007, p. 35)

Therefore, to make a unit of future consumption equivalent to a unit of current consumption a discount rate must be applied. In welfare economics, the formula commonly used for this purpose is:

$$\text{Rate of discount} = \delta + \eta g \qquad (2)$$

Where: δ is the rate of pure time preference (also called the utility discount rate); η is the elasticity of the marginal utility of consumption; and g is the growth rate of per capita consumption.

The literature distinguishes between 'prescriptive' and 'descriptive' approaches to choosing discount rates. The prescriptive approach involves taking an ethical perspective, based around asking 'how (ethically) should impacts on future generations be valued?' (Arrow et al. 1996, p. 129). The descriptive approach asks 'what choices involving trade-offs across time do people actually make?' (Arrow et al. 1996, p. 129). The descriptive approach is used in traditional cost–benefit analysis and is widely favoured for short and medium-term analyses.

However, where intergenerational considerations are important, as they are with climate change, which approach to take remains unresolved (Ackerman and Finlayson 2006; Arrow et al. 1996).

Stern takes a prescriptive approach to choosing δ. The Review concludes, on ethical grounds, that the welfare of future generations should be treated on a par with our own and, therefore, that the future should not be discounted simply because it is the future. This suggests setting δ at zero. Stern, however, settles on 0.1, to allow for the possibility of the human race becoming extinct (and therefore, future generations being absent).

Stern takes η to be 1, 'in line with recent empirical estimates' (Stern 2007, p. 184). This implies that people derive the same utility from an additional 1 per cent of consumption, irrespective of their pre-existing level of consumption.

Substituting these values for δ and η into equation (2) results in a discount rate equal to 0.1 plus the growth rate of per capita consumption. In the analysis conducted for the Review, discount rates vary across scenarios and paths (and over time) depending on the growth rate of per capita consumption.

Mitigation costs

The costs of mitigating climate change were estimated in the Stern Review using a resource cost (or 'bottoms up') approach and a macroeconomic modelling (or 'tops down') approach. Neither approach used the PAGE2002 model.

Similar conclusions arose from the resource cost and the macroeconomic modelling approaches: stabilising GHG concentrations at 500–550ppm CO_2 equivalent[4] (CO_2e) is likely to cost about 1 per cent of global GDP annually by 2050. The Review also concluded that costs are likely to remain at around 1 per cent of GDP for the second half of the century.

Policy objective

The Stern Review's comparison of annual damage costs equivalent to 5 to 20 per cent of GDP (and a central estimate of 10.9 per cent) with annual mitigation costs of 1 per cent of GDP shows stabilisation at 500–550ppm CO_2e to be preferable to doing nothing. Under stabilisation at the top of this range, residual damage costs are estimated to be limited to the equivalent of a 1.1 per cent reduction in GDP each year. So based on the central estimate, mitigation costing around 1 per cent of GDP results in the avoidance of damages equivalent to just under 10 per cent of GDP.

The Review proceeds in a heuristic fashion to settle on a stabilisation target of 450–550ppm CO_2e. In doing so, it argues that mitigation costs increase steeply for stabilisation below 450ppm and damage costs increase steeply above 550ppm. Modelling is used to investigate the latter — stabilisation at 650ppm is estimated to entail damage costs that are equivalent to an additional 0.6 per cent reduction in GDP per year.

The Review uses its stabilisation target to inform a time path for emissions, again proceeding heuristically to move from a stabilisation target to a path for abatement over time. The abatement effort prescribed by the Review is compared with the results of other integrated assessment modelling in the following section.

4 The Review quotes the total radiative effect of GHGs in terms of the equivalent concentration of carbon dioxide.

Other integrated assessment modelling

Integrated assessment modelling has been applied to climate change issues since the late 1980s (Goodess et al. 2003). Integrated assessment is distinguished from disciplinary research because it draws from a breadth of knowledge sources and a variety of disciplines to inform policy and decision making (Weyant et al. 1996). The IPCC reviewed the application of integrated assessment modelling to climate change as part of its second assessment report (Weyant et al. 1996), while more recent reviews include those by Tol (2006), Goodess et al. (2003) and Kelly and Kolstad (1999).

IAMs are divided into two broad classes in Weyant et al. (1996): policy evaluation models and policy optimisation models. Evaluation models consider the effects of a particular policy option. In contrast, optimisation models consider the trade-off between the expected costs and benefits from abatement in order to find the most efficient or 'optimal' policy to control climate change.

In this paper, the Stern Review's policy prescription is compared with policy optimisation models.[5] As mentioned, the Stern Review sets out a target for stabilisation of 450–550ppm CO_2e and its policy prescription is for abatement consistent with this target. Optimisation models do not generally seek a target for stabilisation, but rather solve for an optimal path for abatement over time. This optimal path can be compared with the Review's policy prescription. The optimisation models considered (table 1) are some of the most prominent in the literature, and all are reviewed in either Goodess et al. (2003), Kelly and Kolstad (1999) or Warren et al. (2006). These are referred to henceforth as the 'optimisation IAMs'.

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5 The IAM used for the Stern Review — PAGE2002 — is an evaluation model. Unlike optimisation models, the PAGE2002 modelling did not recommend an optimal policy response, but rather was

Table 1 **Integrated assessment models analysed in this paper**
'Optimisation IAMs'

Model	*Developers*	*Key reference*
CETA	EPRI and Teisberg Associates, USA	Peck and Teisberg (1995)
CSERGE	Maddison, D., Centre for Social and Economic Research on the Global Environment, University College London	Maddison (1995)
DICE	Nordhaus, W., Yale University	Nordhaus (2007)
FUND	Tol, R., University of Hamburg	Tol (1999a)
MERGE	Stanford University	Manne and Richels (2005)

Sources: Kelly and Kolstad (1999); Goodess et al. (2003).

Comparison with the Stern Review

The Stern Review advocates strong abatement effort now and throughout the rest of the century, in contrast with the 'policy ramp' approach typically advocated by other integrated assessment modelling. The policy ramp refers to the finding that optimal policies to control climate change involve modest rates of emission reduction in the near term, before ramping up to sharp reductions in the medium and long term (Nordhaus 2006b).

The remainder of this section shows that different insights can be gained by comparisons using different variables: comparing the social cost of emissions shows that the Stern Review favours more abatement effort now than do optimisation IAMs; comparing the quantity of abatement and cost of abatement shows that the Stern Review advocates more abatement over the remainder of the century.

The social cost of emissions

With the exception of FUND, each of the optimisation IAMs reports a path for the social cost of GHG emissions, under optimal abatement policy, over the twenty-first century. Under

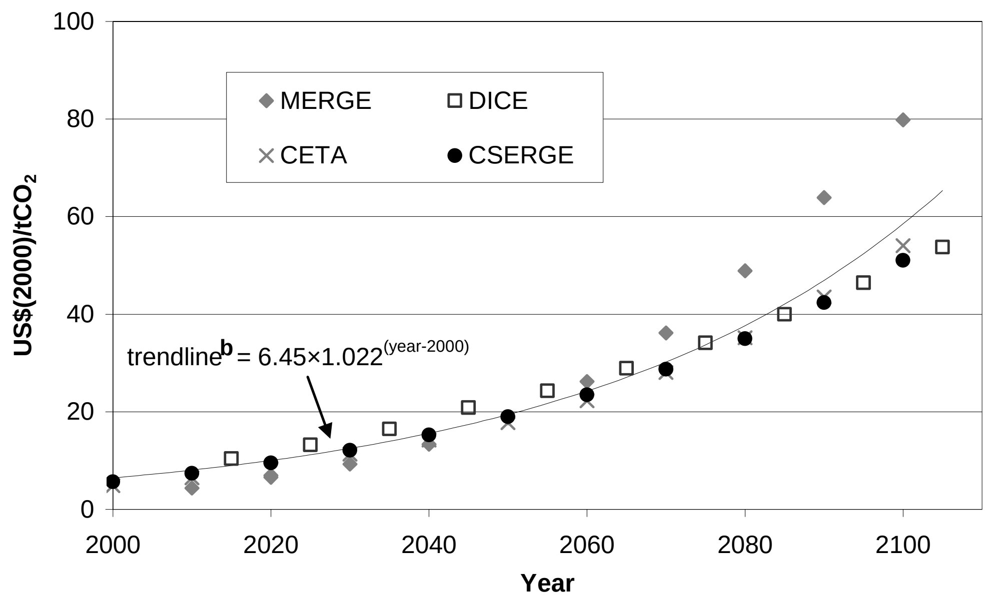
used to inform the Review's policy prescription.

optimal abatement policy, the social cost of emissions will be equal to the emissions price (box 1). Policy is optimal in the sense that it optimally balances the trade-off between the expected costs and benefits from abatement, under full international cooperation.[6]

The optimisation models find that the social cost of emissions — and consequently the emissions price — is initially modest. All suggest that an initial emissions price of US$10/$tCO_2$ or less is optimal (figure 3).

Figure 3 **The policy ramp**

Social cost of emissions (emissions price under optimal policy)[a]



[a] Under an optimal emissions tax or trading system, the social cost of emissions is equal to the emissions price (box 1). [b] Fitted using the Stata statistics package to estimate a nonlinear least squares regression.

Data sources: Maddison (1995); Manne and Richels (2005); Nordhaus (2007); Peck and Teisberg (1995).

[6] The degree of international cooperation is important in determining optimal emissions reduction (Nordhaus and Yang 1996). In fact, Tol (1999b) suggests that the degree of international cooperation is a more important determinant of optimal emissions reduction than the discount rate. Tol estimates that under classic discounting assumptions, optimal emissions reductions are more than 15 times higher with global cooperation.

The optimisation models are similarly consistent in finding that the emissions price should increase over time. Fitting a trendline to these results yields an emissions price that increases at a real rate of 2.2 per cent per annum. This implies a ten-fold increase in the optimal emissions price over the century.

Box 1 **Emissions prices and the social cost of emissions**

The emissions price (often referred to as the carbon price) refers to the tax placed on emissions, or equivalently, the market price of an emissions permit under emissions trading. Prices are generally expressed in dollars per tonne of CO_2 emissions.

The social cost of emissions (also referred to as the social cost of carbon or the marginal damage cost) is the present value of damage costs from now into the future of emitting an extra unit of GHGs now, and can also be measured in dollars per tonne of CO_2 emissions.[7]

Under optimal abatement, the emissions price will be equal to the social cost of emissions (Nordhaus 2007). Under a non-optimal response, the emissions price and social cost of emissions will diverge.

The social cost of emissions is 'path dependent'. This means that it depends on the level of emissions into the future. Future emissions are important because damage costs in the future from a unit of GHGs now will depend on future GHG concentrations. All else equal, the social cost of emissions will be lower the more stringent the abatement effort.

[7] Expressing the emissions price and social cost of emissions in terms of dollars per tonne of CO_2 is shorthand for the social cost (and corresponding price) for each individual GHG. The 'exchange rate' used to convert the social cost of other GHGs into dollars per tonne of CO_2 depends on each gas's global warming potential and the period for which they remain in the atmosphere (Stern 2007).

In contrast, the Stern Review estimates the current social cost of emissions under its policy prescription at US$25–$30/tCO_2 — about five times the median estimate from the optimisation IAMs. The range reflects variation in the cost of emissions across the Review's stabilisation range, with a social cost of emissions around US$25/t$CO_2$ along a trajectory to 450 ppm CO_2e and around US$30/t$CO_2$ along a trajectory to 550 ppm CO_2e. The Review estimates a social cost of emissions that is higher again (US$85/t$CO_2$) under 'business-as-usual' (no abatement) assumptions. The social cost of emissions varies along different emissions paths because it is 'path dependent' (box 1).

If the Review's policy prescription is taken to be close to optimal, the Review's estimate of the social cost of emissions suggests an initial emissions price of around US$25–$30/tCO_2.

The Stern Review does not prescribe a time path for the emissions price. An indication of the abatement path favoured by Stern is given by the prescribed quantity of abatement.

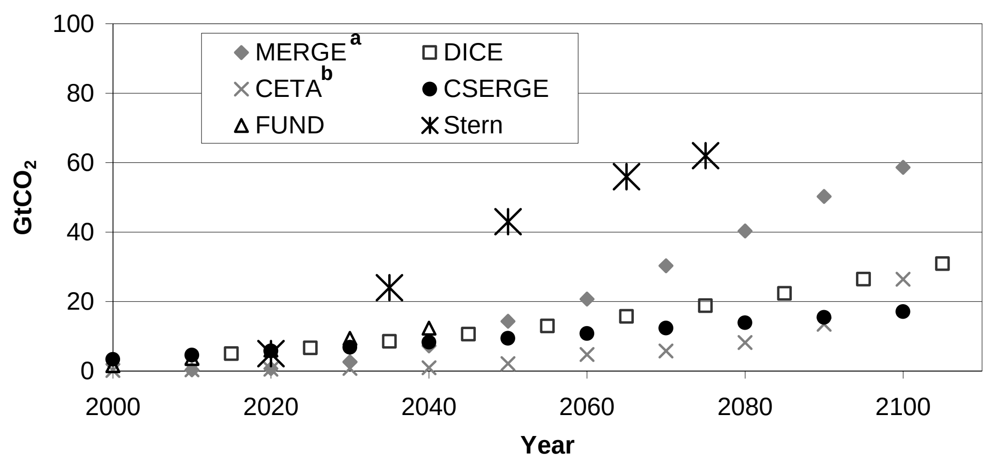
The quantity of abatement

The Stern Review favours a higher quantity of abatement over the twenty-first century than do the optimisation IAMs. In all cases, the quantity of abatement (relative to business-as-usual) increases over time. The rate of increase in abatement advocated by the Stern Review slows in the second half of the century, whereas the optimisation IAMs suggest that abatement should 'ramp up' then.

According to the Stern Review, emissions from fossil fuels need to be reduced by more than 60 gigatonnes of CO_2 (GtCO_2) from business-as-usual projections by 2075 (figure 4). This abatement is required to meet the upper end of the Review's target for stabilisation at atmospheric concentrations of 450–550ppm CO_2e. The quantity of abatement increases rapidly until 2050, then slows somewhat as the increase in business-as-usual emissions slows and as emissions under the abatement scenario drop below 10 $GtCO_2$ per year.

There is significant variation in the quantity of abatement advocated by the optimisation IAMs, but all advocate less abatement than the Stern Review. The variation can be explained by wide disparities across the models in factors including the range of GHGs considered for abatement,[8] baseline emissions projections and assumptions about the relative costs of climate change damages and mitigation.

Figure 4 **Abatement over time**
Annual fossil fuel emissions, deviation from business-as-usual



a Includes non-fossil fuel emissions of CO_2. **b** Under a power function for damages from climate change. Peck and Teisberg (1992) also present results under a linear damage function, which leads to less abatement under optimal policy.

Data sources: Maddison (1995); Manne and Richels (2005); Nordhaus (2007); Peck and Teisberg (1992); Stern (2007); Tol (1999a).

[8] Models that include more GHGs (MERGE and FUND) appear to advocate more abatement, but more data points would be needed to confirm this finding. In general, including a greater range of gases would increase possibilities for abatement, thus opening the possibility of reducing abatement costs and increasing the level of optimal abatement.

The optimisation IAMs all recommend a ramp up in abatement in the second half of the century, typically suggesting that there should be an acceleration in the rate at which abatement increases over time. On average, they recommend that the quantity of abatement in 2100 should be about five times mid-century levels.

The cost of abatement

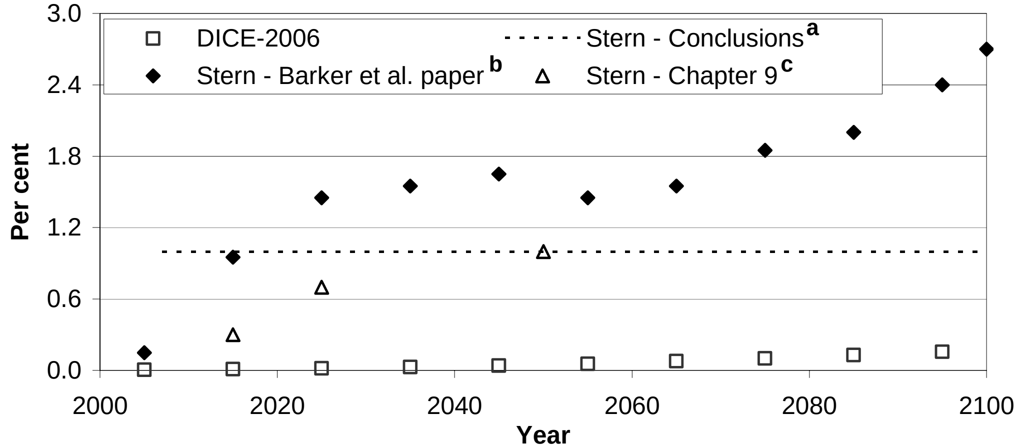
Another method that can be used to compare abatement effort over time is the total cost of abatement, which is generally expressed as an ongoing proportion of global GDP. The Stern Review gives estimates of the likely cost of the recommended abatement throughout the twenty-first century. These are compared with abatement costs from the 2006 version of the DICE model in figure 5 (comparable costs for other optimisation IAMs could not be obtained). The 2006 version of the DICE model is henceforth referred to as DICE-2006.

The Stern Review advocates significantly more expenditure on abatement than does DICE-2006. The additional expenditure continues until at least the end of the century.

The Stern Review's summary conclusion is that abatement costs should be 'around 1 per cent of global GDP each year' (Stern 2007, p. xv). However, a more detailed examination of the Review shows that minimising abatement costs would likely require a ramp up of costs over time. The estimates of abatement costs in chapter 9 of the Review are based on the resource cost approach, and suggest that costs should increase from 0.3 per cent of GDP in 2015 to 1.0 per cent in 2050 (figure 5). The Review's macroeconomic modelling estimates are based largely on a paper by Barker et al. (2006), which suggests that least cost abatement would entail costs increasing from just under 1 per cent of GDP in 2015 to almost 3 per cent of GDP by 2100.

Figure 5 **Abatement costs**

Annual abatement costs as a proportion of global GDP



[a] Stern (2007), summary of conclusions. [b] Used in the Stern Review as a key reference for macroeconomic modelling estimates of abatement costs. [c] Resource cost estimates of abatement costs.

Data sources: Stern (2007); Barker et al. (2006); DICE-2006 model.

In contrast, DICE-2006 results suggest that under optimal policy, significantly less than 1 per cent of global GDP should be spent on abatement. According to the DICE-2006 model, optimal abatement would see costs of 0.01 per cent of GDP in 2015, increasing to just under 0.2 per cent of GDP by the end of the century. The ramp up in costs suggested by DICE-2006 is much steeper than that of the Stern Review, with DICE-2006 suggesting a 15-fold increase in abatement expenditure between 2015 and the end of the century.

Despite the steep ramp up in the DICE-2006 estimates, the Stern Review still advocates much higher abatement effort at the end of the century.

Investigating the differences between Stern and other studies — an application of the DICE model

The Stern Review's policy prescription is significantly different to that of other economic assessments, despite the similarities in economic modelling approaches. This raises the question: why is the Review's policy prescription so different?

The Stern Review points out a few reasons for differences from previous assessments, most notably the inclusion of catastrophic and non-market impacts from climate change and the explicit treatment of uncertainty. However, some of the previous assessments — such as the DICE model — included catastrophic and non-market impacts and went some way to addressing uncertainty.[9]

Various commentators have proposed other reasons why the Review's call for 'strong action now' is so different from the 'policy ramp'. Nordhaus (2006b) concludes that the discount rate is the most important factor. The importance of discounting is stressed within the Review, but it was only with the release of a postscript to the Review that the sensitivity of the Review's modelling to the choice of discount rate was made apparent. Others have suggested that the Review's choice of projections for growth of the population, global economy and GHG emissions is important (Carter et al. 2006). Also, high damage cost estimates coupled with low mitigation cost estimates have been cited as a reason for the Review's conclusions (Tol and Yohe 2006).

9 The DICE model addresses uncertainty about damages from catastrophes, but not the other impacts of climate change (Nordhaus and Boyer 2000).

In this section, DICE-2006 — an optimisation IAM — is used to investigate the importance of these reasons for the Review's departure from the policy ramp result. The DICE-2006 model is used to undertake a sensitivity analysis that illustrates the importance of the Review's choice of discount rates, growth projections and its damage cost function.

The DICE model

The DICE model is the simplest and probably the most widely used of the major economic models of climate change (Ackerman and Finlayson 2006). DICE, developed by William Nordhaus, covers the economics, carbon cycle, climate science and impacts of climate change. The model is global in scope, with no regional disaggregation, and operates using 10-year timesteps. The underlying philosophy of the DICE model is to capture the key factors relevant to climate change using a small and simple model that is transparent and can be easily understood (Nordhaus and Boyer 2000).

DICE was chosen mainly because its structure facilitates sensitivity analysis by allowing for key parameters to be changed easily. DICE has been used previously for sensitivity analysis by Ackerman and Finlayson (2006) and Cline (2004), among others.

The projections and recommendations of the DICE model cannot be considered to be precise, resting as they do on imprecise science and economics. As is the case for all such modelling, results rely on projections for global GDP growth, which are highly uncertain over the centuries-long timescales involved. However, DICE is a useful tool to illustrate the factors that play a key role in determining a reasonable policy response to climate change.

The version of DICE used was DICE-2006, as used by Nordhaus in his critique of the Stern Review (Nordhaus 2006b). DICE-2006 is documented in Nordhaus (2006a), while a more detailed explanation of the DICE model is contained in Nordhaus and Boyer (2000). The DICE-2006 model is available from Nordhaus's webpage on the Yale University website.

Changes to DICE-2006

As it is an optimisation model, DICE-2006 can be used to investigate the implications for the optimal policy response of the parameter choices made in the Review's economic modelling. To do this, parameters in DICE-2006 must be varied around some base scenario. Starting from a base scenario that supports the policy ramp allows the Stern Review's departure from the policy ramp to be investigated.

The DICE-2006 model as set out in Nordhaus 2006a was taken as a base scenario.[10] As previously discussed, this scenario is typical of IAMs in calling for the policy ramp approach to climate change policy.

For the sensitivity analysis, the values of a few key parameters in the DICE-2006 model were changed from those chosen by Nordhaus, to values approximating those used in the modelling undertaken for the Stern Review (table 2). Specifically:

- business-as-usual projections were calibrated to the SRES A2 scenario
- the damage function was calibrated to Stern Review estimates

[10] One change was made to the base DICE-2006 program: the utility function was changed back to a logarithmic form (as in previous versions of DICE). The more flexible constant elasticity form used for DICE-2006 was not required for this study.

- the rate of pure time preference (a discounting parameter) was decreased to 0.1 per cent per annum.

Table 2 **Scenarios modelled**

Name	*Description*
DICE-2006	Version of DICE used in Nordhaus (2006b), with a logarithmic utility function.
DICE + A2	DICE-2006 with business-as-usual population, economic growth and emissions calibrated to the SRES A2 scenario.
DICE + DF	DICE-2006 with the damage function calibrated to figure 6.6 in Stern (2007).
DICE + DR	DICE-2006 with the rate of pure time preference decreased to 0.1 per cent per annum.
SP[a] (DICE + A2 + DF + DR)	DICE-2006 with all three changes detailed above.

[a] Stern parameters.

Business-as-usual projections

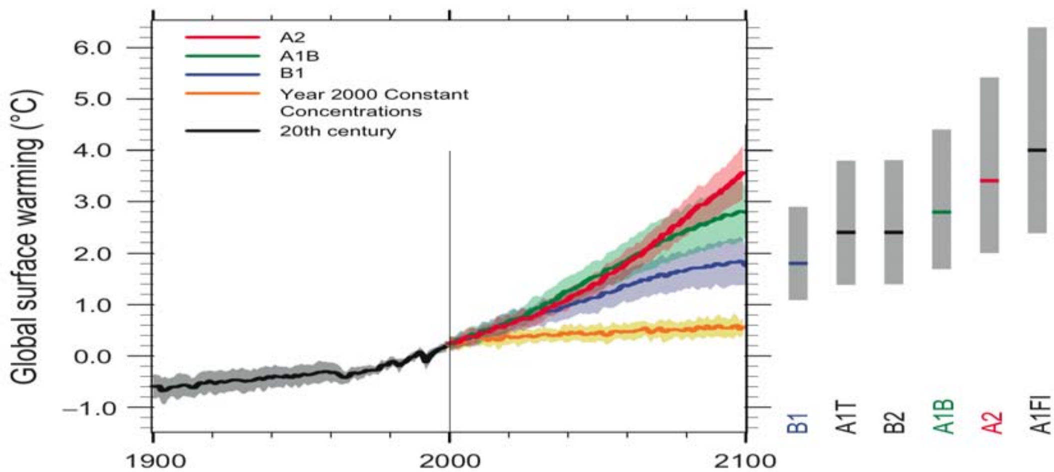
As noted, the PAGE2002 modelling undertaken for the Stern Review used the A2 scenario from the IPCC's SRES projections to estimate 'central case' business-as-usual emissions.

The scenarios that make up the SRES projections are alternative images of how the future might unfold and how this would affect future GHG emission outcomes. The scenarios represent the range of forces that affect emissions into the future, including demographic development, socio-economic development and technological change (IPCC 2000).

The A2 scenario represents a very heterogeneous world. Fertility patterns across regions converge slowly under the A2 scenario, resulting in continued rapid population growth. Per capita economic growth and technological change are more regionalised and slower than in the other scenarios. All else equal, high population growth tends to cause high emissions, while slower economic growth tends to lead to lower emissions.

The A2 scenario is associated with higher global emissions by 2100 than all but one of the five other 'illustrative scenarios' in the SRES, leading to high projected warming by 2100 (figure 6). Compared with four of the five other illustrative scenarios in the SRES (A1T, A1B, B1 and B2) the high population growth in the A2 scenario dominates the slow per capita economic growth, leading to higher overall emissions. The exception is the A1FI scenario, which projects rapid economic growth and higher emissions than any of the other scenarios.

Figure 6 **Multi-modal averages and assessed ranges for global warming**



[a] Solid lines are multi-model global averages of surface warming (relative to 1980-99) for the scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. Shading denotes the +/- 1 standard deviation range of individual model annual averages. The lower line shows concentrations held at year 2000 values. The bars at right indicate the best estimate (solid line within each bar) and the likely range assessed for the six SRES marker scenarios.

Source: IPCC (2007b).

The DICE-2006 model's projections for how the future might unfold were replaced with projections from the A2 scenario. To operationalise the A2 scenario in DICE-2006, the model was calibrated to estimates from the A2 scenario for:[11]

- Population — calibrated to projections from the A2 scenario for 2050 and 2100.

[11] The DICE-2006 baseline estimates were maintained for the initial period (2005), but replaced with A2 projections subsequently.

- Economic growth — calibrated to growth rates from the A2 scenario.[12]
- Industrial emissions of CO_2 — business-as-usual emissions calibrated to projections from the A2 scenario for 2020, 2050 and 2100.
- Radiative forcing from other GHGs[13] — calibrated to projections for 2050 and 2100 using the A2 scenario in IPCC (2001b).

Projections for 2100 in the DICE-2006 baseline, and those from the A2 scenario with which they were replaced, are summarised in table 3. The methodology used to construct projections for population, GDP and CO_2 emissions in the DICE baseline is described in Nordhaus and Boyer (2000). Broadly, population is modelled to fit UN and World Bank projections, GDP comes from a variety of sources including interviews with experts, and CO_2 emissions are based on historical trends in the carbon intensity of output. Radiative forcing from other GHGs is based on projections by the NASA Goddard Institute for Space Studies (Nordhaus 2006a).

Table 3 **Projections for 2100**

Variable	*Units*	*DICE-2006 baseline*	*Stern Review baseline (SRES A2 scenario)*
Population	billion	8.3	15.1
GDP	2006 US$trillion	467[a]	444[b]
CO_2 emissions from fossil fuels	Gt CO_2/yr	21.0	28.9
Radiative forcing from other GHGs	W/m^2	1.15	1.63

[a] Excluding the impact of climate change. [b] Using the growth rate of GDP under the A2 scenario applied to GDP in 2005 from the DICE-2006 baseline.

Sources: IPCC (2000, 2001b); DICE-2006 model.

[12] The A2 projections for GDP were not used directly, because these are consistent with global GDP in 2005 of about US$40 trillion, compared with actual GDP of US$45 trillion (World Bank 2007). Instead, GDP in the DICE-2006 baseline was used in conjunction with growth rates from the A2 scenario.

[13] Other GHGs are an exogenous input to the DICE model. Emissions of other GHGs are not changed as part of policy in DICE, but they will affect results through their effect on overall warming.

Replacing the DICE-2006 baseline with the A2 projections will exaggerate an inaccuracy in the DICE model, as it does not allow for carbon scarcity-induced substitution away from fossil fuels (Nordhaus and Boyer 2000). This is unrealistic, as depletion of some fossil fuels is likely to lead to scarcity rents over the next century. Nordhaus and Boyer (2000) estimate that DICE does not capture scarcity rents of around US$26 per tonne of carbon by 2100, but conclude that this has no substantial impact on results over the next 100 years. Higher fossil fuel use under the A2 scenario (compared with the DICE-2006 baseline) increases the extent to which the absence of fossil-fuel scarcity is unrealistic.

Damage function

The damage function models the relationship between temperature increase and damages from climate change. The damage function in DICE-2006 assumes that damages are proportional to world output and are polynomial functions of global mean temperature change, as set out in (3) below. As explained by Nordhaus (2007) 'this equation is extremely conjectural given the weak base of empirical studies on which it rests' (p. 27).

$$Damages = \left(a_1 T + a_2 T^2\right) \times GDP \qquad (3)$$

where T = temperature increase and a_1, a_2 are constants

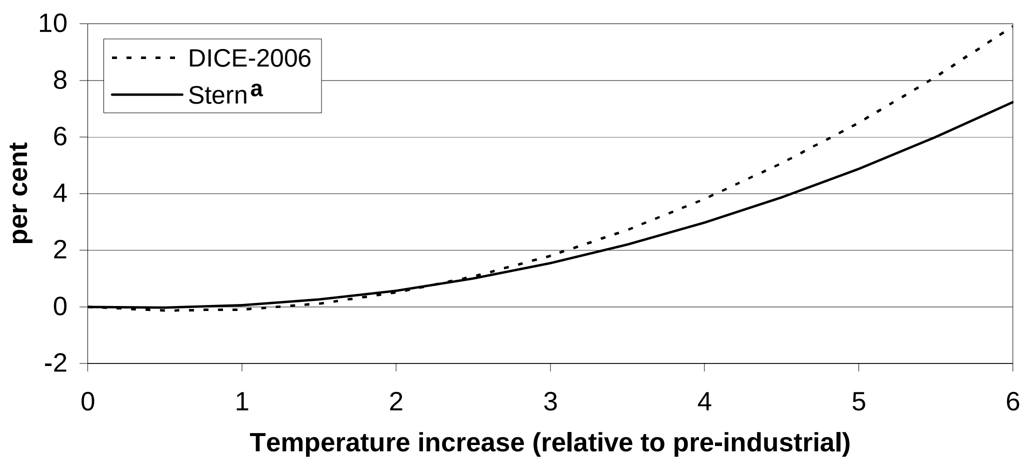
The relationship between temperature increase and damage costs in the Stern Review is modelled by the PAGE2002 damage function. As is evident from comparing equations (1) and (3), the damage function in PAGE2002 is fundamentally different to that in DICE-2006, with uncertainty extended to the power of the polynomial function. There are also differences in the way that damages from catastrophe are modelled: DICE-2006 incorporates catastrophe directly into the damage function, while PAGE2002 models catastrophe separately.

Incorporating the PAGE2002 damage function in DICE-2006 would be difficult because DICE has no regional disaggregation, and damages (as well as adaptation to reduce these damages) differ by region in PAGE2002. Instead, the damage function was calibrated to fit the mean estimate of damage costs under the central case, from figure 6.6 of the Review. These damage costs were estimated using PAGE2002 and include market and non-market impacts as well as the risk of catastrophe. This procedure meant that the damage function in equation (3) was calibrated to be consistent with a 1 per cent loss in GDP for 2.5°C of warming and an 11.3 per cent loss in GDP for 7.4°C of warming.

Compared with DICE-2006, calibrating the damage function to the Stern Review gives less scope for positive effects from warming at low temperature increases, but also less damage at higher temperature increases (figure 7). A subsequent version of DICE (Nordhaus 2007) pushes the damage function higher again.

Figure 7 **The damage function**

Loss in global GDP as temperature increases



[a] Calculated by fitting the DICE-2006 (quadratic) damage function to estimates in figure 6.6 in the Stern Review.

Data sources: DICE-2006; Stern (2007).

One explanation for the lower damage costs at higher temperature increases under the Stern Review calibration is the different treatment of uncertainty inherent in the ‘risk of catastrophe’ in DICE and PAGE2002. The DICE-2006 damage function incorporates a risk premium to account for the uncertainty associated with the risk of a catastrophe, under the assumption of a certain degree of risk aversion. In contrast, the mean damage costs from PAGE2002 reported in the Stern Review do not incorporate any risk premium. Rather, as explained previously, the PAGE2002 modelling employs a Monte Carlo simulation that allowed Stern to account for uncertainty when aggregating damage costs into a single point estimate. Calibrating the damage function to the mean damage costs reported in the Stern Review means that the risk of catastrophe is treated in the same way as market and non-market damages in DICE, with no risk premium.

Rate of pure time preference

The discount rates used for the Stern Review are substantially lower than those used in the optimisation IAMs (table 4). DICE-2006 incorporates discount rates that are typical of those used in the optimisation IAMs, based on a rate of pure time preference of 3 per cent in 2005, declining slowly to about 1 per cent per year in 200 years (Nordhaus 2006b). Nordhaus bases his discounting parameters on historical savings data and interest rates (Nordhaus and Boyer 2000). In contrast, the Stern Review used a rate of pure time preference of just 0.1 per cent, based on a judgement that the welfare of future generations should be treated on a par with our own. This means that under the same growth rate of per capita consumption, the Stern

Review would use a discount rate that is almost 3 percentage points lower than that in DICE-2006.[14]

Table 4 **Initial discount rates**

Optimisation IAMs and the Stern Review

Model	*Rate of pure time preference*	*Real discount rate*
	Per cent per annum	*Per cent per annum*
CETA	3.0	**n/r**
CSERGE	**n/r**	5.0
DICE-2006[a]	3.0	5.3
FUND	1.0	**n/r**
MERGE	**n/r**	5.0
Stern Review	0.1	~1.4[b]

[a] Rates decline over time from initial (2005) levels. [b] This figure is uncertain. In the Review, discount rates vary across scenarios and paths (and over time) depending on the growth rate of per capita consumption. According to Weitzman (2007), the real discount rate will be equal to 1.4 per cent per annum under the Review's preferred base-case parameter values. Byatt et al. (2006), however, claim that HM Treasury has supplied data that imply that Stern used discount rates of 2.1 per cent for the current century, 1.9 per cent for next century and 1.4 per cent thereafter. **n/r:** not reported.

Sources: DICE-2006; Maddison (1995); Peck and Teisberg (1992); Tol (1997); Warren et al. (2006); Weitzman (2007).

In this paper, DICE-2006 is used to investigate the effect of low discount rates, both alone and in conjunction with the other parameter changes discussed above. The rate of pure time preference is reduced to 0.1 per cent, as advocated by the Stern Review.

Results

The modifications to the DICE-2006 model outlined above were undertaken separately, then together. This yielded 5 different scenarios for comparison, with the first being the base DICE-2006 model (table 2).

[14] The Stern Review and DICE-2006 both adopt one as the value for the elasticity of the marginal utility of consumption (η in equation (2)).

Changing business-as-usual projections to match the A2 scenario led to a slight increase in the optimal abatement effort over the next hundred years (table 5). At the same time, the rate of increase in the emissions price was reduced. This can be seen in the 'ramp factor' in table 5, which measures the steepness of the policy ramp. In spite of the increase in abatement effort, atmospheric GHG concentrations are higher by the end of the century under the 'DICE + A2' scenario compared with the 'DICE-2006' scenario. This is because the A2 scenario projects higher business-as-usual emissions (table 3).

Calibrating the damage function to match the Stern Review decreased the abatement effort, while also reducing the slope of the policy ramp (table 5). As reported previously, the mean damage costs in the Stern Review were lower than in the base DICE-2006 model for large temperature increases, but also suggested less scope for positive effects from warming at low temperature increases. The former effect outweighed the latter, resulting in less damages under the Stern Review calibration and a call for less abatement. Less abatement under the 'DICE + DF' scenario leads to a higher concentration of GHGs by the end of the century.

Table 5 **Modelling results**

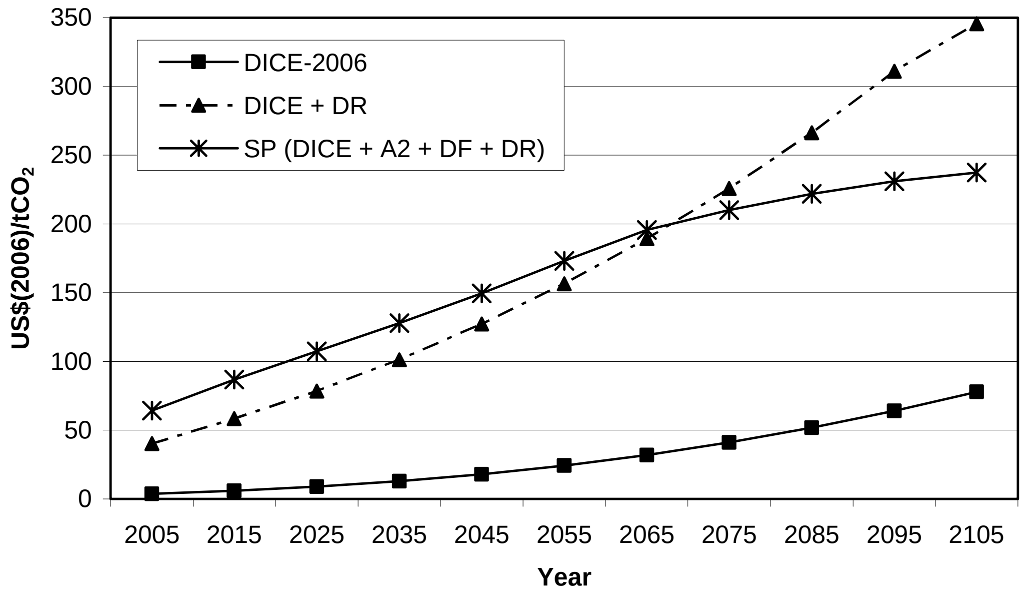
Under optimal policy using the DICE model

Rate of pure time preference	*Scenario*	*Emissions price 2005*	*Emissions price 2105*	*Ramp factor:*[a] $\frac{emissions\ price_{2105}}{emissions\ price_{2005}}$	*GHG concentration 2105*[b]
		US\$(2006) /tCO_2	US\$(2006) /tCO_2		ppm CO_2e
High (3.0, decreasing over time)	DICE-2006	4	78	21	828
	DICE + A2	6	100	16	984
	DICE + DF	3	56	18	853
Low (0.1)	DICE + DR	40	346	9	490
	SP (DICE + A2 + DF + DR)	64	237	4	491

[a] May not be consistent with reported emissions prices due to rounding errors. [b] Atmospheric GHG concentrations estimated from radiative forcing (in watts per square metre) using table TS.2 of IPCC (2007a).

Reducing the rate of pure time preference to 0.1 per cent per year, as in the Stern Review, triggers a large increase in the optimal abatement effort (table 5 and figure 8). The optimal emissions price rises ten-fold, as reported in Nordhaus (2006b).

Figure 8 **Key factors driving the Stern Review's results**
The emissions price under optimal policy using the DICE model



By 2105, with a rate of pure time preference equal to 0.1 per cent, the optimal emissions price is still four times higher than the base DICE-2006 results. As with emissions today, the benefits from emission reductions in 2105 are felt far into the future, and must be weighed against mitigation costs that are incurred immediately. A low discount rate increases the importance of the future benefits, and continues to justify higher abatement.

The increase in abatement effort under a low rate of pure time preference means that GHG concentrations by the end of the century are significantly lower than under the base DICE-2006 model. Changing only the discount rate is enough to bring the estimated GHG concentration by the end of the century into line with the Stern Review's target range for stabilisation of 450–550 ppm CO_2e (table 5).[15] This reduces the predicted increase in temperatures by the end of the century to below 2°C (figure 9).

Incorporating the Stern Review's rate of pure time preference in conjunction with the A2 scenario and calibrating the damage function to the Stern Review yields the 'SP' (Stern parameters) scenario (table 2).

The initial emissions price calculated for the 'SP' scenario is US$64/t$CO_2$, far higher than the original DICE-2006 estimate, and also higher than the social cost of emissions estimated in the Stern Review under its policy target (US$25–$30/tCO_2). The difference between the 'SP' scenario emissions price and the Review's social cost of emissions can be explained by the use of a different IAM — PAGE2002 — for the Stern Review estimates. Compared with DICE, PAGE2002 makes different assumptions about a number of other parameters and employs a different approach to estimating the damage costs from climate change. The use of different IAMs makes it difficult to isolate more specific reasons for the discrepancy (Nordhaus 2006b).

Notwithstanding the higher estimate for the social cost of emissions in the 'SP' scenario than in the Stern Review itself, this scenario is broadly consistent with the Stern Review's target range for stabilisation of 450–550 ppm CO_2e. Atmospheric GHG concentrations by the end of the century are estimated to be just under 500 ppm CO_2e — almost identical to those under the 'DICE + DR' scenario (table 5).

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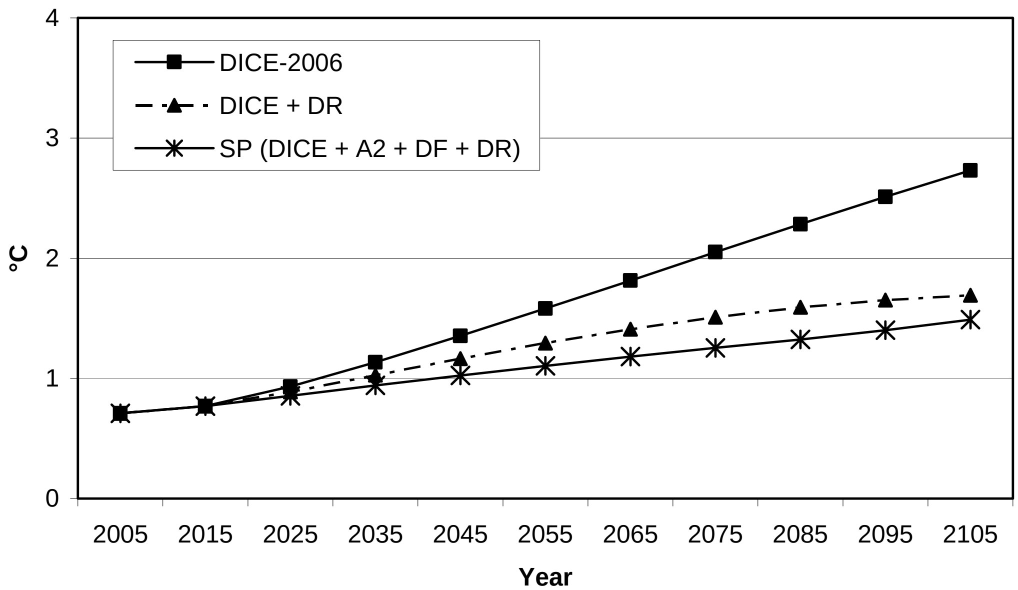
[15] Being an optimisation IAM, the DICE-2006 model does not set a stabilisation target. However, estimates for the 'DICE + DR' and 'SP' scenarios suggest that under optimal policy, atmospheric GHG concentrations would not rise beyond 500 ppm over the next two centuries. As such, these optimal policy paths are consistent with the Stern Review's target.

Figure 9 **Predicted temperature increase under different scenarios**
Relative to 1900



Going from the 'DICE + DR' scenario to the 'SP' scenario, there is little change in total abatement effort over the next hundred years, but some flattening of the ramp is evident (figure 8). That is to say, in the presence of a low discount rate, the Review's choice of growth projections and its estimate of the relationship between temperature increase and damages has little effect on the optimal abatement effort over the century, but does bring the abatement effort forward.

The flattening of the policy ramp under the 'SP' scenario leads to a slight reduction in predicted temperature increases (figure 9). The reduction in temperature is not due to lower cumulative emissions of GHGs under optimal abatement in the 'SP' scenario — cumulative emissions over the next hundred years (and thus atmospheric concentrations by the end of the century) are similar in the 'SP' scenario and the 'Stern + DR' scenario. Instead, the reduction in temperatures is a consequence of lower emissions early in the century under the 'SP' scenario. There are lags in the climate system's response to the volume of GHGs in the atmosphere (IPCC 2007b), meaning that more abatement early in the century continues to contribute to lower temperatures later in the century. The temperature differential is reduced towards the end of the century, as abatement ramps up under the 'DICE + DR' scenario.

There are likely to be interactions between the three modifications made to DICE-2006. For example, the implications of calibrating to the A2 scenario are likely to depend on whether the pure rate of time preference is low or high. Ackerman and Finlayson (2006) found such effects to be important in the DICE model. However, investigating the interactions between different modifications is beyond the scope of this study.

Conclusions

The Stern Review, like many other economic analyses, used integrated assessment modelling to assess the aggregate damages from climate change. However, the Stern Review's call for strong action now can be contrasted with the 'policy ramp' approach — modest early action ramping up to stronger action in the future — advocated by most other economic analyses.

Compared to other IAMs, the Stern Review advocates more abatement effort now and throughout the rest of the century. Notwithstanding the ramping up of abatement effort recommended by other integrated assessments, the Stern Review also recommends more abatement effort at the end of the century than is typical of integrated assessment modelling.

Analysis undertaken using the integrated assessment model DICE has shown that:

- The growth projections used by the Stern Review and its estimate of the relationship between temperature rise and damages tend to flatten the policy ramp somewhat, without having a major impact on overall abatement effort over the next hundred years, when compared with results from the base version of DICE-2006.

- As concluded by others, the discount rates used in the Stern Review lead to much higher abatement effort being optimal immediately and throughout the next hundred years. Changing the rate of pure time preference in the DICE-2006 model to match that used in the Stern Review yields an optimal policy path that is broadly consistent with the Review’s policy prescription.

Accordingly, assumptions made by Stern about future projections of growth and damage costs might be responsible for bringing the abatement effort forward, but do not explain the Review’s radical departure from earlier estimates. The key driver for the departure between the policy path prescribed by Stern and that implicit from other studies is the former’s adoption of relatively low discount rates.

References

Ackerman, F. and Finlayson, I. 2006, *The Economics of Inaction on Climate Change: A Sensitivity Analysis*, Global Development and Environment Institute Working Paper no. 06-07, Medford, USA.

Arrow, K., Cline, W., Maler, K., Munasinghe, M., Squitieri, R. and Stiglitz, J. 1996, ‘Intertemporal equity, discounting, and economic efficiency’, in Bruce, J., Lee, H. and Haites, E. (eds), *Climate Change 1995: Economic and Social Dimensions of Climate Change*, Cambridge University Press, UK, pp. 125–44.

Byatt, I., Castles, I., Goklany, I.M., Henderson, D., Lawson, N., McKitrick, R., Morris, J., Peacock, A., Robinson, C., Skidelsky, R. 2006, ‘The Stern Review: A Dual Critique, Part 2: Economic Aspects’, *World Economics*, vol. 7, no. 4, pp. 199–232.

Barker, T., Qureshi, M. and Köhler, J. 2006, *The Costs of Greenhouse Gas Mitigation with Induced Technological Change: A Meta-Analysis of Estimates in the Literature*, report prepared for the HM Treasury Stern Review on “The economics of climate change”, Cambridge Centre for Climate Change Mitigation Research (4CMR), Department of Land Economy, University of Cambridge, UK.

Carter, R., de Freitas, C., Goklany, I., Holland, D., and Lindzen, R. 2006, ‘The Stern Review: a dual critique’, *World Economics*, vol. 7, no. 4, pp. 165–230.

Cline 2004, ‘Meeting the Challenge of Global Warming’ in Lomborg, B. (ed.) *How to Spend $50 Billion to Make the World a Better Place*, Cambridge University Press, UK.

Dasgupta, P. 2006, *Comments on the Stern Review's Economics of Climate Change*, prepared for a seminar on the Stern Review's Economics of Climate Change organised by the Foundation for Science and Technology at the Royal Society, London, 8 November, www.econ.cam.ac.uk/faculty/dasgupta/STERN.pdf (accessed December 2006).

Dietz, S., Anderson, D., Stern, N., Taylor, C. and Zenghelis, D. 2007, ‘Right for the right reasons: a final rejoinder on the Stern Review’, *World Economics*, Vol. 8, No. 2, pp. 229–58.

Goodess, C., Hanson, C., Hulme, M. and Osborn, T. 2003, ‘Representing climate and extreme weather events in integrated assessment models: a review of existing methods and options for development’, *Integrated Assessment*, Vol. 4, No. 3, pp. 145-71.

Hope, C. 2006, ‘The Marginal Impact of CO_2 from PAGE2002: An Integrated Assessment Model Incorporating the IPCC’s Five Reasons for Concern’, *The Integrated Assessment Journal*, Vol. 6, Iss. 1, pp. 19-56.

IPCC (Intergovernmental Panel on Climate Change) 2000, *Special Report on Emissions Scenarios*, Nakicenovic, N. and Swart, R. (eds.), Cambridge University Press, UK.

—— 2001a, *Climate Change 2001: Impacts, Adaptation and Vulnerability*, Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, UK.

—— 2001b, *Climate Change 2001: The Scientific Basis*, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, UK.

—— 2007a, *Climate Change 2007: Mitigation of Climate Change — Technical Summary*, Contribution of Working Group III to the 4th Assessment Report of the Intergovernmental Panel on Climate Change, Geneva.

—— 2007b, *Climate Change 2007: The Physical Science Basis — Technical Summary*, Contribution of Working Group I to the 4th Assessment Report of the Intergovernmental Panel on Climate Change, Geneva.

Kelly, D. and Kolstad, C., 1999, 'Integrated assessment models for climate change control' in Folmer, H. and Tietenberg, T. (eds), *International Yearbook of Environmental and Resource Economics 1999/2000: A Survey of Current Issues*, Cheltenham, UK.

Maddison, D. 1995, 'A cost-benefit analysis of slowing climate change', *Energy Policy*, Vol. 23, No. 4/5, pp. 337–46.

Manne, A. and Richels, R. 2005, 'MERGE: An Integrated Assessment Model for Global Climate Change', in Loulou, R., Waaub, J. and Zaccour, G. (eds.) *Energy and Environment*, Springer, New York.

Nordhaus, W. and Yang, Z. 1996, 'A regional dynamic general-equilibrium model of alternative climate-change strategies', *The American Economic Review*, Vol. 86, No. 4, pp. 741–65.

—— and Boyer, J. 2000, *Warming the World*, The MIT Press, Cambridge MA.

—— 2006a, *Documentation for DICE-2006,* November 2006 round, http://nordhaus.econ.yale.edu/DICE_documentation_111706.pdf (accessed 6 June 2007).

—— 2006b, *The 'Stern Review' on the Economics of Climate Change,* National Bureau of Economic Research, Working Paper 12741.

—— 2007, *The Challenge of Global Warming: Economic Models and Environmental Policy*, http://www.econ.yale.edu/~nordhaus/DICEGAMS/dice _mss_060707_pub.pdf (accessed 19 June 2007).

Peck, S. and Teisberg, T. 1992, 'CETA: A model for carbon emissions trajectory assessment', *The Energy Journal*, Vol. 13, No. 1, pp. 55–77.

—— 1995, 'International CO_2 emissions control: an analysis using CETA' *Energy Policy,* Vol. 23, No. 4/5, pp. 297–308.

Stern, N. 2006, *The Economics of Climate Change: The Stern Review – Executive Summary*, Cabinet Office – HM Treasury, www.hm-treasury.gov.uk/media/8AC/F7/Executive_Summary.pdf (accessed 5 April 2007).

—— 2007, *The Economics of Climate Change: The Stern Review*, Cabinet Office – HM Treasury, Cambridge University Press, UK.

Tol, R. 1997, 'On the optimal control of carbon dioxide emissions: an application of FUND', *Environmental Modeling and Assessment*, Vol. 2, 151–63.

—— 1999a, 'Spatial and temporal efficiency in climate policy: applications of FUND', *Environmental and Resource Economics*, Vol. 14, pp. 33–49.

—— 1999b, 'Time discounting and optimal emission reduction: an application of FUND', *Climatic Change*, Vol. 41, pp. 351–62.

—— 2006, *Integrated Assessment Modelling*, Research Unit Sustainability and Global Change, Hamburg University and Centre for Marine and Atmospheric Science, Working Paper FNU-102.

—— and Yohe, G. 2006, 'A Review of the Stern Review', *World Economics*, vol 7, no. 4, pp. 233–50.

Warren, R., Hope, C., Mastrandrea, M., Tol, R., Adger N. and Lorenzoni, I. 2006, *Spotlighting Impacts Functions in Integrated Assessment Models*, Research Report Prepared for the Stern Review on the Economics of Climate Change, Working Paper 91, Tyndall Centre for Climate Change Research, Norwich, UK.

Weitzman, M. 2007, *The Stern Review of the Economics of Climate Change,* Book review for Journal of Economic Literature, 31 April.

Weyant, J., Cline, W., Fankhauser, S., Davidson, O., Dowlatabadi, H., Edmonds, J., Grubb, M., Parsons, E., Richels, R., Rotmans, J., Shukla, P. and Tol, R. 1996, 'Integrated assessment of climate change: an overview and comparison of approaches and results', in Bruce, J., Lee, H. and Haites, E. (eds), *Climate Change 1995: Economic and Social Dimensions of Climate Change*, Cambridge University Press, UK, pp. 367–96.

World Bank 2007, Key development data & statistics, Washington, D.C., http://go.worldbank.org/1SF48T40L0 (accessed 27 June 2007).