# CHAPTER 2 TECHNICAL APPENDIX:

# INTEGRATED ASSESSMENT MODELLING

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This Technical Appendix presents the integrated assessment model results referred to in Chapter 2: *Meeting a 2050 target*.

In Chapter 1: *Setting a 2050 target* the Committee concluded that an appropriate global strategy should aim to reduce emissions of all Kyoto GHGs to about 20-24 gigatonnes per annum by 2050 (i.e. about 50-60% below their current level). Chapter 2 states that this reduction could be achieved at a manageable cost of 1-3% of global GDP in 2050, in line with the estimates produced by the Stern Review (2007). The Committee agrees with the Stern Review that the costs of mitigation are substantially lower and pose less of a threat to economic growth and human welfare than the damage costs of uncontrolled climate change. And that the costs of climate change can, to a significant extent, be avoided through the recommended emissions reduction. To test this judgement we have run our trajectories through the *Policy Analysis of Greenhouse Effect* (PAGE)[1] integrated assessment model. This paper sets out our estimates of the damages from climate change, and, the costs and benefits of taking action using PAGE.

This work was undertaken in consultation with Chris Hope (University of Cambridge) and Simon Dietz (Grantham Research Institute on Climate Change & the Environment and London School of Economics). However the analysis and views expressed here are those of the authors[2].

[1] Developed by Chris Hope, University of Cambridge.

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# 1. INTEGRATED ASSESSMENT MODELS

Integrated Assessment Models (IAMs), bridging several disciplines, model the relationship between emissions of GHGs, the effects of GHGs on the climate and the physical, environmental, economic and social impacts caused by climate change.

The literature on IAMs dates back to the mid 1990s and has grown in volume and prominence as our understanding of the issues has improved, and our modelling capabilities have advanced. There are many types of models and they tend to fall into two broad categories: policy optimisation and policy evaluation. Climate change IAMs are typically used in cost-benefit analyses to determine an "optimal" climate change policy and to estimate the social cost of carbon[3].

Models vary in their complexity, coverage, focus and methodology. Our focus is on models which estimate the aggregate monetary impact of climate change and some of the main models include MERGE, MiniCAM, EPPA, DICE, FUND and PAGE. Integrated assessment modelling estimates are highly sensitive to underlying assumptions. The parameters that have significant influence are the discount rate, climate sensitivity, the damage function and, the treatment and aggregation of impacts. Sensitivity analysis around each of these parameters gives a wide range of estimates and optimal emissions paths. Our analysis examines how different discount rate assumptions influence the result. This is a particularly contentious issue in economics since, in the context of climate change, current generations will have to bear the costs of action and future, wealthier generations will receive the benefits.

For the reasons outlined below we have chosen to use the *Policy Analysis of Greenhouse Effect* (PAGE) model, which uses relatively simple equations to simulate the effects of GHG emissions under different scenarios for eight regions of the world.

- The model estimates market and non-market impacts, and the impacts associated with an abrupt climate catastrophe. Most other models, with the exception of the DICE model developed by Nordhaus and Boyer[4], do not explicitly include the impacts arising from catastrophic events.

- PAGE, using the Monte Carlo statistical method, allows us to model parameters in a way that reflect the risks and uncertainties associated with climate change. Each of the 31 uncertain parameters in the model is defined by a triangular probability distribution with minimum, mode and maximum values[5]. For each run – 1000 runs in this case – the model randomly draws values for each parameter from the range of possibilities allowing the model to generate probability distributions of results rather than single estimates.

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[3] Social cost of carbon measures the marginal damage cost of an additional tonne of carbon emitted to the atmosphere.

[4] Nordhaus, W. D., & Boyer, J., (2000) *Warming the World: Economic Models of Global Warming.* London, MIT.

[5] We use the following to denote the values in the distribution [min, mode, max].

- The parameter ranges used in the model are calibrated to the latest scientific and economic literature on climate change, and are designed to span the range of estimates described in the literature. This is a very valuable feature of the model which has, in the past, led PAGE to produce mean estimates of the aggregate costs of climate change that are close to the centre of a range of estimates produced by other studies.

Understanding the magnitude of global impacts is crucial for the development of future policies to tackle climate change. In order to do this IAMs have to make a number of simplifying assumptions at each stage in the analysis. Therefore, whilst these models are useful and perform a unique function, the results are driven by underlying assumptions and should be interpreted with caution. Disaggregated impact studies, considered in Chapter 1 offer a complementary and more detailed investigation of the consequences of rising global mean temperatures by sector and region.

IAMs have an important role but they also have limitations. Our understanding of the science and economics of climate change is constantly evolving and there are still considerable gaps in our knowledge. As such these models have to cope with sparse and sometimes non-existent observational data, especially on the impacts associated with very high temperatures. Even for the impacts that can be observed it can be conceptually, ethically and empirically challenging to place a monetary value on them, particularly for non-marketed impacts such as those on health and the environment. And where we can monetise impacts the levels of uncertainty are usually very large. Given the considerable uncertainties involved we have not tried to generate 'optimal' trajectories. Rather we compared different levels of effort to make a judgement about an appropriate global policy.

## 2. INTEGRATED ASSESSMENT MODEL USED BY THE CCC

In this section we outline the modifications we have made to the standard PAGE[6] model to reflect the latest developments in our understanding of climate change.

A large number of IAMs are based on literature from 2000 and earlier. However since then there have been several major advances in our understanding of climate change and new evidence has emerged. For example new information suggests there is a greater risk of higher and more rapid temperature increases. The most recent version of PAGE draws heavily on the IPCC's Third Assessment Report (TAR) (2001). The latest evidence is embodied in the IPCC's Fourth Assessment Report (AR4) (2007) and we have drawn upon this and other peer reviewed studies to update parameter ranges in the standard PAGE model.

[6] 'Standard PAGE' or PAGE2002 refers to the original (unchanged) and most recent version of the PAGE model.

**Table 1.** New parameter ranges used as model inputs in PAGE

| Parameter | Min | Mode | Max | Source |
|---|---|---|---|---|
| **Sulphate direct effect** | -0.9 | -0.6 | -0.3 | IPCC AR4, WGI, Ch2, p161 |
| **Sulphate indirect effect** | -0.7 | -0.36 | -0.1 | IPCC AR4, WGI, Ch2, p180 |
| **Equilibrium warming** | 2 | 3 | 5 | IPCC AR4, WGI, Ch10, p799 |
| **Damage function** | 1 | 2 | 3 | Ackerman & Stanton (2008), Stern Review (2007) |
| **Low cost control measures ($/tCO$_2$)** | 0 | 20 | 40 | IPCC AR4, WGIII, TS, p77 |
| **Low cost abatement potential (% of base year emissions)** | 23 | 34 | 45 | IPCC AR4, WGIII, TS, p77 |
| **Additional abatement costs ($/tCO$_2$)** | 50 | 75 | 100 | IPCC AR4, WGIII, TS, p77 |

**Sulphate direct and indirect effect.** Following an assessment of the evidence the IPCC concluded in their latest report, AR4 (2007), that direct and indirect sulphate effects are likely to be somewhat smaller than previously estimated. The probability distributions in PAGE have been updated to reflect this.

**Equilibrium warming.** Equilibrium warming is the global average temperature expected to occur once the climate system has adjusted to a doubling in atmospheric carbon dioxide concentrations (relative to pre-industrial levels). The likely range for equilibrium warming, or 'climate sensitivity' as referred to in TAR (2001) is estimated to be 1.5$^o$C to 4.5$^o$C and standard PAGE uses a range of [1.5, 2.5, 5]. Since the publication of TAR, many studies have attempted a much more comprehensive estimate of likely values for climate sensitivity. Following an assessment of the evidence the IPCC have concluded that it is likely[7] to lie in the range of 2$^o$C to 4.5$^o$C with a most likely value of about 3$^o$C. However there is a non-trivial possibility that the climate sensitivity lies outside this range and takes a value greater than 4.5$^o$C. We have updated the values in PAGE to [2, 3, 5] to reflect this.

**Damage function[8].** A damage function sets out the relationship between temperature change and damage, and it is critical in determining the scale of the estimated impact. There is a significant body of literature on the scale of damages associated with smaller temperature increases but a dearth of literature on those associated with larger temperature increases, particularly for temperatures exceeding 5$^o$C. In Chapter 1 we drew upon the analysis of the IPCC AR4 (2007), which sought to identify the relationship between rising global mean temperature and the potential impact. The evidence suggests the relationship is

[7] The IPCC term 'likely' suggests there is a >66% of climate sensitivity lying within the specified range.

[8] Referred to as the 'impact function exponent' in PAGE.

very likely[9] to be strongly 'non-linear' e.g. a 4°C rise is highly likely to be much more than twice as harmful as a 2°C rise. In theory if the monetary costs of specific impacts could be estimated, the aggregate monetary impact should equal the estimates produced by IAMs. However, as noted earlier, there are considerable data limitations and, it is empirically and ethically challenging to place monetary values on some impacts, especially non-market impacts. For these reasons IAMs tend to employ a general damage function, based on evidence in the literature, to model the relationship between temperature change and damage across a range of sectors.

The standard PAGE model estimates damage as a power function of temperature change. The power function has the following distribution [1, 1.3, 3] where a value of 1 implies that damages increase linearly with temperature, for example, a doubling of temperature leads to twice as much damage.  While a value of 3 implies a cubic relationship between damage and temperature change, where, a doubling of temperature leads to 8 times ($2^3$) the damage. This range is based on results from several previous studies discussed in IPCC's TAR (2001).

Recent analysis suggests a mode of 1.3 may not adequately reflect the degree of convexity between temperature change and likely damages. The Stern Review suggests that strong convexities could arise from interactions between impacts, which have not been fully captured in aggregate analyses. For example an increase in global mean temperatures may increase the incidence of drought, heightening damages in sectors such as health and agriculture. Sensitivity analysis undertaken by Stern using a distribution of [1.25, 2.25, 3] in the standard PAGE model showed damage estimates increased by up to 50% when using a higher and wider range for the power function[10].

The use of a higher power function may also be justified on the grounds that IAMs do not capture the full range of impacts. A study by Watkiss et al. (2005)[11] assessed the coverage of impacts across existing IAMs and showed that not all possible impacts are captured. Omissions include those impacts that are the most difficult to quantify, are surrounded by the greatest uncertainty and are likely to inflict the greatest damage. For example few models capture the socially contingent responses to climate change. However the steep(er) damage functions used by some IAMs, like PAGE and DICE[12], may implicitly capture impacts that have not been explicitly modelled.

In light of this we have changed the probability distribution to [1, 2, 3]. The new distribution lies within the same range used previously but shifts the weight (mode) more towards the higher end of the distribution than before.

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[9] The IPCC term 'very likely' suggests there is a >90% of climate sensitivity lying within the specified range.

[10] Stern, N., (2007) *The Economics of Climate Change. The Stern Review.* UK, Cambridge University Press. Technical Annex to Postscript.

[11] Watkiss, P. et al. (2005) *Methodological Approaches for Using Social Cost of Carbon Estimates in Policy Assessment. Final Report.* Culham, AEA Technology Environment.

[12] DICE model employs a quadratic damage function.

**Abatement costs and potential.** In PAGE abatement costs depend upon how far $CO_2$ emissions in each region fall below baseline emissions, where baseline emissions are defined as what would have happened without significant policy action. Three uncertain parameters are used to represent abatement costs and potential in the model; (i) the price of low cost control measures per tonne of $CO_2$ abated, (ii) the maximum percentage of emissions in 2000 (the base year) that can be abated using low cost control measures, and (iii) the additional cost per tonne of $CO_2$ abated in excess of the low cost abatement range.

Standard PAGE assumes that a large percentage of emissions can be abated relatively cheaply, at a likely cost of approximately 10 US$/t$CO_2$. IPCC's AR4 (2007) [13] suggests there is less potential for cheap abatement and the average cost is higher than is assumed in the PAGE model.

There is uncertainty surrounding the potential costs of abatement and estimates will change with the pace of technological progress and the impacts of cumulative investment in new technologies. We have updated abatement costs and potential for $CO_2$ in standard PAGE using information reported in the IPCC's AR4 (2001)[14] as this represents the consensus view. However it should be noted that the IPCC figures refer to the amount, and cost, of abatement achieved in 2030. Abatement costs could rise significantly after 2030 as the opportunities for low cost abatement are exhausted.

The abatement cost and potential values for the two other gases explicitly modelled in PAGE – methane ($CH_4$) and sulphur hexafluoride ($SF_6$) – have not been changed.

**Table 2.** Comparison of abatement cost and potential values in standard PAGE and the IPCC's AR4 (2007)

| **Parameters** | **Standard PAGE** | | | **IPCC (2007) (rescaled to 2000 base year)** | | |
|---|---|---|---|---|---|---|
| | **Min** | **Mode** | **Max** | **Min** | **Mode** | **Max** |
| **Low cost control measures (2000US$/t$CO_2$)** | -20 | 10 | 40 | 0 | 20 | 40 |
| **Low cost abatement potential (% of 2000 emissions)** | 30 | 60 | 100 | 23 | 34 | 45 |
| **Additional abatement costs in addition to low cost value (2000US$/t$CO_2$)** | 20 | 35 | 50 | 50 | 75 | 100 |

[13] Intergovernmental Panel on Climate Change, (2007) *Fourth Assessment Report.* Cambridge University Press. Working Group III, Technical Summary, pp77, Table TS.16.

[14] 'Low cost abatement potential' has been calculated using 'economic potential' estimates from the IPCC's TS.16 table (A1B scenario) and base year emissions in PAGE which are estimated to be 40 Gt$CO_2$e in 2000. According to the IPCC, 9-18 Gt$CO_2$e can be abated at low cost (mode of 20 US$/t$CO_2$e) which translates in to 23-45% of base year emissions in our model.

Independent analysis by International Energy Agency (IEA) (2008)[15] suggests that under their modelled scenario, the marginal cost of abatement could rise to somewhere in the range of 200-500 US$/t$CO_2$ by 2050, with average costs of 38-117 US$/t$CO_2$[16]. Our changes imply that if we use the mode values in table 2, then the average cost of abating 48 Gt$CO_2$ is approximately 80 US$/t$CO_2$, i.e. within the range of the IEA estimates for average abatement costs[17].

## 3. EMISSIONS TRAJECTORIES

**Baseline scenario.** The baseline climate scenario in standard PAGE is the IPCC's A2 SRES[18] scenario. In our version of PAGE we have used the A1B SRES scenario as the baseline. As the Technical Appendix to Chapter 1 sets out this scenario seems to offer the best fit to: (i) current emissions, (ii) $CO_2$ emissions forecasts by independent forecasters (for example the IEA), and (iii) forecasts of economic growth and population.

IPCC SRES scenarios project emissions up to 2100 whilst the modelling horizon in PAGE extends to 2200. In our baseline scenario – which assumes no policy action to reduce emissions – we have needed to model how emissions will behave between 2100 and 2200. We therefore assumed that under the baseline the world is likely to become increasingly resource constrained since fossil fuels are a finite resource, and the unfolding impacts of climate change are likely to lead to changes in fossil fuel use, by 2100, if not before. As fossil fuel supplies are depleted, less will be available for consumption and fossil fuel emissions will necessarily fall. In our model we have therefore assumed that emissions of $CO_2$, $CH_4$ and $SF_6$ post-2100 will fall at a rate of 2.5% per annum.

**Mitigation trajectories.** The number of mitigation trajectories which could be modelled is potentially very large. The CCC have chosen to focus on a small number of trajectories which together cover the range of possible emissions scenarios. The mitigation trajectories vary along three dimensions; (i) the year in which emissions reductions peak, (ii) the pace of emissions reductions thereafter, and (iii) the ultimate emissions floor[19].

The four trajectories we have selected to run through PAGE project global emissions peak in 2016 with subsequent rates of reduction of 1.5% per annum, 2% per annum, 3% per annum and 4% per annum. These are denoted as follows 2016:1.5%, 2016:2%, 2016:3%low and 2016:4%low. $CO_2$ and $SF_6$ emissions fall at the same per annum rate. Methane emissions

[15] International Energy Agency, (2008) *Energy Technology Perspectives.* Paris, International Energy Agency.

[16] These are in US$2005 values, deflating these to US$2000 values using the US GDP deflator gives a range between 33 – 103 US$. Source: IMF World Economic Outlook Database, April 2008.

[17] Based on 29 Gt$CO_2$ in the base year (2000). Low cost abatement is approximately 10 Gt at 20US$/t$CO_2$ with the remainder, 38 Gt, at 95US$/t$CO_2$.

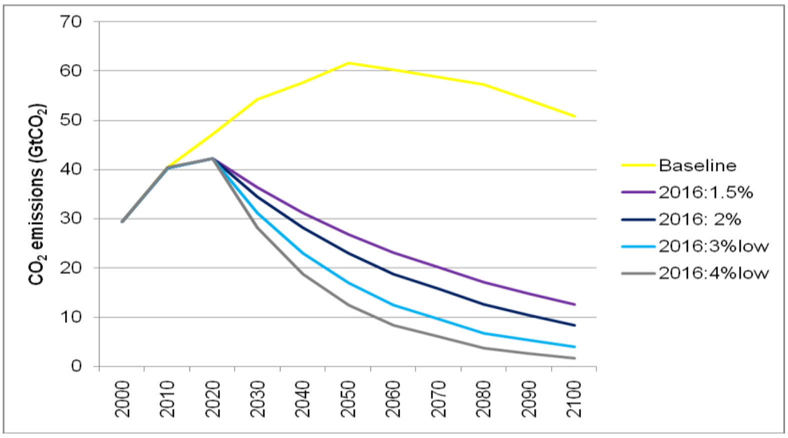
[18] Special Report on Emissions Scenarios (SRES) was prepared by the IPCC. Developed six families of scenarios : A1B, A1FI, A1T, A2, B1 and B2.

[19] 'Low' denotes that the trajectory allows emissions to fall to a lower emissions floor than the other trajectories - see Technical Appendix to Chapter 1 for further details.

also fall to an ultimate emissions floor of 150 Mt and remain constant thereafter. Detailed assumptions regarding baseline and mitigation trajectories are described in the Technical Appendix supporting Chapter 1.

These scenarios deliver different levels of abatement in terms of $CO_2$, $CH_4$ and $SF_6$ emissions. However, for the other Kyoto gases such as $N_2O$, HFCs and PFCs[20], PAGE calculates an excess forcing value which is held constant in both the baseline and mitigation trajectories. PAGE does not therefore abate these gases in our scenarios.

**Figure 1**. $CO_2$ abatement delivered under different trajectories 2000-2100




**Adaptation to climate change.** We have not changed the adaptation functions from the standard PAGE model. The model assumes that investment in adaptation can increase the tolerable level of temperature change before economic losses occur and reduces the intensity of both market and non-market impacts if the tolerable temperature change is exceeded. Adaptive costs are discounted and aggregated over time in the same manner as climate change impacts and mitigation costs. The mitigation costs reported in this paper do not include adaptation costs.

## 4. CLIMATE MODEL WITHIN PAGE2002

Climate modellers have developed dedicated climate models for estimating the climate response to various levels of GHG emissions. However these are too complex to be included in IAMs, particularly in ones that are used for optimisation. Instead, IAMs use relatively simple climate change models to capture the relationship between emissions and the dynamics of climate change, and economic models to estimate the impact of climate change.

The climate change model embodied in PAGE produces similar results to dedicated climate change models[21]. The CCC have used the MAGICC climate model to project GHG concentrations and global mean temperatures (GMT) for different emissions trajectories. For

[20] Nitrous oxide, Hydrofluorocarbons and Perfluorocarbons.

[21] 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,* 6, pp. 19-56.

completeness we ran our emissions trajectories through both PAGE and MAGICC, using updated equilibrium warming values included in IPCC's AR4 (2007), to see how well PAGE replicates the results of MAGICC.

Projections from both models are broadly comparable for the baseline scenario. The mean PAGE results predict global mean temperature will rise by 4.1$^{o}$C by the end of the century if emissions continue to grow unabated and MAGICC predicts a rise of 4.0$^{o}$C (relative to pre-industrial levels).

**Figure 2.** PAGE and MAGICC GMT estimates for the baseline scenario (relative to pre-industrial)

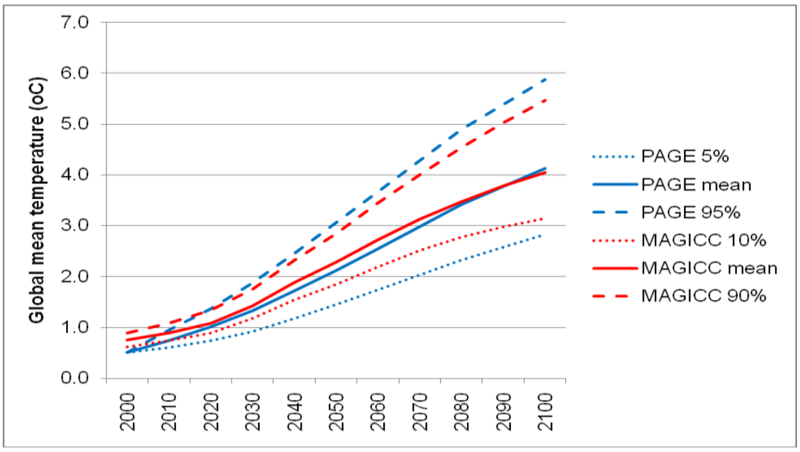
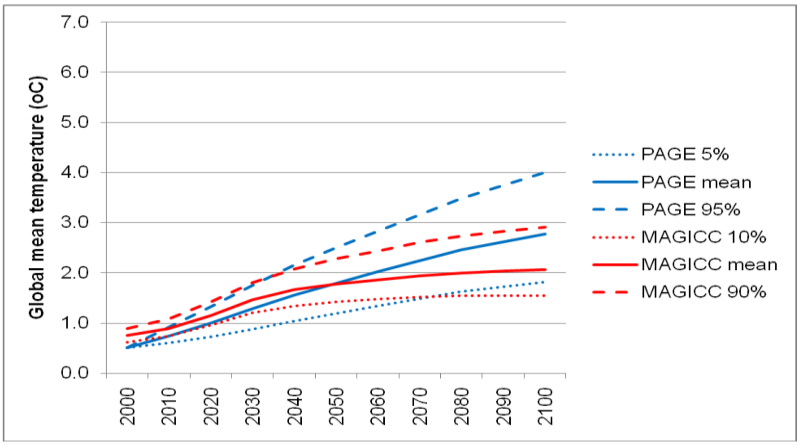



**Figure 3.** PAGE and MAGICC GMT estimates for 2016:4%low emissions reduction trajectory (relative to pre-industrial)




For the emissions reduction trajectories PAGE estimates noticeably higher mean GMTs compared to the MAGICC model. Figure 3 illustrates GMT estimates for 2016:4%low trajectory. There are several possible explanations for this variation. The Stern Review[22] suggests this may be a product of the wider combinations of parameters explored by PAGE. Alternatively it could be the way in which the model treats radiative forcing, in particular for gases that are not modelled directly. Or the way PAGE and MAGICC model carbon cycle

[22] Stern, N., (2007) *The Economics of Climate Change. The Stern Review.* UK, Cambridge University Press. pp. 175

feedbacks. To investigate this, we have compared both the radiative forcing and $CO_2$ concentration outputs produced by PAGE and MAGICC for the 2016:4% trajectory. Early results suggest that the variation is caused by two factors in roughly equal measure: the baseline excess forcing used by PAGE for the emissions reduction trajectories, and the relatively strong carbon cycle feedback it employs.

# 5. DISCOUNTING

## 5.1 Theory of discounting

To estimate the aggregate impacts of climate change we have to compare the value of costs incurred now with benefits incurred in the future. Discounting is a technique employed in economic appraisal to convert costs and benefits that occur in different time periods to equivalent 'present values' so that they can be compared.

In cost-benefit analysis we use the social discount rate which is usually presented in the following form, known as the Ramsey (1928) equation[23]:

$$S = \rho + \mu g$$

Where 'S' is the social discount rate, '$\rho$' is the rate of pure time preference, '$\mu$' is the elasticity of the marginal utility of consumption and 'g' is the rate of growth of per capita consumption.

The parameter $\rho$, the rate of pure time preference, discounts costs and benefits on the basis of time, that is individuals are impatient and have a preference for consumption now rather than later. It also includes a catastrophic risk element. This is the likelihood of an event taking place that will eliminate or radically alter the expected returns from any given policy action. In the context of climate change this represents the risk of a catastrophe eliminating the human race. The product $\mu g$ infers that people are likely to be richer in the future (assuming g is positive) and therefore the utility they will derive from an additional unit of consumption will fall as consumption rises (captured by $\mu$).

PAGE uses the Ramsey formula to calculate the discount rate. The model requires us to specify values for $\rho$ and $\mu$, then using baseline scenario projections for the rate of growth of GDP per capita[24], it derives regional and time varying discount rates. Importantly our version of PAGE uses the same discount rate in both the baseline and emissions reduction trajectories, i.e. it assumes that climate change will affect the level of output but not its rate of growth. If the growth rate is endogenous, i.e. climate change affects growth rates, then the benefits of action to prevent climate change would be greater than presented here[25].

[23] Ramsey, F. P., (1928) A mathematical theory of saving. *Economic Journal,* 38, pp. 543-559.

[24] Strictly speaking 'g' should be the growth rate of per capita consumption, however in PAGE we use GDP per capita growth rates.

[25] The lower growth rate in the baseline scenario would lead to smaller discount rate which would increase the damages from climate change. The benefits of mitigation – damages under the baseline less damages under the mitigation scenario – would be correspondingly greater.

**Discount rate.** Discounting is a controversial issue in economics because it depends upon ethical judgements that can be contested. In terms of climate change policy, the debate, for the most part, has centred on the emphasis we should place on the welfare of future generations compared to current generations. Especially since the current generations will have to bear the costs of action and future, wealthier, generations will receive the benefits. But whilst discounting does present us with a particular dilemma, not discounting has its own ethical implications. Not discounting essentially means the discount rate takes the value zero. This implies that we care as much for someone now as we do for someone a hundred years from now, and even a thousand years from now. And would therefore be willing to sacrifice much larger amounts of consumption than we currently do for the future[26].

## 5.2 Discounting in the Stern Review

Recent economic modelling undertaken for the Stern Review used an unusually low discount rate. This decision was based on the team's judgment that it would be unethical to assume that future generations' welfare should matter less in present-day decisions. Stern therefore set the rate of pure time preference close to zero, only allowing a small value for the risk of a catastrophe. Stern assumes the probability of this happening to be 0.1% per year, meaning there is a 10% chance of the human race not surviving in 100 years time. The elasticity of the marginal utility of consumption is assigned a value of 1 which implies the value of an increase in consumption is inversely proportional to income. So the Stern discount rate is calculated as follows, assuming g = 1.3%:

$$S = \rho + \mu g = 0.1 + (1 * 1.3) = \underline{1.4\%}$$

Some economists have criticised Stern for the value he assigns to $\rho$ and his choice of discount rate. A detailed discussion of the critics' arguments is given in a paper by Simon Dietz (2008)[27]. However debates over the precise value of the social discount rate may be less important than they first appear. Weitzman[28] shows that even if there is a very small risk of very large damages from climate change then this can overwhelm all other considerations in estimating the cost of climate change, including the choice of discount rate.

## 5.3 Other approaches to discounting

Nordhaus, amongst others, suggests that if we observe the behaviour of individuals we can deduce a value for $\rho$ and S from their revealed preferences. For many economists, in a perfect market economy, the discount rate would equal the market interest rate, since both concepts express individuals preferred trade-off between consumption now and in the future. Nordhaus believes the discount rate should initially, at least, align with an interest rate of approximately 5% above inflation. To achieve this, the rate of pure time preference should

[26] Pearce, D., et al. (2003) 'Valuing the Future: Recent advances in social discounting.' *World Economics*.

[27] Dietz, S., (2008) *A long-run target for climate policy: the Stern Review and its critics.* Available at www.theccc.org

[28] Weitzman, M.L. (2008). The role of uncertainty in the economics of climate change. Mimeo. Cambridge, MA, Harvard University, Department of Economics.

be at least 3% and some well known studies such as Nordhaus and Boyer (2000)[29] use values as high as this.

However we do not live in a perfect market economy. Markets are imperfect in a number of ways and there are several reasons why private market interest rates may not be suitable for determining social discount rates. A case in point is that interest rates reflect the short-run private decisions of individuals and not public decisions affecting intra and inter-generational issues.

Dasgupta agrees with Stern's position on the importance of taking future generations' welfare into account, but disagrees with the value assigned to $\mu$ which he says does not reflect the inequalities in wealth that exist today and will exist in the future. Dasgupta advocates using a higher value for $\mu$ on the basis that an increase in consumption will be of greater value to a poorer person. In principal a higher value for $\mu$ will lead to a higher discount rate and should depress the present value costs of climate change. However recent analysis[30] has shown that the role of $\mu$ is ambiguous and it can actually increase the present value costs of climate change. This ambiguity arises from the fact that $\mu$ plays three separate roles. It captures the change in marginal utility as consumption changes over time, space and uncertain states of the world.

HM Treasury's The Green Book[31] (2003) provides guidance on discounting for policy appraisal and evaluation in Government. It recommends using a rate of pure time preference of 1.5% and calculates the discount rate as follows assuming $\mu = 1$ and $g = 2\%$:

$$S = \rho + \mu g = 1.5 + (1 * 2) = \underline{3.5\%}$$

The value assigned to $\rho$ consists of 0.5% to reflect individuals impatience and a risk of catastrophe of 1%. These values were drawn from a range of possible values, details of which can be found in The Green Book (Annex 6).

In the context of climate change a value of 1% for the risk of catastrophe implies there is a 63% chance of the human race not surviving 100 years. Stern argues that this seems implausibly high, asserting that higher values for risk are relevant for the assessment of public sector projects but not for climate change and sets a much lower value of 0.1%. Later we present results using the Green Book valuation of impatience (0.5%) and the Stern Review risk of catastrophe (0.1%) to derive a value for $\rho$ of 0.6% to generate an alternative discount rate.

[29] Nordhaus, W. D., & Boyer, J., (2000) *Warming the World: Economic Models of Global Warming.* MIT.

[30] Dietz, S., (2008) *A long-run target for climate policy: the Stern Review and its critics.* Paper available from www.theccc.org

[31] HM Treasury, (2003) *The Green Book: Appraisal and Evaluation in Central Government.* London, TSO. Annex 6, pp. 97-100.

The impacts of climate change span such long periods of time that it is seems unlikely the discount rate will remain constant over this period. Weitzman (1999)[32] and Gollier (2002)[33], drawing on their work on the economics of uncertainty favour discount rates that decline over time. Nordhaus assumes the pure rate of time preference declines over time because of the assumption of declining impatience. He employs a rate of time preference of 3% per year in 1995, declining to 2.3% per year in 2100 and to 1.8% per year in 2200.

The Green Book also advocates the use of declining discount rates for projects where the costs and benefits span periods greater than 30 years and provides a schedule of gradually declining discount rates ranging from 3.5% to 1%. A fixed schedule of declining rates does not fit readily with the PAGE model, which calculates regional and time specific discount rates using the regional growth rate. To use a declining discount rate the user has to overwrite the discount rate computation in PAGE and substitute in declining discount rates (Table 3).

**Table 3.** Declining long-term discount rates used in the model taken from The Green Book.

| **Analysis years in PAGE** | **2010** | **2020** | **2030** | **2040** | **2050** | **2060** | **2080** | **2100** | **2150** | **2200** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Discount rate (%)** | 3.5 | 3.5 | 3.5 | 3.0 | 3.0 | 3.0 | 2.5 | 2.5 | 2.0 | 2.0 |

## 6. DISCOUNT RATES USED BY THE CCC

We have, albeit briefly, touched upon several approaches for deriving the social discount rate. We have used a range of these approaches, as drawn from the literature, in our model to establish if the benefits of climate change exceed the costs of mitigation for a range of discount rate assumptions[34]. These are:

- a rate using Stern Review parameters
- a rate based on Green Book parameters
- Green Book declining discount rates
- a hybrid rate using assumptions from the Green Book and the Stern Review

Table 3 sets out the values we have assigned to $\rho$, $\mu$ and g drawn from the literature. At this point it is important to note that we have not explored alternative values for $\mu$. We have used a value of 1 or a distribution of [0.5, 1, 1.5] where the most likely value for $\mu$ is 1 in our

[32] Weitzman, M., (1999) 'Just keep on discounting, but...' in P.P Portney and J. Weyant (eds), *Discounting and Intergenerational Equit.,* Washington DC, Resources for the Future.

[33] Gollier, C., (2002)*Time Horizon and the Discount Rate.* IDEI, University of Toulouse. Gollier, C., (2002) 'Discounting an uncertain future', *Journal of Public Economics,* 85, pp. 149-166.

[34] Sensitivity analyses by the Stern Review team showed that with either a $\rho$=1.5% or a $\mu$=2, a substantial portion of the present value of climate change damages would be eliminated but the remaining damages still exceed the costs of mitigation.

PAGE runs. Discount rates are denoted by the value taken by $\rho$ and are as follows: DR:0.1, DR:0.6, DR:1.5 and DR: declining.

**Table 4.** Discount rate parameters used as inputs in the model

| Discount rate | $\rho$ | µ | g (range) | Discount rate range | Average discount rate |
|---|---|---|---|---|---|
| **DR: 0.1** | 0.1 | 1 | A1B scenario (1.1 – 4.8%) | 1.2 – 4.9% | 2.8% |
| **DR: 0.6** | 0.6 | [0.5, 1, 1.5] | A1B scenario (1.1 – 4.8%) | 1.7 – 5.4% | 3.3% |
| **DR: 1.5** | 1.5 | [0.5, 1, 1.5] | A1B scenario (1.1 – 4.8%) | 2.6 – 6.5% | 4.2% |
| **DR: declining** | - | - | - | 3.5 – 2.0% | 2.9% |

The last two column sets out the range of regional and time varying discount rates, and the average discount rate generated by the model for different combinations of $\rho$, $\mu$ and g. The lowest values are generated by DR:0.1 and DR: declining, and the highest by DR:1.5.

# 7. MODELLING RESULTS

## 7.1 Damage costs of climate change

Estimates of the likely damages resulting from unmitigated climate change vary widely, largely due to differences in modelling and the coverage of impacts between IAMs. PAGE models damages in two sectors – market (e.g. energy, agriculture and coastal) and non-market (e.g. health and environment) - and considers the possibility of catastrophic events[35].

There is a small but growing body of literature on the climate catastrophes. The limited understanding that we do have regarding the threshold global mean temperature above which the catastrophe becomes possible, the probability of a catastrophic event and the scale of the impact is very uncertain at present. However whilst the evidence base is thin, there is a non-trivial risk of such an event taking place which cannot be ignored. Indeed, Weitzman has explored the impact of such a possible catastrophe and concludes that the costs of climate change could be unbounded, that is, it could lead to an infinite reduction in future consumption.

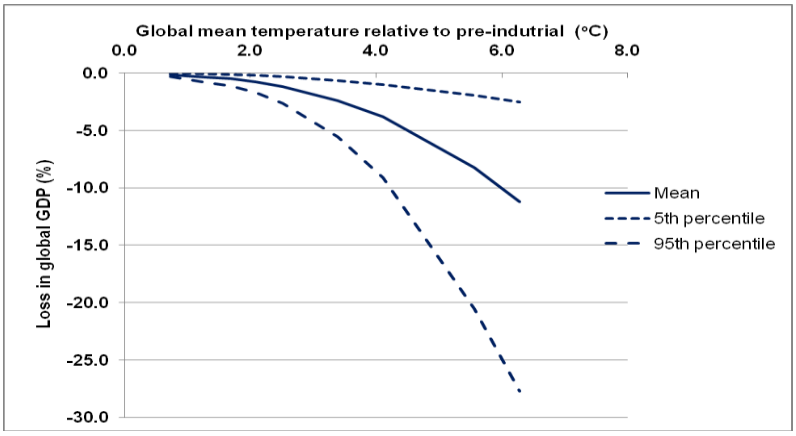
As expected, as GMT rises the damage costs of climate change rise, and at an increasing rate. Previous studies reported in the IPCC's AR4 (2007)[36] have also found this relationship

[35] The model assumes that once a threshold temperature is reached, which is uncertain but averages 5°C above pre-industrial levels in PAGE, the probability of a catastrophe increases by 10% for every additional degree of warming.

[36] Intergovernmental Panel on Climate Change, (2007) *Fourth Assessment Report*, Cambridge University Press. Working Group II, Chapter 20, pp 822.

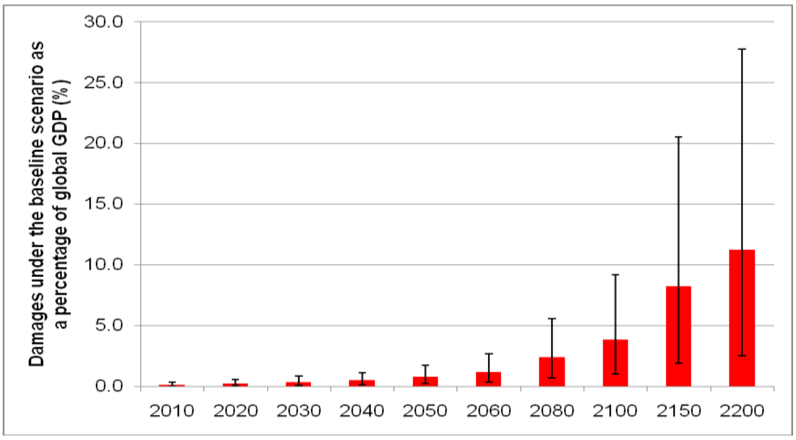
to be true although there is some uncertainty surrounding the net effect for small changes in GMT. There is for example the potential for beneficial climate change in agriculture for small increases in temperature in some regions.

**Figure 4.** Damage costs under the baseline scenario, as a percentage of global GDP for increases in GMT.




Due to long lags between emissions, concentrations and temperatures, undiscounted damages from climate change under the baseline scenario begin to increase significantly towards the end of the century. PAGE estimates that mean undiscounted damage costs could be approximately 4% of global GDP by 2100, with a $5^{th}$ and $95^{th}$ percentile range of 1 - 9% of global GDP. This could rise to 11% in 2200 with a range of 3 – 28% of global GDP. The wide ranges represent the risk and uncertainty that is inherent in this type of modelling and is a risk which cannot be ignored. These figures are comparable with those of the Stern Review, which estimated mean damage costs of 3% in 2100 and 14% in 2200 of global GDP per capita.

**Figure 5.** Mean undiscounted damages as a percentage of global GDP under the baseline[37]




Emissions remain in the atmosphere for decades, even centuries after they are emitted. Therefore past emissions have already committed the world to a certain level of damage over the next few decades and beyond. As these impacts are likely to be felt far in to the future, estimates of damage costs will be sensitive to discount rate assumptions. To

[37] Error bars report $5^{th}$ and $95^{th}$ percentile range.

illustrate, mean total damage costs for the baseline scenario for the entire analysis period are estimated at $65 trillion using DR:1.5 compared to $603 trillion using the lower DR:declining.

## 7.2 Costs of mitigation.

Emissions have to fall if we are to avoid 'dangerous' climate change. Emissions are long-lived, so the cost of reaching a particular stabilisation target depends on the current stock as well as the flow of emissions to the atmosphere. The longer we wait to act, the higher the atmospheric concentration and the more drastic the cutbacks in emissions that will be required to limit our chances of dangerous climate change. The trajectories we have chosen to run through PAGE - 2016:1.5%, 2016:2%, 2016:3%low and 2016:4low% - reflect a commitment to early action combined with a wide range of decline rates.

Our analysis of the climate science and emissions trends in Chapter 1 suggests that if we are to keep central estimates of global mean temperature close to 2°C in 2100 and reduce the risk of very severe climate change (e.g. a temperature increase of 4°C) to very low levels, then we will need to reduce emissions by at least 3% per annum. Our analysis therefore focuses on the following emissions reduction trajectories: 2016:3%low and 2016:4%low.

**Figure 6.** Total mean discounted mitigation costs for the period 2000-2200

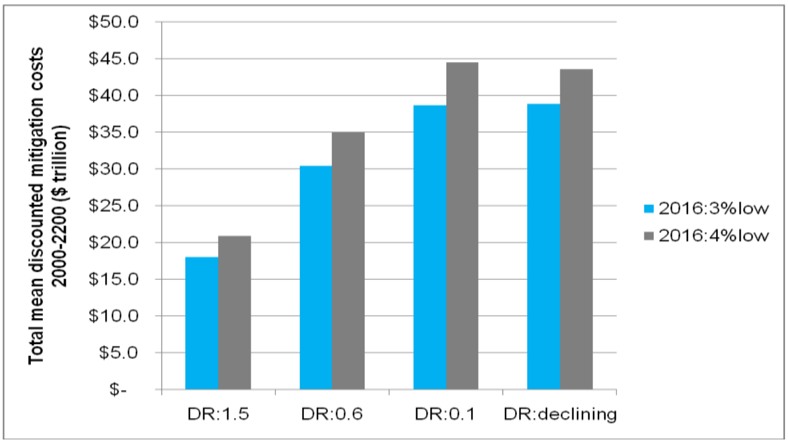



Figure 6 illustrates that firstly, the costs of mitigation are lower than the damage costs that we would incur under the baseline. And, secondly, mitigation costs are less sensitive to discount rate assumptions than damage costs. This is largely because the costs of action occur in the more immediate future and are not subject to such heavy discounting.

PAGE estimated that undiscounted mitigation costs for the most 2016:4%low trajectory would be between 1-2% of global GDP in 2050 delivering 48 $GtCO_2$ of abatement. This figure is cited in Chapter 2 of the CCC main report. This range sits within the ranges estimated by other analyses – see Table 5. The total resource cost implied by the IEA analysis ranges between 0.8 to 2.4% of global GDP in 2050 for 48 $GtCO_2$ abatement depending on the carbon price assumed. Estimates of the costs of reducing emissions are conditional on the abatement assumptions embedded within these models and vary given the intrinsic uncertainty in determining future abatement options.

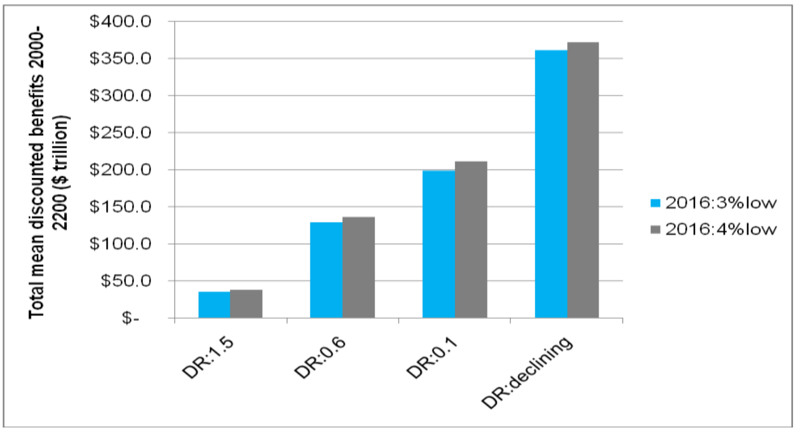
**Table 5.** Summary of global mitigation cost estimates.

| | Mitigation costs as % of GDP in 2050 | Abatement delivered in 2050 | |
|---|---|---|---|
| **PAGE** | 2016:3% low = 0.9-1.5%<br>2016:4% = 1.0-1.7% | 44 $GtCO_2$<br>48 $GtCO_2$ | No negative cost abatement measures |
| **IEA (ETP) 2008** | 0.8-2.4% | 48 $GtCO_2$ | 15 $GtCO_2$ of negative or zero cost abatement measures |
| **Stern Review**[38] | -1.0-3.5% with a mean of 1%. Trajectory similar to 2016:3%low | 43 $GtCO_2$ | Negative cost abatement measures considered |
| **GLOCAF** | 2016:3% low = 2.4%<br>2016:4% = 3.3% | 51 $GtCO_2e$<br>55 $GtCO_2e$ | No negative cost abatement measures considered |

## 7.3 Benefits

Benefits refer to the damages avoided by taking action to reduce emissions. It is the difference between damages under the baseline case and the mitigation trajectory. Benefits are highly sensitive to discount rate assumptions as they tend to occur in the distant future and are therefore subject to heavy discounting, as illustrated in Figure 8.

**Figure 8.** Total mean discounted benefits over the period 2000-2200




Benefits are higher under the 2016:4%low trajectory for all the discount rates used. Mean benefits are estimated to be around $372 trillion for the 2016:4%low scenario when using Green Book's declining discount rates. This is approximately ten times larger than estimated benefits using the Green Book equivalent, non-declining discount rate (DR: 1.5).

## 7.4 Costs and benefits

To establish if action on climate change is justified on economic grounds, that is if the net present value of action is positive, we have to compare discounted costs and benefits. Some

[38] Anderson, D. (2006) *Costs and finance of carbon abatement in the energy sector.* Paper available from www.sternreview.org.uk

critics have argued that cost-benefit analysis is an inappropriate tool for appraising climate change policy because:

- Cost-benefit analysis is a marginal approach relevant for estimating marginal perturbations around a specific economic path. Whereas climate change policy is a non-marginal issue that could arguably shift us onto different economic paths.
- Climate change policy concerns the welfare of present and future generations. Sen (1982) has argued the welfare economics framework is not suitable for dealing with intergenerational issues, particularly the rights and responsibilities of future generations.

Notwithstanding these issues Hepburn (2006) argues that so long as a social discount rate can be specified, climate change policy could be assessed by comparing the flow of utility with and without policy action.

For 2016:3%low and 2016:4%low trajectories the mean benefits of action outweigh the mean costs of mitigation for all discount rates used. This supports the conclusion reached by Stern that when using higher discount rates, the value of damages from climate change will be reduced, but the remaining damages still exceed the costs of action.

**Figure 9.** Comparison of mean discounted costs and benefits for 2016:3%low

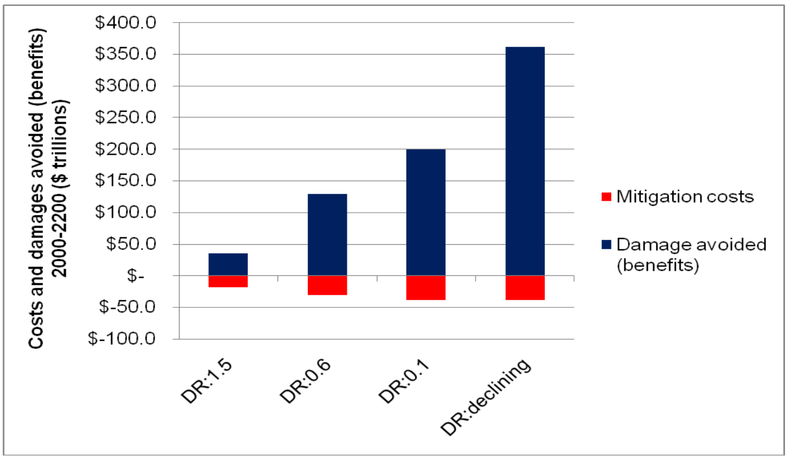
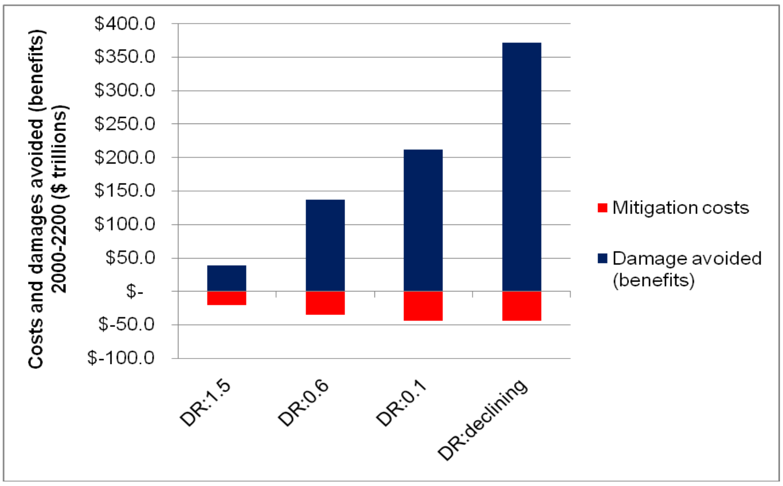
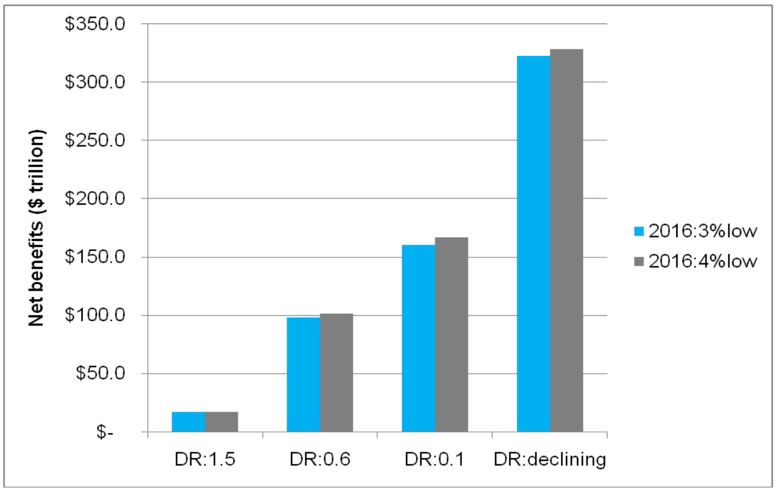



**Figure 10.** Comparison of mean discounted costs and benefits for 2016:4low%



In theory, in the context of climate change, the higher the discount rate the smaller the net benefits, as future benefits will be more heavily discounted than the upfront costs. Whilst our analysis shows that this is true, it also importantly shows that regardless of the discount rate used, there are still substantial mean net benefits from taking action to reduce emissions. Using DR:1.5, the mean net benefit for 2016:4%low trajectory is approximately $18 trillion. Using DR: declining, the mean net benefit is approximately $329 trillion.

**Figure 11.** Net benefits 2000-2200




To test whether the benefits exceed costs for higher discount rates than we have explored here, we ran PAGE using higher values for ρ. The range of values we used and the social discount rates generated are set out in table 6.

**Table 6.** Discount rate parameters used as inputs to the model.

| Discount rate | ρ | μ | g (range) | Discount rate range | Average discount rate |
|---|---|---|---|---|---|
| **DR: 3** | 3.0 | [0.5, 1, 1.5] | A1B scenario (1.1 – 4.8%) | 4.1 – 7.8% | 5.7% |
| **DR: 2.5** | 2.5 | [0.5, 1, 1.5] | A1B scenario (1.1 – 4.8%) | 3.6 – 7.4% | 5.2% |
| **DR: 2.25** | 2.25 | [0.5, 1, 1.5] | A1B scenario (1.1 – 4.8%) | 3.3 – 7.1% | 5.0% |
| **DR: 2** | 2.9 | [0.5, 1, 1.5] | A1B scenario (1.1 – 4.8%) | 3.1 – 6.8% | 4.7% |

Our analysis showed that mean net benefits are positive so long as the rate of pure time preference is 2.25% or lower. Mean net benefits are positive when ρ takes a value of 2.25% and are negative when ρ takes a value of 2.5%. This implies a break-even point, where benefits equal the costs of action, for a value of ρ between 2.25% and 2.5%, and an average social discount rate just above 5.0%.

## 8. CONCLUSIONS

Our analysis shows that:

- There are substantial damage costs from climate change under the baseline and that our estimates are broadly in line with the Stern Review.
- The mitigation costs are small compared to the damage costs of climate change, even for relatively large emissions reductions.
- There are net benefits from taking action to reduce emissions for a range of discount rates and the case for large emissions reduction holds for a range of discount rates, including those used in Government appraisals.

This analysis therefore supports the Committee's judgement that the costs of mitigation are substantially lower and pose less of a threat to economic growth and human welfare than the damage costs of uncontrolled climate change. Although given the many modelling uncertainties the Committee's judgement on the case for action rests on the dangers of significant climate change set out in Chapter 1 of the main report. The Committee believes that in particular the danger of self-reinforcing feedback loops and irreversible effects can reasonably be judged to be so great that if they can be avoided by a small sacrifice to GDP they should be.