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Executive Summary

The Stern Review on the Economics of Climate Change compares costs and benefits of stringent climate policy and concludes that the benefits of stringent policy considerably outweigh the costs. Many other cost-benefit analyses have come up with less ambitious optimal emission reductions. The enormous variation in recommendations between the different cost-benefit studies lead to much criticism on the use of CBAs to define optimal mitigation targets. This has led to several authors and organisations proposing the precautionary approach as an alternative method to inform policy-makers about the right mitigation target. Instead of finding an optimum policy as CBA aims to do, the precautionary principle aims to minimise the risks of large costs. So-far, however, the precautionary principle was only applied in a very limited way (qualitatively for only extreme policies). We instead compared the results of different assumptions in standard CBA with applying the precautionary principle in a quantitative way and included intermediate policies as well. As such, we explored how the outcomes of the Stern analysis compare to the results of Nordhaus.

We find that the preferred climate policy according to cost-benefit analysis can range from very ambitious emission reductions – meaning reducing emissions by 36% below the 1990 level in 2050 globally – to very modest emissions reductions (47% above the 1990 level in 2050). This wide range of preferred climate policy can be largely explained by the discounting method, followed by mitigation cost and climate change damage estimates. While the discounting method and (monetisation of) climate change damages involve important value judgements, this means that value judgements always will remain an important factor in cost-benefit analyses of climate change.

Another interesting finding of cost-benefit analysis of climate policy is that the costs of not reaching the preferred target is considerably less than sometimes suggested by reporting only a preferred concentration target. In most cases, the extra costs of not reaching the target or implementing more ambitious emission reductions than prescribed by the preferred target are very small. This indicates that other factors than those taken into account in the analysis (co-benefits, asymmetrical weighting of risks) may strongly impact results.

Taken together, the strong influence of value judgements on the outcome of cost-benefit analysis and similar costs for a wide range of climate policy targets raise questions with respect to the value of cost-benefit analysis in informing decision-makers about the preferred long-term climate target. In the case of climate policy, uncertainties and value judgements – especially the latter – have such a strong impact on results that in the end choosing long-term targets remains within the realm of decision-makers and other societal actors.

Applying the precautionary principle instead of standard CBA leads to somewhat different conclusions. This is especially the case when the precautionary principle is applied strictly – meaning using the extreme value for each individual input parameter – in combination with a low or medium discount rate. For these cases, the precautionary principle clearly leads to the conclusion that stringent greenhouse gas reduction policies should be implemented as soon as possible. Under these assumptions, the results are also very robust: the costs are considerably

lower for the preferred ambitious climate policy target than for less ambitious emission reductions. However, the results also show that if a high discount rate such as suggested by Nordhaus is chosen, the precautionary principle does not lead to such far-reaching implications: neither the preferred concentration level nor the robustness of the target differs substantially from standard cost-benefit analysis. The results of the precautionary principle do thus depend on the discounting method as well.

If the precautionary principle is applied less strictly – meaning using only extreme values for some of the input variables – these results can not be replicated. If only either a high sensitivity or high damage estimates are assumed, both the preferred climate policy target and the robustness of the target does not differ from standard cost-benefit analysis. This can be explained by the fact that the precautionary principle works in two directions: it not only takes into account uncertainty on the impact side, but on the mitigation side as well. This leads to the conclusion that the precautionary principle results in a more robust advice for policy making only if a rather strict application of this criterion is applied and if relatively low discount rates are used.

1 Introduction

The UNFCCC calls for the stabilisation of greenhouse gas concentration at a level “that would prevent dangerous anthropogenic interference with the climate system” (Article 2 UNFCCC). Different methods have been proposed to make this objective operational. Widely used in this regard are integrated assessment models, which use cost-benefit analysis (CBA) to inform policymakers about attractive climate response strategies. Most of these economic cost-benefit studies suggest that the trade-off between uncertain, future climate damages and the certain, present costs for controlling greenhouse emissions only justifies lower levels of near term abatement (Keller et al., 2004; Maddison, 1995; Manne and Richels, 2004; Mendelsohn et al., 2000; Nordhaus, 2008; Pearce, 2003; Tol, 2002). These studies come up with an optimal temperature target substantially higher than 2ºC above the pre-industrial level. For example, Nordhaus (2008) arrives at an optimal concentration of CO_2 close to 700 ppm, corresponding to a CO_2-equivalent concentration of 800-850 ppm in 2200 resulting in a temperature increase of around 3.4ºC. Tol (2002) arrives at a lower concentration level of 550 ppm CO_2, corresponding to around 650 ppm CO_2-equivalent. At a mean value of climate sensitivity, defined as the equilibrium global mean surface temperature increase caused by a doubling of pre-industrial atmospheric CO_2, this still leads to almost 3ºC warming compared to the pre-industrial level.

On the other hand, Stern (2006) concluded that “the benefits of strong, early action considerably outweigh the costs” and that it is economically desirable to stabilise greenhouse gas concentrations in the range of 450-550 ppm CO_2-equivalent. Although Stern said nothing about the optimal level of abatement efforts – he only compared the costs and benefits for the baseline emissions (without climate policy) with the emission pathway for stabilisation at 450-550 ppm CO_2-equivalent[1] – it is one of the few economic studies on climate change that favours early emission reductions.

Several authors have criticised the Stern Review, especially regarding the subjective choices in the analysis and that it lacks a sensitivity analysis or uncertainty range (Dasgupta, 2006; Dietz et al., 2007; Nordhaus, 2007; Pielke Jr., 2007; Weitzman, 2007; Yohe and Tol, 2007). This especially relates to Stern’s choice of a low discount rate, pessimistic assumptions about damages, and the treatment of abatement cost estimates. At the same time, there are also several reasons why some of the CBA literature might underestimate the optimal abatement effort. First of all, some of these studies include abatement of CO_2 only (Hasselmann et al., 1997; Nordhaus, 2008) and therefore disregard possibly cheaper abatement options of non-CO_2 greenhouse gases and sinks. This could overestimate abatements costs by over 60% (Reilly et al., 1999). Second, abatement costs are often incomplete and strongly stylised. For example, Nordhaus (2008), Hope (2006) and Hasselmann et al. (1997) estimate abatement

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[1] Note that the Stern Review does compare mitigation costs for different stabilisation targets in Chapter 13, but does not optimise mitigation costs and climate change damage because this would be too misleading and dangerous (also see Dietz and Stern (2008)). Furthermore, Stern indicated in his speech at the Copenhagen Conference in Copenhagen (March 2009) that he underestimated the damages of climate change, which would mean that stabilisation targets should be even more ambitious than advocated in the Stern Review.

costs using a single function. Third, damage functions often exclude costs of important (potential) damages. For example, Mendelsohn (2000) does not include non-market costs, and Tol (2002) excludes the possibility of a catastrophic event due to climate change. Finally, Goulder and Schneider (1999) argue that the presence of induced technological change implies lower costs of achieving a given abatement target, increasing the optimal abatement effort.

The enormous variation in recommendations between the different cost-benefit studies lead to much criticism – from both economists and non-economists – on the use of CBAs to define optimal mitigation targets (Azar, 1998; Azar and Lindgren, 2003; Barker, 2008; Dietz et al., 2007; Weitzman, 2007). This criticism has mainly focused on the inability of CBA to deal with risks and fundamental uncertainties and the subjective choices involved in dealing with intergenerational equity. In this context, several authors and organisations have proposed an alternative method to inform policy-makers about the right mitigation target. Instead of comparing costs and benefits quantitatively, they use an approach based on the precautionary principle (or minimax approach). Instead of finding an optimum policy as CBA aims to do, the precautionary principle aims to minimise the risks of things going wrong. Applying this principle is especially useful for decision-making under uncertainty or if the possibility of irreversible mistakes is of great concern (Froyn, 2005; Loulou and Kanudia, 1999).

However, no efforts have been made yet to apply the precautionary principle quantitatively within an integrated assessment model. The only examples of applying the precautionary principle quantitatively in climate change policy are in adaptation strategies (Harry, 2008; Prato, 2008), although recently there has been some studies analysing the effect of risk aversion, uncertainty or time preference on climate change policy (e.g., Anthoff et al, 2009 and Held et al, 2009). The current report fills this gap and compares the results and the sensitivity of value judgements of a quantitative analysis based on the precautionary principle with a standard cost-benefit approach of climate mitigation policy.

For both approaches, we use an integrated assessment model. First, we analyse the effect of uncertainty and value judgements on the outcome of CBA by systematically varying a set of critical parameters. By doing so, we quantitatively explore how such wide ranges in outcomes of CBA studies may come about – and in particular, what role the choices made in the Stern Review play in the final policy advice. Like Stern, we have focused on all greenhouse gases, including non-CO_2 gases, and have presented mitigation costs and climate change damages for a longer time-horizon (2005-2250). But unlike Stern, we have provided a comprehensive sensitivity analysis of the effect of a range of value judgements (i.e. discounting) and scientific uncertainties (climate change damages, baseline emissions and abatement costs) on the cost-optimal greenhouse gas mitigation strategy and corresponding greenhouse gas concentration and temperature.

Second, we compare the outcomes of these cost-benefit approaches with the outcomes of applying the precautionary principle. We apply the precautionary principle by minimising the maximum expected costs that society might be faced with. Van den Bergh (2004) already concluded that according to this criterion, stringent climate policy would clearly be preferred to no climate policy at all. However, his conclusion was based on a qualitative discussion and

– like the Stern Review – he only compared two, very extreme, policy alternatives, namely 1) no climate policy whatsoever to 2) a “stringent” climate policy. If only these two extreme cases would be analysed, most CBAs – including the ones recommending only modest emission reductions – would conclude that a stringent climate policy is preferred to no climate policy at all. Instead, our analysis is based on a large database of technically feasible global emissions mitigation pathways leading to a wide range of concentration levels. Moreover, we perform a quantitative analysis of costs and benefits, as opposed to the qualitative approach of van den Bergh. Van den Bergh argues that a quantitative approach is not possible mainly because of the uncertainty and value judgements involved in projecting climate change impacts. While we agree that these two factors will always bring in a certain form of uncertainty and subjectivity, we feel that a careful quantitative analysis still adds value to the even more subjective qualitative analysis of van den Bergh with only two alternatives. After all, the implicit judgements on the range of possible climate change damages made in a qualitative analysis are made explicit in a quantitative analysis.

This report is organised as follows. Section 2 provides some theoretical background, introduces the model used for the analysis and describes the cost-benefit methodology and the precautionary principle. Section 3 shows the results of the analysis and section 4 provides a discussion of the results and concludes.

2 Method

2.1 Analytical framework

In considering the attractiveness of different climate policies, several factors play an important role, including: 1) the costs of reducing greenhouse gas emissions; 2) the potential damages of climate change and our ability to adapt to climate change; 3) the relationship between greenhouse gas emissions, atmospheric greenhouse gas concentration and changes in climate; 4) the weighing of costs for different actors (intragenerational equity) and across time (intergenerational equity) and 5) other factors than climate policy that influence greenhouse gas emissions. Integrated assessment models are developed to account for the dynamic interactions between these factors. In this report, we use the integrated modelling framework FAIR 2.1 model for our analysis (den Elzen et al., 2008; den Elzen and van Vuuren, 2007; Hof et al., 2008). This model describes the most important interactions between all the factors mentioned above including relevant uncertainties. The calculations in the FAIR 2.1 model are at the level of 17 world regions, but the present study only presents aggregated global results. The FAIR model is not formally set up as an optimisation tool, but instead, it is able to evaluate a set of emission pathways, each meeting a certain pre-defined CO_2-equivalent concentration target. This leads in practice to a similar capability as a full optimisation tool.

The FAIR model consists of the following six sub-modules: 1. a scenario module, calculating the GDP growth projection until 2250 for different scenarios; 2. an emissions pathway module, calculating multi-gas emission pathways for the six greenhouse gases covered under the Kyoto Protocol (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6) (den Elzen and van Vuuren, 2007); 3. a climate module, calculating temperature implications (den Elzen and Meinshausen, 2005; den Elzen et al., 2007); 4. a mitigation costs module, calculating the mitigation costs (den Elzen et al., 2007); 5. a damage module, calculating the climate change damages, and 6. a macroeconomic growth model, calculating the direct and indirect consumption loss of mitigation and damages. Finally, the calculated discounted consumption losses of the different emission mitigation pathways determine the preferred emission pathway with the corresponding temperature increase. Figure 1 summarises the methodology and also lists the main uncertainties associated with each step.

[Figure 1 about here]

2.1.1 Baseline scenario module

The baseline scenarios used in this study were based on the recently updated IMAGE 2.3 implementation of the IPCC SRES scenarios (Nakicenovic et al., 2000) as described in van Vuuren et al. (2007). For the current analysis, we use the IMAGE/TIMER SRES B2 scenario (B2) and the IMAGE/TIMER SRES A1b scenario (A1b). The B2 scenario represents a medium emissions scenario. The A1b scenario, in contrast, represents a world with fast economic growth and correspondingly higher emissions early in the scenario. The scenarios originally ran to the year 2100. For this study, we extrapolated the scenarios to the year 2250 based on the GDP per capita growth rate per region between 2050 and 2100. Using these

GDP per capita growth rates, we fitted a function estimating GDP per capita growth rates based on the GDP level.

2.1.2 Emission pathway module

The set of emission pathways used for this analysis are taken from den Elzen and van Vuuren (2007). These pathways lead to a certain peak in concentration, after which the concentration decreases again. Compared to stabilisation profiles, peaking profiles can achieve long-term temperature targets with more likelihood under lower mitigation costs, as shown by den Elzen and van Vuuren. We analyse 25 pathways in total, of which the lowest leads to a peak in CO_2-equivalent concentration of 500 ppm and the highest to a peak in CO_2-equivalent concentration 800 ppm (see Figure 2). Assuming a climate sensitivity of 3°C, these pathways lead to a maximum temperature increase of 2°C for the 500 ppm concentration peak and 4°C for the 800 ppm concentration peak.

[Figure 2 about here]

2.1.3 Mitigation costs module

FAIR 2.1 calculates mitigation costs according to a least-cost approach using regional marginal abatement costs (MAC) curves for the different greenhouse gases and emissions sources (den Elzen et al., 2008). The cost estimates for non-CO_2 gases are based on MAC curves of the EMF-21 study for 2010 (Weyant et al., 2006). The EMF-21 curves are made time-dependent to account for technologic change, baseline development and reduction of the implementation barriers (Lucas et al., 2007). The curves for carbon plantations were developed from the IMAGE model (Strengers et al., 2008). Carbon credits from forest management are included, based on a conservative, low estimate taken from an extension of the Marrakesh Accords (den Elzen and de Moor, 2002; van Vuuren et al., 2003). Finally, for CO_2 emissions from the energy system, we derived MAC curves from the energy model TIMER (van Vuuren et al., 2004; van Vuuren et al., 2007). In this model, costs strongly depend on the emission reduction pathway through (1) technological change and (2) inertia. In the FAIR 2.1 model, this is captured by using several sets of MAC curves from TIMER that differ in timing of climate policy. In the calculations, we scale these curves based on the actual reduction path.

2.1.4 Climate module

For calculating the temperature implications of the different emission pathways we use the MAGICC 4.1 model (van Vuuren et al., 2007; Wigley, 2003; Wigley and Raper, 2001). MAGICC consists of a suite of coupled gas-cycle, climate and ice-melt models and determines changes in greenhouse-gas concentrations, global-mean surface air temperature, and sea level resulting from anthropogenic emissions. Regarding aerosol forcing assumptions and temperature-related feedbacks on the carbon cycle we apply the default settings as used for the IPCC Third Assessment Report (as described in detail in Meinshausen et al., 2006).

2.1.5 Climate change damage module

Damage estimates of climate change involve wide ranges of scientific uncertainties (e.g., impact of climate change on the number of storms or change in mortality) as well as value judgements (e.g., how to monetise non-market damages and how to deal with uncertainty, see Azar, 1998; Dietz et al., 2007; Weitzman, 2007). Therefore, damage estimates of climate change vary widely in literature. The 2001 IPCC Third Assessment Report (Smith et al., 2001) compared damage projections as function of global mean temperature increase of Mendelsohn et al. (2000), Tol (2002), and Nordhaus and Boyer (2000). This comparison shows that for a 4°C increase in global mean temperature compared to the pre-industrial level, estimates of global damages vary from practically zero to approximately 5% of world GDP. These differences can largely be explained by the number of sectors and the types of damages that are included. The damage function of Mendelsohn et al., for instance, give the lowest impact for a 4°C increase in temperature, but only include market impacts. The damage functions of Tol also include non-market impacts, resulting in climate change damages of about 1% to 1.5% of world GDP (depending on whether regional damages are aggregated according to output or population, respectively). Finally, damage estimates of Nordhaus and Boyer not only include non-market impacts, but they also take into account the chance of catastrophic impacts, arriving at damages of 4% to 5% of world GDP (again aggregated according to output or population, respectively).

Based on this information, we have chosen to include the damage function of PAGE (Hope, 2006) and the newest DICE model (Nordhaus, 2008). Both the PAGE and DICE damage functions include market and non-market costs, as well as the risk of a discontinuity (e.g. collapse of the thermohaline circulation). The PAGE damage function is probabilistic and based on the above-mentioned IPCC (2001) impact estimates. The global damage function of DICE is based on own bottom-up impact estimates. Compared to the earlier DICE damage estimates from Nordhaus and Boyer (2000), the major revisions in DICE from Nordhaus (2008) involve recalibration the costs of catastrophic damages and using revised estimates of the overall impacts for low damages. The result is that damages for small temperature changes are positive in the newest DICE model, whereas they were negative in the previous DICE model.

2.1.6 Economic growth module

We use a simple global economic growth model to analyse the direct and indirect consumption losses of climate change mitigation and damages. This model is based on a Cobb-Douglas production function, as described in detail in Hof et al. (2008). This approach has been commonly used for similar purposes in integrated assessment modelling (Messner and Schrattenholzer, 2000; Nordhaus, 2008). The equations used are:

$$Y_t = AK_t^{\alpha} L_t^{1-\alpha} \tag{1}$$

$$K_{t+1} = K_t - \eta K_t + I_t \tag{2}$$

$$Y_t = C_t + I_t + EC_t + D_t \tag{3}$$

where Y stands for GDP, A for technological progress, K for capital, L for labour, α for the capital elasticity of production, η for the depreciation rate, I for investment, C for consumption, EC for mitigation costs and D for climate change damages. The subscript t refers to year t.

The production function (1) uses two production factors, capital and labour. We assume that trends in labour force follow from trends in global population. Population estimates are taken from the long-term UN population projections (medium for B2 and low for A1b). The initial capital stock in 2005 is set at US$100 trillion, based on the IIASA growth study datasets (Miketa, 2004). For the capital elasticity of production we assume a value of 0.3. The development of A is calibrated so that that the GDP level corresponds with the exogenously baseline income development in the B2 and A1b baseline.

The capital accumulation function (2) states that the capital stock K is equal to the capital stock of last year minus depreciation (η) plus investment (I). Depreciation of the capital stock is set at 5% per year.

Equation (3), finally, states that damages and mitigation costs reduce both consumption and investment. The way in which damages replace investment and consumption have been adjusted for the damage functions used – to make them consistent with the way these curves are used in the original IAM model. In the PAGE model, damages replace consumption only. In the DICE model, the share of abatement costs replacing investment is determined by the savings rate (close to 21% in DICE). If damages are deducted from consumption, the impact of costs on consumption is obviously direct. Replacement of investment leads to an indirect effect of damages; since investment is reduced, the amount of capital in the next period is lower (equation (2)). This leads in turn to a lower GDP (equation (1)), which again leads to lower consumption (equation (3)). For mitigation costs, we adopted the same methodology as used in the DICE model. This means that, as with damages, the savings rate determines by how much mitigation costs replace investment. For the sake of simplicity, we assume that the savings rate is constant over time at 21%.

2.1.7 Determining the least-cost mitigation target

In our analysis, we look at the discounted consumption loss as percentage of discounted consumption – which we name discounted consumption loss from now onwards – for the range of emission pathways analysed. The preferred mitigation target is determined by the emission pathway leading to the lowest discounted consumption loss over the selected evaluation period. The discounted consumption loss consists of both direct and indirect consumption loss of damages and abatement. Note that the maximum temperature increase of the emission pathways does not have to occur in 2250; it is very possible that temperature will decreases again after peaking sometime during the scenario period. All temperature numbers therefore refer to the maximum transient temperature increase compared to the pre-industrial level that will be reached sometime between 2005 and 2250 (also see den Elzen and van Vuuren, 2007).

2.2 Application of the CBA and the precautionary principle

CBA aims at minimising the expected total costs of climate policy. Therefore, the input parameters have to be set at their most likely or mean values. As already mentioned in the introduction, different opinions exists on what are the mean values of the input parameters, especially regarding climate change impacts, mitigation costs and the discounting method. Stern (2006) and Nordhaus (2008) represent two, very differing, opinions on these input parameters. Both have been very influential in the economic analysis of climate change policy. We will therefore analyse the effect of applying the parameter values in line with the ideas of Stern ("Stern settings"), Nordhaus ("Nordhaus settings") and with more average assumptions on the input parameters ("standard CBA"). For the standard CBA case, we will apply different discounting methods to clearly illustrate the effect of discounting on the outcomes.

We apply the precautionary principle by minimising the *maximum* expected costs that society might be faced with, in line with the minimax decision rule (Rawls, 1971). Therefore, input parameters should not be set on their most likely value like in CBA, but on extreme values instead. An extreme value could be defined as the 95th percentile of a probability distribution function[2]. For most variables involved in climate policy, however, this is far from straightforward as the probability distribution is not known exactly. In the sub-sections below, we explain how we set the maximum ranges for each of the parameters for the precautionary principle and the mean values for the CBAs.

Applying the precautionary principle according to the method of using extreme input parameters means that uncertainty and risks are better taken into consideration compared to the standard CBA. However, it should be noted that there are other limitations to the CBA approach not solved in the precautionary principle applied here. For instance, both approaches require monetisation of all climate change impacts; both require aggregation of damage estimates; both require the same method of evaluation of costs. However, our application of the precautionary principle deals with the most important criticism from Weitzman (2009) that low-probability, high-impact consequences of climate change are not sufficiently dealt with in CBA of climate change. Still, there are other possible climate policy evaluation methods that do not require monetisation of all climate change impacts. A notable example is the multi-criteria multi-actor approach using multi-dimensional indexes, often employed by the European Commission when assessing new policies. Therefore, the current study should not be regarded as a comprehensive analysis of different climate policy evaluation methods. Rather, it aims at comparing the results and the sensitivity of value judgements between two often used climate policy evaluation methods.

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[2] We do acknowledge the fact that choosing the 95th percentile of the probability distribution function includes some value judgements about how strict the precautionary principle should be implemented. Therefore, it should be noted that our application of the precautionary principle is certainly not completely free of value judgement.

2.2.1 Baseline

The development of baseline emissions over time greatly influences the costs needed to achieve a certain mitigation target. If baseline emissions grow faster, emissions have to be reduced more on order to reach a certain target. There is not much disagreement regarding the mean baseline emissions in CBA; we therefore assume that emissions follow the medium emissions B2 baseline in all three CBA settings.

For implementation of the precautionary principle, we assume that the economy, and therefore emissions, grow faster especially early in the scenario. This is represented by the A1b baseline. Therefore, we have decided to use this scenario (instead of choosing the even higher A2 scenarios – whose storyline seems to be inconsistent with ambitious climate policy).

2.2.2 Mitigation costs

To analyse the effect of different mitigation costs estimates, we included the mitigation costs function of DICE (Nordhaus, 2008) in the CBA apart from our own mitigation cost estimates as described in section 2.1.3. The DICE mitigation cost function assumes that abatement costs are proportional to global output and to a polynomial function of the reduction rate. This function is highly convex, indicating that the marginal cost of reductions rises from zero more than linearly with the reductions rate. We use the default FAIR mitigation costs for the standard CBA and the Stern settings and the DICE mitigation costs for the Nordhaus settings.

Figure 3 compares the mitigation costs as calculated by the FAIR model and the DICE model. The FAIR calculations result in higher mitigation costs in the short run compared to the DICE model. This could be explained by the fact that the MAC curves of the energy model TIMER, on which the mitigation costs of FAIR 2.1 are based, account for inertia in the energy system. Therefore, early replacement of existing fossil-fuel-based capital stock could be associated with high costs. In the longer term, mitigation costs of DICE are higher than the FAIR 2.1 estimates. This is probably due to more optimistic assumptions about technological improvements and learning effects in FAIR 2.1. The end result is that the DICE abatement cost function results in higher mitigation costs, especially for higher concentration peak targets. The higher costs of DICE are also consistent with literature, since the model only takes abatement of CO_2 into account (for a comparison of multi-gas versus CO_2-only strategies, see van Vuuren et al. (2006b)).

[Figure 3 about here]

For the precautionary principle, we need an indication of the maximum likely mitigation costs. The IPCC (2007a) gives the 10th and 90th percentile range of the estimated global macro-economic costs in 2030 and 2050 for different long-term stabilisation levels. Table 2 compares these ranges with the mitigation costs calculated with our own model. From this comparison, it follows the 90th percentile value of the IPCC could be about 50% higher than the maximum of the range as calculated with the FAIR model. Therefore, we multiplied our own estimates of mitigation costs with a factor of 1.5 for the calculations of the precautionary principle.

[Table 1 about here]

It should be noted that we assume a global emissions trading scheme from 2012 onwards. The costs of mitigation will be higher when major emitting countries delay their participation in such a global emissions trading scheme. We have not account for this factor which would lead to a further increase of costs. Furthermore, we did not take into account possible positive or negative non-market side-effects of greenhouse gas mitigation, such as reduced air pollution or the impact of bio fuels on land use. For implementing the Kyoto Protocol in Western Europe, van Vuuren et al. (2006a) showed that the avoided air pollution control costs could be up to 50% of the mitigation costs. Bollen et al. (2007) looked at a joint climate change and local air pollution control strategy and concluded that such a joint strategy increases the benefits by at least a factor three compared to a climate change control strategy alone. On the other hand, the use of nuclear energy, hydroelectric dams, and carbon capture and storage involve non-market costs which are difficult to monetise but which could increase the mitigation costs substantially. Finally, the costs of mitigation might also be reduced if current under-employed and unemployed resources are drawn into productive activities via climate policy measures or if climate policy is designed such that it accelerates investment in low-carbon technologies, for example via auctioning carbon permits and using the revenue raised to stimulate low-carbon technological innovation (Barker and Scrieciu, 2009).

2.2.3 Climate sensitivity

The climate sensitivity is the equilibrium global mean surface temperature increase due to a doubling of pre-industrial atmospheric CO_2. Obviously, the way in which greenhouse gas emissions affect climate change is an extremely important parameter for climate policy assessment. For the CBAs, we use the latest central estimate of the IPCC Fourth Assessment Report (IPCC, 2007b) of 3.0°C.

There is much more uncertainty regarding the estimations of the 95th percentile value of the climate sensitivity necessary for our precautionary principle. The IPCC (2007b) gives a likely range of the climate sensitivity from 2°C to 4.5°C. In IPCC terminology, a likely range means that the actual value has a probability of 66% of being in this range – although the report also warns that they were not able to quantitatively bound the value of climate sensitivity on the high-end range. The IPCC does not provide a value for the 95th percentile. There is a whole range of studies available that provide probability density functions with the 95th percentile lying often in a range of 4.5°C up to extreme values of 10°C or more (Meinshausen, 2006). An example of a rather constrained probability density function is that of Annan and Hargreaves (2006) who combine several independent lines of evidence, and find a 95th percentile value of the climate sensitivity of 4.5°C. We use this value for the precautionary principle approach. Compared to the IPCC range this might be seen as an underestimate of the real range, but combined with the relatively high damage function (see section 2.2.4) this provides a rather extreme outcome of impacts compared to concentrations. A climate sensitivity of 4.5°C implies that the equilibrium (i.e. long-term) temperature increase is 50% higher than for the mean value of 3°C. However, the effect of a different climate sensitivity only slowly builds up over time. Here, we use the development over time for a 4.5°C relative to a 3°C transient climate run as can be derived from Van Vuuren et al. (2008a). In 2040, the temperature increase is 20% higher for a climate sensitivity of 4.5°C instead of 3°C and in 2100 it is 23% to 28% higher, depending on the concentration target. After 2100, we assume that the equilibrium temperature is reached in 2400 consistent with a wide range of different models (van Vuuren et al., 2008b).

2.2.4 Climate change damages as function of temperature

As mentioned in section 2.1.5, we include the damage function of the PAGE model (Hope, 2006) and the DICE model (Nordhaus, 2008) in our analysis. For the CBA with the Nordhaus settings, we use the DICE damage function and for the Stern settings we apply the mean PAGE damage function, as this is the model used by the Stern Review. For the standard CBA we use the damage function of the DICE model, because this is the most recent estimate of climate change damages.

For the precautionary principle we can use the probabilistic damage function of the PAGE model. The mean estimate of climate change damages according to the PAGE damage function is about 3% of world GDP for a 4°C increase in temperature, while the 95th percentile indicates damages of about 8% of world GDP. As this highest estimate is indeed at the high-end of the full literature range, we have decided to base the damage function for the precautionary principle on the 95th percentile of the PAGE damage function. We approximated this 95th percentile by using Table 6.1 of the Stern Review. This table shows that the discounted damages of the 95th percentile are 2.5 times the mean estimates. Therefore, we multiply the mean damages by 2.5 for the precautionary principle.

Figure 4 compares the resulting damages of the different damage functions, using the temperature and income development of the B2 baseline (therefore without climate policy). This figure shows that the damage curve of DICE is the more pessimistic about climate-induced damages than the PAGE mean damage function, but that that the 95th percentile of the PAGE damage function results by far in the highest damages.

[Figure 4 about here]

2.2.5 Discounting method

In the discussion on the Stern Review, various authors have elaborated on the discount rate chosen by Stern. In evaluating policies over time, a social discount rate is employed. There is now some consensus that the social discount rate should be based on the social rate of time preference (SRTP), which is the value society attaches to present consumption relative to future consumption (Guo et al., 2006). The SRTP can be estimated by the Ramsey equation. This equation states that the discount rate is equal to $\rho + \mu g$, where ρ is the rate of pure time preference (sometimes also called "impatience"), μ the negative of the income elasticity of marginal utility, and g the per capita growth rate of consumption. The first term ρ in the Ramsey equation reflects the discount rate that would apply if future generations had the same wealth as the current generation. The second term μg is the wealth-based component and reflects the assumption that one extra dollar is worth more to a poor person than to a rich person. Therefore, the richer future generations are, the higher the discount rate.

The choice of the rate of pure time preference (ρ) involves a value judgement about the importance attached to the welfare of future generations; the income elasticity of marginal utility (μ) involves a value judgement about the utility derived from an extra unit of income as our income level increases. Different views on these values have been presented by Nordhaus (2007; 2008) and Stern (2006) among others. Nordhaus chooses ρ (1.5%) and μ (2.0) at such levels that the discount rate reflects the return on investment (also called the descriptive approach). In contrast, Stern stated that it is ethically indefensible to treat the current generation as more important than future generations; he therefore chose a much lower value for ρ of 0.1% (the prescriptive approach). When combined with a value for μ of 1, this results in a much lower social discount rate than Nordhaus.

Both Nordhaus and Stern base the social discount rate on valid arguments, with Nordhaus emphasising the consistency with the rate of return on investment and Stern emphasising ethical issues. We do not choose to make a judgement between these two views and include both approaches in our analysis.

Another view on which discount rate to use for long term social CBAs has been proposed by the UK Treasury in its Green Book (2003). Here, a decreasing discount rate over time for long term appraisals is advocated. We will include the Green Book discounting method as well in our analysis. The discount rates for the different approaches are compared in Figure 5.

[Figure 5 about here]

2.2.6 Overview of the different settings

Table 1 summarises the parameter settings for both the standard cost-benefit approaches and the precautionary principle. Note that parameter settings of the strict precautionary principle are based on their individual ranges. The chance of these parameters being all at their extreme values is considerably lower (if they indeed represent 95th percentiles, the changes of both climate sensitivity and the damage function being at their extreme value is only 0.25%). Therefore, we also perform a sensitivity analysis for which we compare two less extreme cases of the precautionary principle: one in which we apply a climate sensitivity to 4.5°C and assume high mitigation costs, while keeping the other parameters at their default values and one in which we apply the PAGE 95th percentile damage function and again assume high mitigation costs.

We realise that real uncertainty range stretches far beyond the quantified uncertainty space here. In reality, our understanding of what could happen under extreme assumptions is relatively poor – and certainly for the interaction of various uncertainty factors. This is probably most noteworthy for climate damages. The impacts of a possible 6°C temperature increase are extremely difficult to estimate. How fast could sea level rise be under such a scenario; and to what level? Will agriculture systems still be able to adapt? Could high temperatures lead to the release of methane from tundras resulting in even further temperature change? Will the climate system itself undergo dramatic phase shifts?

One may argue that is nearly impossible to provide any meaningful quantitative estimate. It is therefore not the intention of this paper to focus on the exact quantitative outcome, but rather to explore whether the precautionary principle leads to an outcome that is more robust and quantitatively different from standard CBA; and if so, in what range these outcomes are found. It should be noted that the highest concentration target analysed leads to a peak in CO_2-equivalent concentration of 800 ppm. Combining this target with a high climate sensitivity of 4.5°C leads to an increase in temperature of 5.5°C compared to the pre-industrial level in the next 250 years. Higher increases in temperature are therefore not accounted for.

[Table 2 about here]

3 Results

First, we will present the results of the different settings of the CBAs. Section 3.2 will then present the results of the different applications of the precautionary principle and compares these with the CBA results.

3.1 CBA results

3.1.1 Undiscounted consumption loss for the default settings

The model evaluates the total discounted consumption loss across the total evaluation period (2005-2250) to find the preferred emission reduction pathway. In order to better understand the discounted results, we will first discuss the undiscounted direct consumption loss of damages, mitigation activities, the indirect consumption loss, and the total consumption loss for the standard CBA settings (Figure 6).

[Figure 6 about here]

For most emission pathways, direct consumption loss due to damages increase over time due to rising temperatures. The temperature actually peaks before 2100 only for the lowest concentration peak targets, with damages showing a similar trend. The direct damages in 2100, using the DICE damage curve, range from 1.2% loss in consumption for the lowest 500 ppm CO_2-equivalent concentration peak level to 2.6% loss in consumption for an 800 ppm CO_2-equivalent concentration peak level. Under the B2 baseline scenario – without any extra abatement activities – the estimated loss of consumption in 2100 is 3.5%.

In contrast to damages, direct consumption losses due to abatement activities are higher for lower targets. Interestingly, their profile over time is different from the damages, since they increase more rapidly in time. In other words, consumption loss of mitigation occurs in the near future, whereas consumption loss of damages occurs in the longer term. Using the default FAIR 2.1 abatement cost curve, direct consumption loss of mitigation for the most stringent (500 ppm) pathway reaches a maximum level in 2040 of almost 2.6%. An interesting finding is that under these default settings, consumption loss due to climate change damages is higher than due to mitigation from 2100 onwards, even for the lowest concentration peak level. For concentration peaking levels of 550 and higher, consumption loss due to climate change damages even exceed consumption loss due to mitigation from the very start.

3.1.2 Discounted consumption loss for the standard CBA

Figure 7 shows the discounted consumption loss for all concentration peak levels for the default settings, the Nordhaus settings and the Stern settings (see Appendix A for more detailed results on the resulting temperature target, concentration peak level, maximum increase in emissions, level of emissions in 2050, and consumption loss estimates). For the standard settings of CBA, the figure clearly shows that discounting has a huge impact on the results. When applying the Stern discounting method one would expect a more ambitious concentration target than when applying the Nordhaus discounting method, as damages in the long term are discounted away with higher discount rates. This effect is indeed very strong, as shown in Figure 7. The Stern discounting method results in a concentration peak target of 520 ppm CO_2-eq. with a corresponding maximum temperature increases of 2.4°C, whereas consumption loss is minimised at a concentration target of 720 ppm CO2-eq. with a maximum temperature increase of 4.0°C when applying the Nordhaus discounting method. The figure shows the importance of discounting in long-term CBA, which is confirmed by the discussions currently taken place in the economics literature in response to the Stern Review. The impact of the discount rate can also be vividly illustrated by showing the implied global emissions in 2050 (see Appendix A). Nordhaus discounting results in a mitigation target corresponding to a global emission target in 2050 of 47% above the 1990 level, whereas the emission target in 2050 according to Stern discounting should be -26%.

[Figure 7 about here]

When applying the discounting method of the UK Green Book – meaning discount rates in between those of Nordhaus and Stern (see Figure 5) – discounted consumption loss due to climate change damage increases from 0.9% for the lowest concentration peak target to 2.0% for a concentration peak target of 800 ppm. Damages do increase with higher concentration targets, but this increase levels off when the concentration targets become higher. This might sound counterintuitive, as damages are assumed to increase quadratically with temperature rise. The reason for the decreasing of the damage curve in Figure 7 is discounting: damages start to diverge much later between two different high concentration targets compared to two equally different low concentration targets. The discounted direct consumption loss due to mitigation range from 1.2% for the lowest concentration peak level to 0.1% for an 800 ppm concentration peak level. As shown in the figure, consumption loss due to climate change damage outweigh consumption loss due to mitigation costs for all concentration targets except the lowest. The target with the lowest total discounted costs is found at a CO_2-equivalent concentration peak level of 540 ppm. This results in a maximum temperature increase of 2.8°C (for the default climate sensitivity of 3°C). The total discounted consumption loss is 2.3% in this case. In order to reach this target, emissions should peak in 2015 at 35% above the 1990 level. After that, global emissions should decrease to a level of 13% below 1990 in 2050.

The final important insight from Figure 7 is that the total discounted consumption loss is relatively constant over a wide range of different concentration peak levels for both Nordhaus discounting and UK Green Book discounting. When applying the UK Green Book discounting method, the total discounted consumption loss of all concentration peak levels between 510 and 650 ppm are in the narrow range from 2.3% to 2.5%. With Nordhaus discounting, the total consumption loss curve is even flatter: it ranges from 1.3% to 1.5% for all concentration peak targets between 550 and 800 ppm. The fact that the total discounted consumption loss is rather flat is partly caused by the inertia in climate change. While higher concentration levels are likely to lead to larger damages - part of these larger damages also lie further out in time. Discounting (even with low discount rates) implies that these future costs do not have such a strong impact. The flat total discounted consumption loss curve implies that, while there is a target for which discounted consumption loss is minimised, many targets result in almost equal consumption loss. In other words, there is a wide range of possible outcomes that decision-makers could consider as being near-optimal.

3.1.3 Discounted consumption loss for the Nordhaus and Stern settings

The model calculations of “Nordhaus settings” and “Stern settings” are very similar to the opposing positions in the discussion on the outcomes of the Stern Review (Figure 7). The preferred emission path in the Nordhaus settings leads to a concentration peak target at 800 ppm CO_2-equivalent. This is the least ambitious emission mitigation path included in our database. This corresponds well to the around 690 ppm CO_2 only reported as the optimal target by Nordhaus (2008). With the “Stern settings”, the FAIR model finds a preferred concentration peak at 600 ppm CO_2-equivalent leading to a maximum temperature increase of 2.8°C (see Appendix A). Even though this is less ambitious than Stern, a direct comparison is difficult because Stern only compared a very ambitious target (similar to our 500 ppm mitigation target) to no mitigation at all. Indeed, our model results also prefer a 500 ppm concentration peak target to the baseline. The large discrepancies between the Nordhaus settings and Stern settings two cases are mainly different settings for discounting, but mitigation cost and damage estimates play an important role as well.

3.2 Results of the precautionary principle

Figure 8 shows the total discounted consumption loss according to the different settings of the precautionary principle, compared with the standard CBA. The results are presented for the three different discounting methods. Obviously, for each concentration peak target the precautionary principle leads to much higher consumption losses than the standard CBA, due to the higher damage estimates, climate sensitivity, mitigation costs and baseline emissions. The preferred peaking target of both the standard CBA and the precautionary principle strongly depends on the chosen discounting method.

Recapping, under the standard CBA the preferred peaking concentration target using the Stern and UK Green Book discounting method were 520 and 540 ppm CO_2-equivalent, respectively. The Nordhaus discounting method leaded to a preference for a peak concentration target of 720 ppm. A strict application of the precautionary principle (i.e. assuming a climate sensitivity of 4.5, high climate change damages, high baseline emissions and high mitigation costs) leads to different results, and interestingly, the discount rate still plays an important role. When using the discounting method of Stern or the UK Green Book, the precautionary principle clearly leads to the conclusion that emissions should be reduced as stringently as possible. Discounted consumption loss is minimised when CO_2-equivalent concentrations peak at 530 ppm, meaning that global greenhouse gas emissions should peak in 2015 at 24% above the 1990 level and should be 30% below the 1990 level in 2050. According to our model, lower concentration peak targets are not possible starting from the relatively high A1b baseline emissions due to the lack of mitigation potential. The preferred target according to the precautionary principle is thus similar to the one according to the CBA for these discounting methods. However, the costs of not reaching this target are much more severe now: discounted consumption loss sharply increases for less ambitious concentration targets. This indicates that for these discount rates the conclusion of the precautionary principle – reduce emissions by as much as possible – is very robust. The standard CBA leads to a much less robust signal.

- insert Figure 8 about here –

Using the Nordhaus discounting method leads to completely different outcomes. First of all, the discounted consumption loss for both the standard CBA and the precautionary principle is much lower due to the relatively high discount rate. Second, also the difference between the precautionary principle and the standard CBA is much smaller. In fact, it is very hard to define a preferred concentration peak target for the precautionary principle since discounted consumption loss is practically the same for all peaking targets in the range of 600 to 800 ppm. Therefore, the hypothesis that the precautionary principle automatically leads to the conclusion “reduce emissions as stringent as possible” does not hold using the Nordhaus discounting method.

As mentioned before, we apply the precautionary principle rather strictly by assuming both a high damage function and a high climate sensitivity. This combination has a very low probability, meaning we adopt a very extreme criterion. For comparison we compare the results of two more relaxed applications of the precautionary approach: one in which only the parameters of the damage function are set at the chosen extreme values (high damage only case) and one in which only the climate sensitivity is set at the extreme value (high climate sensitivity only case). For both cases, we also assume high mitigation costs. Unsurprisingly, when using the discounting method of Nordhaus, lowering the strictness of the precautionary principle does not lead to more stringent nor more robust targets. After all, even the strict application of the precautionary principle hardly resulted in different outcomes than the standard CBA.

For the other two discounting methods, the discounted consumption loss in the high damage case and the high climate sensitivity case is much lower than in the strict application of the precautionary principle. To illustrate this, discounted consumption loss for a CO_2-equivalent concentration peak target of 800 ppm when using Stern discounting reaches more than 10% in the strict application of the precautionary principle, 3.6% in the high climate sensitivity case and 5.5% in the high damage case. The sensitivity analysis shows that if we lower the strictness of the precautionary principle, the finding that the precautionary principle leads to a more robust concentration peak target compared to the standard CBA can not be replicated. The high damage only case does lead to higher discounted consumption losses than the standard CBA, but this does not have a large influence in either the preferred target or the robustness of the target since the slope of the total discounted consumption loss curve is similar.

4 Discussion and conclusions

In the past, using CBA to determine a preferred climate policy has been criticised for limitations in dealing with risks and uncertainty. The precautionary principle – meaning that the maximum expected costs that society might be faced with should be minimised – has been proposed as an alternative framework, which would meet the criticism of standard CBA. So-far, however, the precautionary principle was only applied in a very limited way (qualitatively for only to extreme policies). We instead compared the results of different assumptions in standard CBA with applying the precautionary principle in a quantitative way and included intermediate policies as well. As such, we explored how the outcomes of the Stern analysis compare to the results of Nordhaus.

In our results, we find the preferred CO_2-equivalent peaking concentration target according to CBA can range from very low values such as 520 ppm (which requires early and steep emission reductions) to more than 800 ppm. This wide range of preferred targets can be largely explained by the discounting method, followed by mitigation cost and climate change damage estimates. While the discounting method and (monetisation of) climate change damages involve value judgements, this means that value judgements always will remain an important factor in CBAs of climate change.

Despite these wide ranges in preferred outcomes, an interesting and important finding is that the costs of not reaching the preferred target is considerably less than sometimes suggested by reporting only a preferred concentration target. In most cases, the total discounted consumption loss is rather flat over a wide range of concentration targets – indicating that other factors than those taken into account in the analysis (co-benefits, asymmetrical weighting of risks) may strongly impact results. Because the function of discounted consumption loss plotted against the concentration target is especially flat for high concentration targets, much lower concentration levels than the preferred level can easily be justified.

Taken together, the strong influence of value judgements on the outcome of CBA and the relatively flat results for wide ranges of concentration levels raise questions with respect to the value of CBA in informing decision-makers about the preferred long-term climate target. As previously argued by Azar (1998), the value of CBA is that it makes a systematic analysis of all costs and benefits in a formal framework possible (and if done properly, including a systematic consideration of uncertainty). However, CBA is unlikely to give a single, clear answer to decision-makers about the optimal climate target. In the case of climate policy, uncertainties and value judgements – especially the latter – have such a strong impact on results that in the end choosing long-term targets remains within the realm of decision-makers and other societal actors.

Applying the precautionary principle instead of standard CBA leads to somewhat different conclusions. This is especially the case when the precautionary principle is applied strictly – meaning using the extreme value for each individual input parameter – in combination with a low or medium discount rate. For these cases, the precautionary principle clearly leads to the conclusion that stringent greenhouse gas reduction policies should be implemented as soon as possible. Under these assumptions, the results are also very robust: the costs are considerably lower for the preferred concentration level than for other concentration levels. However, the results also show that if a high discount rate such as suggested by Nordhaus is chosen, the precautionary principle does not lead to such far-reaching implications: neither the preferred concentration level nor the robustness of the target differs substantially from standard CBA. The results of the precautionary principle do thus depend on the discounting method as well.

If the precautionary principle is applied less strictly – meaning using only extreme values for some of the input variables – these results can not be replicated. If only a high climate sensitivity or high damage estimates are assumed, both the preferred concentration target and the robustness of the target does not differ from standard CBA. This can be explained by the fact that the precautionary principle works in two directions: it not only takes into account uncertainty on the impact side, but on the mitigation side as well.

It should be noted that the results of the analysis should be mainly interpreted in terms of the qualitative messages. The uncertainties in many factors cannot be really quantified in a strict quantitative sense (see Section 2.2). Still, the analysis does provide insight in the influence of various factors. This does lead to the conclusion that the precautionary principle results in a more robust advice for policy making only if a rather strict application of this criterion is applied and if relatively low discount rates are used.

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Appendix A: Detailed results

	climate		global emissions		total discounted consumption loss			
	CO$_2$-eq. concentration peak target (ppm)	max. temp. increase (°C above pre-industrial)	emission peak level rel to 1990	emissions in 2050 rel. to 1990	damage	mitigation	indirect	total
CBA:								
Stern discounting	520	2.4	+31%	-26%	1.1%	0.6%	0.7%	2.4%
Nordhaus discounting	725	4.0	+56%	+47%	0.9%	0.1%	0.3%	1.3%
UK Greenbook disc.	540	2.8	+35%	-13%	1.1%	0.6%	0.6%	2.3%
Nordhaus settings[a]	≥800	≥ 4.0	≥+66%	≥62%	≈1.0%	≤0.1%	≈0.3%	≤1.3%
Stern settings[b]	600	2.8	+43%	+22%	1.4%	0.4%	0.2%	1.9%
Precautionary principle:								
Stern discounting:								
Strict application[c]	530	2.9	+24%	-31%	4.4%	0.8%	0.4%	5.6%
High climate sensitivity[d]	540	3.0	+35%	-13%	1.6%	0.7%	0.3%	2.7%
High damages[e]	520	2.2	+31%	-26%	2.2%	0.9%	0.4%	3.5%
Nordhaus discounting:								
Strict application	≥790	≥5.4	≥+48%	≥+48%	≥2.3%	≤0.2%	<0.1%	≤2.5%
High climate sensitivity	≥800	≥5.5	≥+66%	≥+62%	≥0.8%	≤0.1%	<0.1%	≤0.9%
High damages	760	3.8	+63%	+57%	2.2%	0.9%	0.4%	3.5%
UK Greenbook disc.:								
Strict application	530	2.9	+24%	-31%	4.2%	1.0%	0.4%	5.7%
High climate sensitivity	600	3.8	+43%	+22%	1.7%	0.4%	0.1%	2.2%
High damages	570	2.6	+40%	+7%	2.5%	0.6%	0.2%	3.2%

[a] B2 baseline emissions, DICE (Nordhaus, 2008) mitigation cost function, climate sensitivity of 3.0, DICE (Nordhaus, 2008) damage function. Nordhaus (2008) discounting.

[b] B2 baseline emissions, FAIR mitigation costs, climate sensitivity of 3.0, PAGE mean damage function, Stern discounting.

[c] A1b baseline emissions, high mitigation costs, climate sensitivity of 4.5, PAGE (Hope, 2006) high damage function.

[d] B2 baseline emissions, high mitigation costs, climate sensitivity of 4.5, PAGE (Hope, 2006) damage function

[e] B2 baseline emissions, high mitigation costs, climate sensitivity of 3.0, PAGE (Hope, 2006) high damage function.

Tables

Table 1. FAIR 2.1 macro-economic mitigation cost estimates in 2030 and 2050 for different long-term stabilisation levels compared with the range given in IPCC (2007a)

Stabilisation levels (ppm CO_2-eq.)	**Median GDP reduction in IPCC (%)**	**Range of GDP reduction in IPCC (%)[a]**	**Range of GDP reduction in FAIR 2.1 (%)**	**Max. range IPCC/max. range FAIR**
Estimated global macro-economic costs in 2030				
590-710	0.2	-0.6 – 1.2	0.01 – 1.2	1.0
535-590	0.6	0.2 – 2.5	0.1 – 1.8	1.4
445-535	NA	<3	0.3 – 2.5	<1.2
Estimated global macro-economic costs in 2050				
590-710	0.5	-1.0 – 2.0	0.1 – 1.5	1.3
535-590	1.3	slightly neg. – 4	0.7 – 2.9	1.4
445-535	NA	<5.5	1.5 – 3.5	<1.6

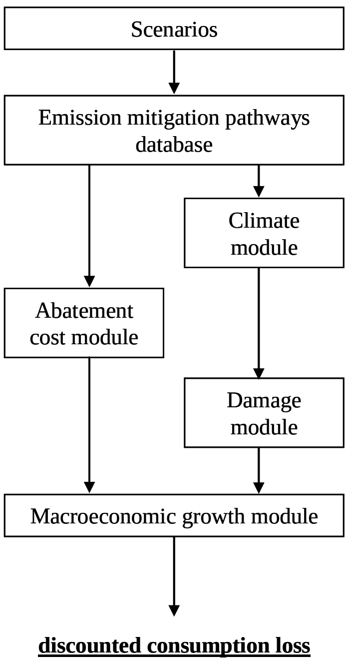
[a] The median and the 10th and 90th percentile range of the analysed data are given.

Table 2. Parameter settings of cost-benefit analyses and the precautionary principle

	Base-line	**mitigation costs**	**climate sensitivity**	**damage function**	**discounting method**
Cost-benefit analyis:					
Standard	B2	FAIR	3.0	Nordhaus	All three
Nordhaus	B2	Nordhaus	3.0	Nordhaus	Nordhaus
Stern	B2	FAIR	3.0	PAGE mean	Stern
Precautionary principle:					
Strict	A1b	FAIR * 1.5	4.5	PAGE 95th	All three
Relaxed: high climate sensitivity	B2	FAIR * 1.5	4.5	PAGE mean	All three
Relaxed: high damages	B2	FAIR * 1.5	3.0	PAGE 95th	All three

Figures

Figure 1. Schematic representation of the methodology with the main uncertainties and value judgements listed



Module	Objective	Main uncertainties and value judgements
Scenarios	Projection of economic growth and emissions until 2250	Baseline emissions
Emission mitigation pathways database	Defining greenhouse gas emission pathways and corresponding CO_2-eq. concentration levels	
Climate module	Calculating global temperature increase for each emission pathway	Climate sensitivity
Abatement cost module	Calculating global abatement costs for each emission pathway	Mitigation cost estimates
Damage module	Calculating global damages for each emission pathway	Damage estimates
Macroeconomic growth module	Calculating direct and indirect consumption loss due to abatement and damages	
discounted consumption loss	Calculating the optimal emission pathway by minimising discounted sum of consumption loss due to damages and abatement	Discounting method

Figure 2. Emission reduction pathways analysed in our study. All pathways lead to a predefined CO_2-equivalent concentration peak, indicated by a P before the concentration level

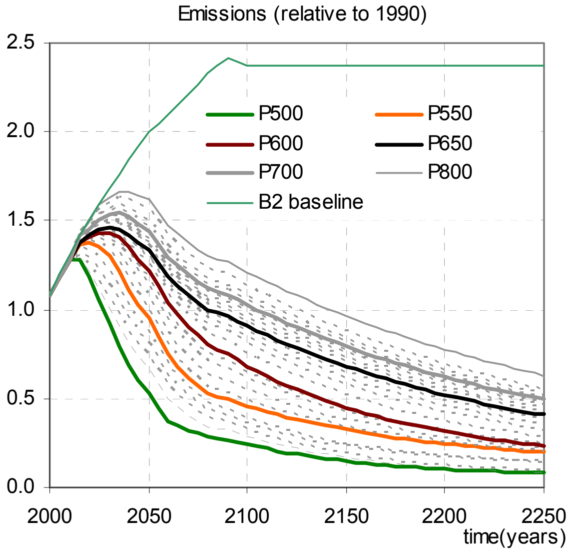


Figure 3. Direct consumption loss due to mitigation for concentrations peaking at 500, 600, 700 and 800 ppm CO_2-eq. according to FAIR 2.1 (solid lines) and DICE-2007 (dashed lines) assuming a B2 baseline

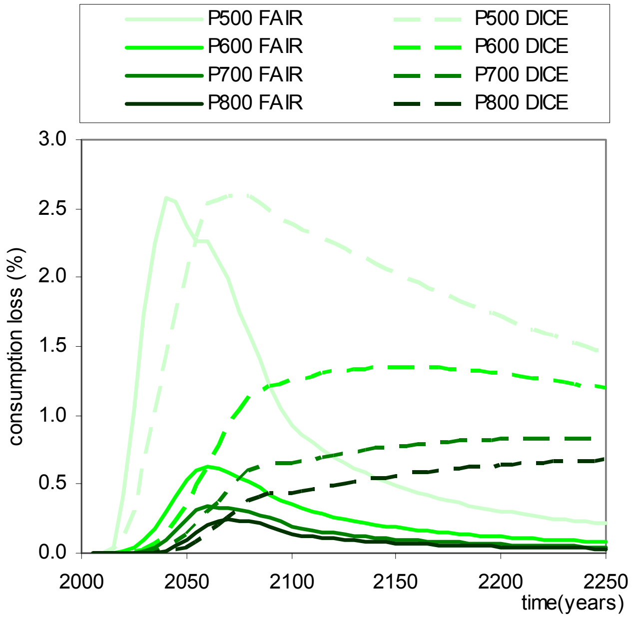


Figure 4. Consumption loss as share of GDP according to the damage functions of DICE (Nordhaus, 2008), PAGE mean and PAGE high (Hope, 2006), assuming a B2 baseline

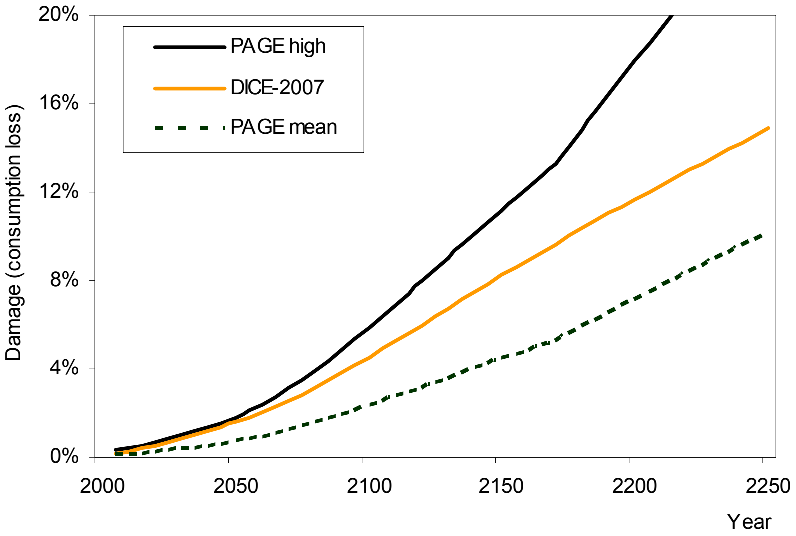


Figure 5. Discount rates over time for the three discounting methods applied in our analysis, assuming a B2 baseline

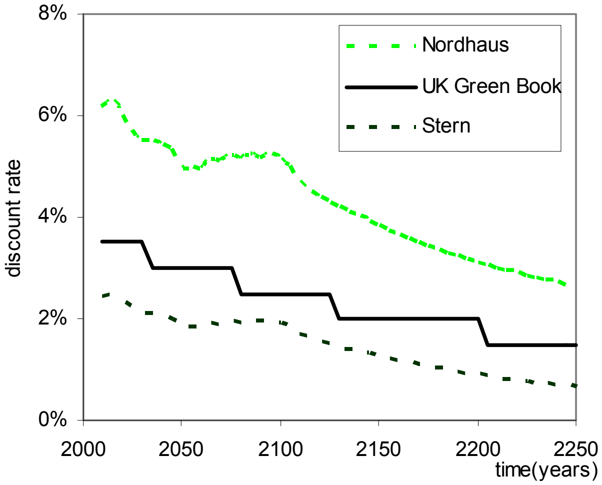


Figure 6. Global consumption loss due to damages (a), mitigation costs (b), indirect effects (c), and the sum of all (d) of the B2 baseline and of emission reduction pathways corresponding with concentrations peaking at 500, 550, 600, 650, 700 and 800 ppm CO2-eq.

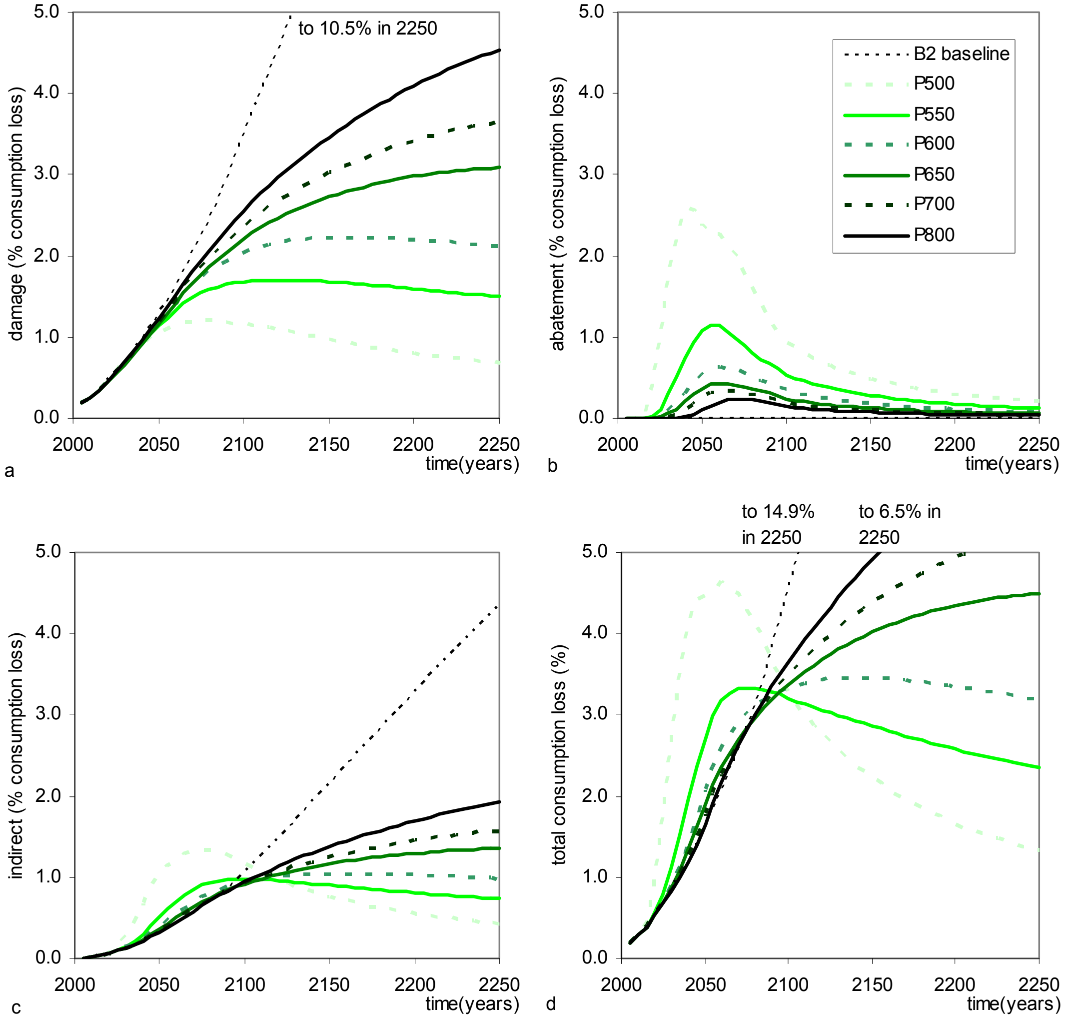


Figure 7. Discounted consumption loss due to mitigation costs, climate change damages, indirect costs, and the sum of all for different concentration peaking targets for different discounting methods and settings of the CBA

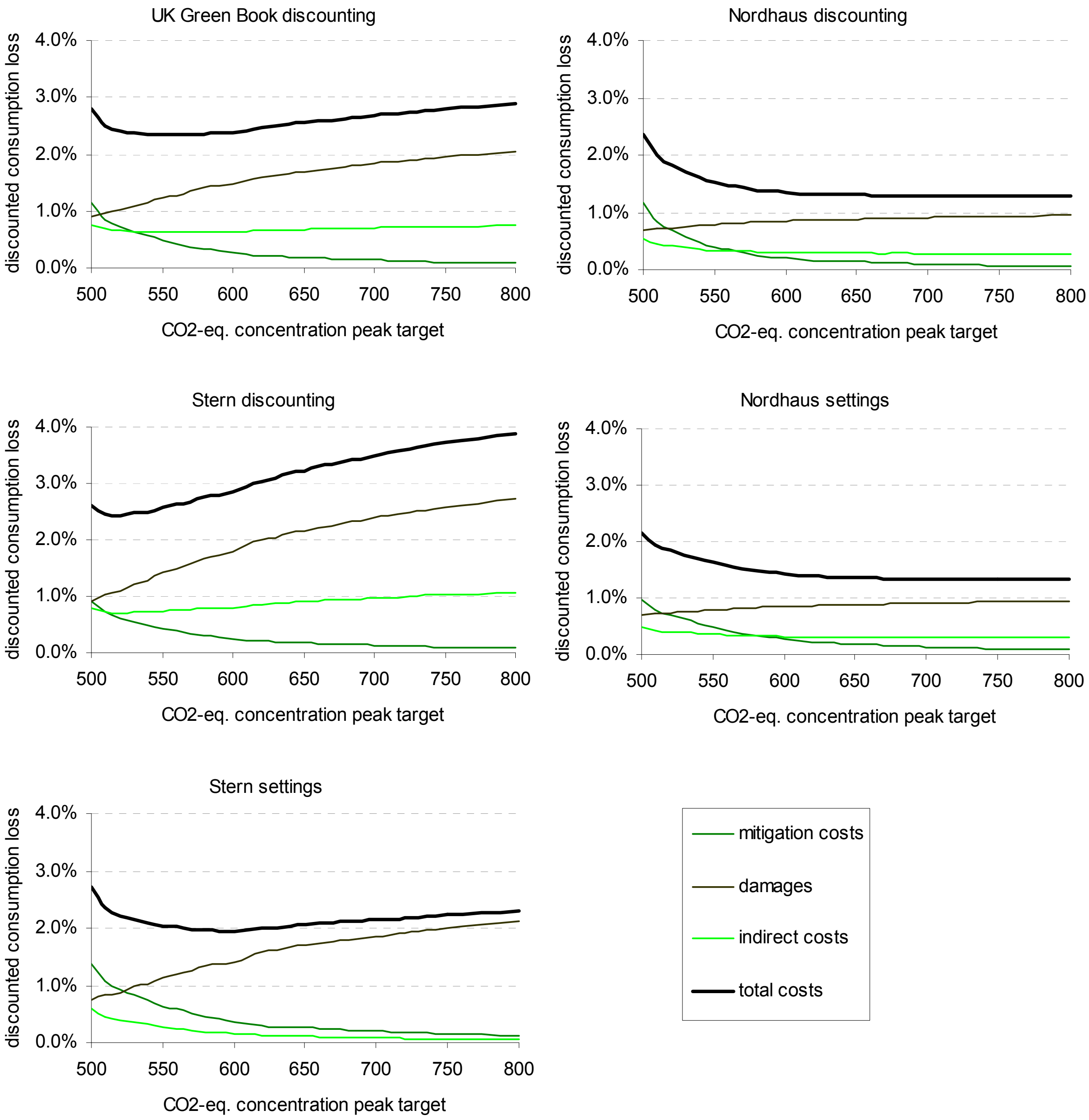


Figure 8. Total discounted consumption loss for different concentration peaking targets and discounting methods according to standard cost-benefit analysis (CBA) and the precautionary principle