Assessing Dynamic Cost-Benefit Analysis of Climate Policy: the Stern Review

Diplomarbeit

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Berlin, den 16.05.2008

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Acronyms

AOGCM: Atmosphere Ocean General Circulation Models

CO_2: Carbon Dioxide

CO_2e: Carbon Dioxide equivalent

DAI: Dangerous Antropogenic Interference

DICE: Dynamic Integrated Model of Climate and the Economy

EW: Equity Weighting

FUND: The Climate Framework for Uncertainty, Negotiation and distribution

GCM: Global Circulation models

GDP: Gross Domestic Product

GHG: Greenhouse Gases

GWP: Gross World Product

IAM: Integrated assessment model

LEWE: Large Scale Extreme Weather Event

NPV: Net present value

PAGE2002: Policy Analysis of the Greenhouse Effect 2002

PDF: Probability Distribution Function

SCD: Simple Climate Demonstrator

THC: Termohaline Circulation

UN: United Nations

WTP/A: Willingness to Pay/ to accept Payments

1. Introduction

When I first started reading the Stern Review, I was impressed by its unambiguous message: *Climate change will most likely have very severe consequences in the future, and it leaves us little time to react.* Upon reading the NORDHAUS (2006) critique, my impression was then that the discounting scheme was the core reason for STERN's alarming results. Therefore, the original focus of the present work was directed at discounting future utility. However, the more information I found, the more I got the impression that the disagreement between STERN and his critics is more complex than I had suspected and that discounting is only one important aspect of it. In accordance with my supervisors, Ottmar EDENHOFER and Georg MERAN, I widened the view of my work in order to capture a more complete range of controversial aspects within economic climate policy assessment. After finding ever more relevant aspects, in the end, narrowing down the scope of this work was probably just as important as widening it in the in the first place.

1.1. Stern's Approach to Climate Policy Assessment

Climate change is a long term problem, as what we do today will determine what happens many years from now. To assess it a dynamic comparison of future outcomes and today's actions is indispensable. This comparison is particularly difficult as climate change affects all important spheres of life and is related to considerable risk and uncertainty (Throughout this work I will not distinguish between uncertainty and risk as for instance WEITZMAN 2007a, b; 2008 does. Although a relevant distinction, for the purpose here it is of secondary importance). Accordingly when economists try such a comparison, aiming to find efficient policy responses to climate change by hand of dynamic Cost Benefit Analysis (CBA), they have to assess of extremely different impact types that occur unevenly distributed over time and space.

In a narrow sense, a CBA of climate change would imply to compare marginal costs of GHG abatement with marginal damages caused by emissions. This would then deliver an optimal emissions trajectory and thus a goal for climate policy. The Stern Review doesn't follow this approach, arguing that estimates of marginal damages from carbon dioxide (CO_2) are not adequate. There are two core reasons for that; the decisions for different *climate policy paths* are *non-marginal,* meaning that they strongly influence the marginal cost of CO_2. Further a marginal approach is not apt to cover the large uncertainties that are related to the effect that emissions have on the climate system.

Instead of a marginal comparison, STERN does a two step CBA. First he analyses the impact risks caused by an imaginary *no-climate policy* business as usual (BAU) path using an Integrated Assessment Model (PAGE2002). Then, as a second step, modelled cost of climate policy paths that limit greenhouse gas (GHG) concentrations in the atmosphere are presented (concentrations measured in CO_2 equivalents – hereafter CO_2e. See STERN 2008 for an explanation of the choice of concentration levels rather than other possible scales as unit for climate policy targets). Finally, the costs that different policy paths are expected to cause are compared to the amount of avoided impacts (in reference to BAU impacts). Accounting for uncertainties involved, STERN identifies a range of recommended GHG concentration targets. The Stern Review is not limited to the use of economic models; it also gives many static bottom-up estimates that back up the main findings. These will be referred to in my treatment of the Review in section 3.

1.2. Subject and Structure of this Work

The novelty of STERN's modelling results is that they justify early and strong climate policy (i.e. mitigation of GHG emission) on economic grounds. This is contrary to the often found *climate policy ramp,* which suggests that little mitigation efforts now and stronger action in the future is economically favourable. Accordingly, the main question of this work is if the Review's objection of the *climate policy ramp* is defensible.

In order to do that, I will analyse the way STERN aggregates and assesses climate related data in economic models. This particularly involves focussing on comprehensiveness, modelling technique and ethical judgements involved. The aim of this study is not to examine the scientific fundament of the Review, or to assess the way the Review's authors interpreted or applied scientific data. It is assumed that the Review is based on the latest and best available information and that STERN's team did all to avoid factual errors.

This work is structured as follows: I will start by explaining the state of the art in modelling for climate policy assessment and derive *good practice* criteria for all central issues a CBA of climate policy has to consider (section 2). This shall build a frame for debating the Review. Having built this frame, the next section will give a detailed explanation and discussion of how STERN addresses these individual issues. For that purpose, I will also consider several other economists' critiques of the Review. In a summary, I will then critically assess

STERN's results. A short outlook on future development of CBA of climate policy concludes the study.

2. Assessment Criteria for CBA of Climate Policy

In this section I will discuss what requirements an adequate dynamic CBA approach for climate policy should fulfil. Mainly three categories serve as a guideline here:

- Methodology (how are the models designed and what data is employed?)
- Ethics (are ethical concerns well accounted for?)
- Comprehensiveness (are all important climate change related processes included?).

Each section will briefly present the respective state of the art in scientific research, give examples of modelling approaches used in CBA and will conclude with a discussion of assessment criteria in terms of *good practice*. Problematic aspects of CBA will also be addressed. The aim of this part is to set up a frame to evaluate different CBA approaches and generate critical questions about CBA as such in the climate context.

As a first step in section 2.1, the use of projections and external data is introduced. In section 2.2, the latest scientific results that estimate climate sensitivity are discussed. Next, section 2.3 describes the contemporary status of scientific research in climate impact assessment. The counterpart of investigating the impact of climate change, estimating the cost of mitigating or of adapting to it, is discussed in section 2.4. Aspects of inter- and intra-generational aggregation and justice are subject of section 2.5.

Within all sections the aim is not to exactly determine the importance of any aspect in monetary terms. Rather, specific quantifications are offered to help expound upon each aspect's relative importance.

2.1. Projecting Future Trends- the SRES Scenarios

The main driving forces of greenhouse gas (GHG) emissions are population trends, socio economic development and technological change. Whenever models are used for climate policy analysis, these driving forces have to be estimated for the future. All models named in this work use supplemental external data to do that, e.g. they use external projections of gross world product (GWP) growth and population trends, if not as direct inputs then at least to for their calibration (typical reference sources are the World Bank or the United Nations (U.N.) estimates, see WEYANT 2000:9).

The external data is important for a model's *baseline case* (also known as the *base* or *business-as-usual* case). The higher the projected baseline emissions, the higher the necessary emission savings or *mitigation gap* (and thus the mitigation costs) to reach a fixed climate goal; the higher the projected (baseline) impacts, the higher the potential benefit of climate control. Comparing different models in a meta-analysis shows that, in fact, baseline cases differ widely (e.g. WEYANT 2000, EDENHOFER, LESSMANN, KEMFERT, GRUBB and KÖHLER 2006). Within the Innovation Modelling Comparison Project (IMCP) the authors state:

> *"It is known that the business-as-usual scenario has strong impact when evaluating the consequences of climate policies: assuming lower economic growth and therefore lower CO_2 -emissions implies that climate protection poses a lesser challenge to the economy"* (EDENHOFER, LESSMANN, KEMFERT, GRUBB AND KÖHLER 2006:69)

Because of different baselines, models are often hard to compare, and it is difficult to isolate a particular aspect's effect on models' results. One effort to address this problem is the SRES (Special Report on Emissions Scenarios, Intergovernmental Panel on Climate Change -IPCC- 2000), in which different scenarios of future development are developed (another such intent is the Common Poles Image- CPI described in V.VUREN ET.AL. 2003). These scenarios are intended to establish a common data reference for modellers.

In the SRES there are four basic *story lines* (A1, A2, B1, B2) differentiated. Each of them is further split up into sub-scenarios. Together the 40 scenarios „*cover a wide range of the main demographic, economic, and technological driving forces of GHG and sulphur emissions and are representative of the literature*" (IPCC 2000:3). The scenarios calculate future GWP and population development, GHG emissions, energy output composition, and carbon intensity. All 40 scenarios project a future that is much more affluent than the present (by 2100 GDP is projected to be between 10 and 26 times 1990's GDP, IPCC 2000:13). Mostly they assume incomes to converge worldwide. In terms of future population they differ considerably.

A lot of models use the SRES scenarios as calibration references or as sources of external data (e.g. DICE-99, PAGE2002 or FUND, see WARREN ET AL.2006), thereby increasing their comparability. Using different SRES scenarios further has the advantage that the solidness of a model's results can be check against different future developments by using various scenarios. This way part of the unavoidable uncertainty related to future trends can be accounted for. Also the effect of a specific measure can be checked in different scenarios to identify its influence on the outcome (IPCC 2000:11).

As common reference the SRES scenarios are also helpful judging outcomes of different studies. Knowing the underlying scenario the results are more transparent. Also instead of discussing each modeller's projections separately a discussion about SRES in general can be led (as in TOL and V. VUREN 2005).

Nevertheless, even with the wide range of different scenarios, predicting complex future trends until 2100 remains a heroic task and as IPCC (2000:3) state, "*The possibility that any single emissions path will occur as described in scenarios is highly uncertain*". For instance, modelling GWP development is already highly difficult on the short run; SANSTAD and GREENING 2005 name a 5 to 10 years range for GWP predictions by economic models, similarly population growth is usually forecasted only until 2050 (see U.N. http://www.un.org/esa/population/pubsarchive/chart/3.pdf, last visit 8.5.2008).

Furthermore many scientists doubt the plausibility of long-term continued economic prosperity and converging incomes as SRES predict. They argue that, besides the difficulty of predicting political factors (e.g. wars or other major political developments), environmental sustainability (which is in fact closely related to climate change) can become a major determent to the economy's ability to grow. They stress the dependence of past economic growth on finite natural resources. As a result they predict a *plateauing* of growth or even fear a *crash of civilization* due to overuse of natural resources (SHERWOOD, 2007:210, LEIST 2005:40). Without going into further detail, this suggests that forecasting key parameters of CBA into the far future is necessarily speculative.

Nevertheless, common references such as the SRES are recommendable as input for modelling; they form a transparent base of projections that improves comparability and transparency. To consider uncertainty about future developments it is recommendable to use different scenarios in a CBA.

2.2. Climate Sensitivity

Possibly the most important physical relation when calculating costs and benefits of climate policy is between GHG emissions and the consequent change of global average temperatures- this is called climate sensitivity. Climate sensitivity is usually referred to as the equilibrium temperature change for a doubling of GHG concentrations (in CO_2 equivalents) – so called *equilibrium climate sensitivity*. The IPCC defines it as follows: *"the annual mean global* *surface temperature following a doubling of the atmospheric equivalent carbon dioxide concentration*" (IPCC 2007:943).

The better this relation is understood the better consequences of emissions can be estimated. Unlfortunlately, climate sensitivity is all but precisely predictable as many processes that determine it are not sufficiently understood yet (e.g. feedbacks in the climate system caused by GHG emissions; see section 2.3.2 or the role of aerosols that might have prevented an important share of warming so far; see SCHNEIDER and MASTREANDREA 2004).

There are several methods to estimate climate sensitivity; it can be derived from historical temperature developments (e.g. from paleoclimatic data) alternatively Global Circulation Models (GCM) and Atmosphere Ocean General Circulation Models (AOGCM) can be used. Expert surveys are also a possibility to get an impression on possible values (IPCC 2007 chapters 9 and 10 or SCHNEIDER and MASTRANDREA 2004 for more details).

Until now equilibrium climate sensitivity has been estimated to lie between 1.5-4-5C° (IPCC 2007:800, the precedent Third Assessment Report -TAR- reported the same range). In this sense, there have not been significant changes since the TAR (SCHNEIDER and MASTRANDREA 2004 list a number of studies finding wider ranges). However, while in the TAR the range of temperatures could not be assigned with probabilities, the FAR reports probability distributions for the level of climate sensitivity:

> "*Basing our assessment on a combination of several independent lines of evidence, […] we conclude that the […] 'equilibrium climate sensitivity', is likely to lie in the range 2°C to 4.5°C, with a most likely value of about 3°C. Equilibrium climate sensitivity is very likely larger than 1.5°C. For fundamental physical reasons as well as data limitations, values substantially higher than 4.5°C still cannot be excluded, but agreement with observations and proxy data is generally worse for those high values than for values in the 2°C to 4.5°C range.*" (IPCC 2007:749, very likely corresponds to a 90%-, likely to a 66% probability range)

Accordingly, the IPCC sees a relevant probability of climate sensitivity values (*substantially*) higher than 4.5C°. This results in a long, *fat* - tailed probability distribution function of climate sensitivity (PDF- see IPCC 2007:798 for illustrated climate sensitivity PDFs); referring to WEITZMAN (2008:3) a PDF is here defined as *fat*-tailed when the tail probability approaches zero more slowly than exponentially. WEITZMAN (2008) argues that the way in which these fat-tailed PDFs are dealt with in CBA determines to a large degree the outcome of climate policy recommendations from economic modelling. In any case, a CBA has to account for the wide climate sensitivity range.

2.3. Assessment of Climate Impacts

Global warming will have manifold impacts on both human and natural systems. An overview from the representative literature (e.g. TOL and FANKENHAUSER 1998 :64, NORDHAUS and BOYER 1999 ch. 4, STERN 2006 ch. 6, WARREN ET AL. 2006) shows impacts predicted for agriculture, energy, coastal zones (sea level rise), forestry, fishery, water systems, vegetation, vector borne diseases, heat and cold stress, air pollution, migration, tropical cyclones, amenity, river floods, tourism, mining, transport and construction. There is also growing agreement about the risk of *catastrophic events* caused by climate change, e.g. weakening of the Thermohaline Current (THC). In addition, an increased frequency and intensity of *extreme weather* events due to global warming is predicted. Further, scientists consider possible amplifying feedbacks in the climate system, e.g. additional methane emissions from thawing permafrost.

To handle impact types in a CBA, it is practical to categorise them in groups. In the IAM PAGE2002, impacts are split into market and non-market sectors, adding an extra category for "*large scale discontinuities*"(HOPE 2006, equivalent to what I defined as catastrophic events). In DICE-99 (NORDHAUS and BOYER 1999 ch.4), sectors such as agriculture or health are considered individually, and a residual category captures the relevant rest. Such aggregated categories are helpful and do not necessarily imply defects in totality of damage representation. Nevertheless, it is unlikely that any model can cover all climate impacts (TOL and FANKEHAUSER 1998).

In the following paragraphs, I will give an overview of the status of climate impact research. To this end, I distinguish two impact groups: *standard impacts*, which are relatively well understood (orientated on TOL 2002a, b) and connected to manageable levels of uncertainty, and *uncertain impacts*, namely *amplifying feedbacks*, *catastrophic events* and *extreme weather events*. The latter are less investigated, their occurrence is uncertain but they potentially cause severe impacts.

Besides discussing these two damage categories, impact assessment has the difficult task to value non-monetary impacts (i.e. impacts on human health, ecosystems etc.) in monetary terms. This problem is discussed in section 2.3.3. Temporal and regional aggregation of impacts is discussed separately in section 2.5. Section 2.6 will tie the findings together in conclusion.

2.3.1. Standard Impacts

There is a series of relatively well-studied impacts, characterised by a lower level of uncertainty about possible outcomes. Typically, these impacts refer to economic activities (agriculture, fisheries and forestry), consequences of sea-level rise on human settlements and coastal zones, influence on human health, water resources, energy consumption and ecosystems (see TOL 2002a, b or WEYANT 2000 for overviews). Many previous CBAs of climate change focussed on these impacts only, the results of which gave little reason for introducing and enforcing strict climate policy. Nevertheless, such studies tended towards higher damages in developing countries, due to their higher vulnerability. Consequently, aspects of intra-generational justice had high relevance for the discussion of climate change from the beginning (see sections 2.3.3 and 2.5.1). Standard impacts' estimates are usually based on specific studies for one sector; thus studies as a source of information will be discussed in the following paragraph.

As climate change's impacts are best understood for western industrialised countries (The U.S. and Europe), studies are often based on estimates for these regions. It is common practice to extrapolate EU or U.S. results to the rest of the world. This practice results in a limited representation and understanding of impacts in other world regions. (see e.g. WARREN ET AL. 2006:3-4, or NORDAHUS and BOYER 2000 ch.4). One possibility to avoid this deficiency is to only rely on studies that are globally comprehensive, as TOL (2002a) suggests. However this implies that impacts for which adequate data is lacking will not be considered.

To have a common benchmark projection, most studies calculate impacts for an equilibrium doubling of atmospheric CO_2e concentrations in today's conditions. This implies calculating with a range of climate change as that of climate sensitivity as discussed in section 2.2. The results then are added, sector by sector, culminating in a projected overall impact. As climate change happens gradually and can go beyond doubling concentrations, the so-called *$2xCO_2$ scenarios* have to be extrapolated into a continuous estimation. The extrapolation from static to continuous depiction is obtained using statistical methods assuming correlations e.g. between GDP and vulnerability, usually orientated on empirical findings (TOL 2002b describes specific extrapolation methods for different impact sectors in detail). Nevertheless, even including such correlations, combining studies' results sector by sector cannot account for interactions and repercussions between impacts, e.g. rising levels of pests may aggravate declines in agricultural production caused by heat or changes in water availability (WARREN ET. AL. 2006:5, STERN 2006:152).

If available for one sector, several studies' results can be averaged to broaden the scientific base. Further, to ensure the credibility of CBAs, studies should represent the state or the art in research and their results should be peer-reviewed. However, such up-to-date studies are not always available; most impact modelling relies on studies that date from before 2000 (WARREN ET. AL. 2006:3).

To summarise, besides considering all well studied forms of impacts, a good CBA should use up-to-date, peer-reviewed literature that is globally representative (at least data extrapolation from regional to global should be transparent). It seems preferable to base sectoral estimates on more than one study, if available. Understanding the interactions between different types of impacts is a field in need of further investigation.

2.3.2. Uncertain Impacts

This section will address processes that increase climate impact estimates or further accelerate climate change especially at higher levels of warming; *amplifying feedbacks, catastrophic events* and *extreme weather events*.

Both feedbacks and catastrophic events occur when a climate related sub-system (due to strong warming) passes a *tipping point* and alters to a new equilibrium. Such effects are nonlinear and can be irreversible (even when radiation levels are brought back to the former level the equilibrium may not switch backwards). The website of the Potsdam Institute for Climate Research (PIK) gives an overview of the most prominent such effects www.pik-potsdam.de/infothek/kipp-prozesse, last visit 8.5.2008). To roughly distinguish between the two, I argue that the former predominantly cause indirect effects, while the latter are characterised by direct negative impacts.

Amplifying feedbacks are triggered by climate change and they reinforce it with more GHG-emissions or more heat absorption of the earth's surface. For instance, warming induced melting of permafrost can cause large extra methane emissions, loss of snow covers or ice shields lowers the earth's albedo (which means that more heat remains in the atmosphere), collapses of great carbon sinks such as the Amazon Rain Forest or reduced carbon absorptive capacity of the oceans (see STERN 2008:14) mean more CO_2 in the atmosphere. Scientific research on these processes is still in an early stage. They can be integrated in models in the form of extra GHG emissions (as in the Stern Review). This way, they mainly amplify the effect of human GHG emissions and thus indirectly cause more impacts. However, feedback effects also have direct negative impacts, as argued below in this section.

Catastrophic events cause direct negative impacts. They are particularly harmful as they occur rapidly leaving little time to adapt to changes. One of the most prominent catastrophic risks is the shutdown or weakening of the THC (Thermohaline Circulation) – which could cause temperatures in north western Europe to fall by several degrees (the THC works as a *heating system* for northwest Europe, transferring warm water from the Equator to Polar Regions). SCHNEIDER and MASTRANDREA (2001) combine an older version of the DICE model (a version yet without consideration of catastrophic events) with a simple climate demonstrator (SCD) that simulates the THC; they argue that, by altering DICE's damage function with an exponent determined by the SCD, results

> "*indicate that the incorporation of large non-linear damages—the 10–25% THC damage cases [% refer to GDP]—even if […] delayed by a century or more, significantly increases (by a factor of several) present optimal carbon taxes, using conventional discounting with PRTPs [pure rate of time preference] of 1.5–3%. Furthermore, if the model uses a low PRTP — or a hyperbolic discounting function — present "optimal" carbon taxes […] are increased by an order of magnitude relative to conventional IAMs"* (p.443).

As another example, focussing on vegetable carbon sinks particularly in Africa, South Asia, and Australia but also the Amazon, SCHNEIDER (2004) argues that changes of vegetation covers can induce alterations of precipitation schemes and lead to catastrophic consequences such as changing monsoon patterns (upon which the food systems of millions of people depend). In this instance, the line between catastrophic events and feedback effects is not clear cut.

NORDHAUS and BOYER (1999, ch.4) include catastrophic risks in DICE-99, although they state that the particular phenomena "*have not been adequately studied*" and that "*there are no established methodologies for valuing catastrophic risks*". They use an expert survey dating from 1994, asking for the likelihood of catastrophic events (costing >25% of overall GDP) in case of strong temperature increases (3 C° to 6 C° until 2090 and 2165 respectively). Because of post-1994 evidence pointing towards even more rapidly increasing likelihood, particularly of THC shutdown, they further increased the survey's estimates. The authors conclude that of all considered impacts, catastrophic events dominate their impact values "*the major concerns are the potentially catastrophic impacts. […] the estimated catastrophic costs are estimated to be twice as large as all other impacts combined for a 2½ ºC warming*." (NORDHAUS and BOYER 1999 chapter 4:25)

SCHNEIDER and MASTRANDREA (2001) stress that the impact of catastrophic risk in models depends largely on the assumed discount rate (DR) and the projected impact of the event. Also, when a model uses certainty equivalent damage-estimates and assumes risk aversion, due to strong negative impact and low probability, catastrophic events will be valued higher than the mere product of probability and predicted damage (SCHNEIDER 2004). Altogether, the uncertain occurrence probability and the possible range of damage severity coupled with set factors like the DR and risk aversion leaves a wide range for valuation of catastrophic risks.

Until now, economic modelling of catastrophic risk's impacts is in its infancy, and the approach taken in DICE-99 is a good example for this; it is strongly generalised, all catastrophic risks are aggregated in one category, and their specific impact conditions and probabilities of occurrence are unaccounted for. On the other hand, studies such as those of SCHNEIDER and MASTRANDREA (2001) exclusively illustrate the risk of one catastrophic event. However, despite their different approaches, both cited examples suggest that including catastrophic risks in impact assessment has major influence on impact estimates.

The second impact type, for this section, is the climate induced increment of frequency and intensity of *extreme weather events,* such as storms, floods, droughts or heat waves. WARREN ET. AL.(2006:5) compare damage assessments offered by the most representative IAM's and come to the conclusion that:

> "*Most models do not take into account the influences of extreme weather events which are likely to contribute very strongly to economic impacts; […], albeit that literature on potential changes in the frequency and intensity extreme events is in its infancy*"

In a recent paper, HALLAGATTE (2007) develops a framework to incorporate extreme events, which he calls large scale extreme events (LEWE), into a formal model frame. He specifies that the damage of such an event has to be at least 0.1% of the European GDP, or O.8 G€, with the monthly occurrence probability set at 0.06. Based on several scientific studies, HALLEGATTE argues that, due to climate change, economic costs of such events increase. Particularly, he suggests that heat waves similar to those experienced across Europe in 2003 could become normality, as well as more flooding due to higher yearly precipitation in the U.S. and Europe. Additionally, intense tropical storms in the U.S. may become even more disastrous due to trajectory shifts into areas that are not prepared (thus more vulnerable). There is no overall prediction of the damage that these processes are likely to cause, but some tentative estimates indicate that they are very relevant (e.g. due to a doubling of CO_2e concentrations, flood and hurricane damages in the U.S. are predicted to increase by 100-300%, HALLEGATTE 2007:333).

HALLEGATTE further argues that the impact of extreme events cannot be limited to its immediate costs; rather the economic conditions and the capacity to reconstruct the original state represent a further determining factor. The idea behind this is compelling; when a sufficiently big impact occurs, a society has to rebuild its productive capacity, so the impact turns the system into a disequilibrium influencing productivity for some period. To measure this overall impact the author introduces the "Economic Amplification Ratio" (EAR); as ratio of an event's overall production loss and its direct costs. If the capacity to rebuild is more than sufficient, and thus reconstruction happens quickly, the ratio is small. On the other hand, if this capacity is low because the country is poor or there are technical or organisational constraints for short-term reconstruction, the ratio is higher. The impact can even cause a bifurcation of economic development leading to dramatic GDP losses. This risk is greater corresponding to the intensity of frequency of such events. HALLEGATTE (2007:339) concludes that "*assessing future damages requires both taking into account the distribution of extreme events instead of just their average cost, and making explicit assumptions about the organization of future economies.*"

In summary, both effects presented in this section are potentially very significant and difficult to include in economic models. Catastrophic risks are characterised by large uncertainties about effects and occurrence probability, which makes them hard to value in CBAs. However, it seems clear that higher GHG emissions contribute to higher catastrophic risks, causing stricter optimal climate policy when catastrophic events are accounted for. In contrast to catastrophic events, extreme weather events have already occurred in the recent past and thus their consequences can be predicted more adequately. However, their link with climate change and the destabilising potential they have for economies appear to be important fields of research based on the information offered in the above paragraphs.

In conclusion, a thorough assessment of possible climate change impacts cannot omit either of the two impacts, making it necessary for a CBA to find a way of including them. Otherwise, results cannot be regarded as comprehensive.

2.3.3. Monetising Metrics - The WTP Approach

A considerable share of climate impacts will affect fields that are typically non-monetary, for instance impacts on human health or the environment. For a CBA such impacts have to be expressed in monetary terms. Notwithstanding the ethical controversies (e.g.. when assigning a monetary value to a decrease in human life expectancy or the distinction of biological species), this task is also methodologically challenging- Can a monetary value satisfactory capture the worth of its subject- and if not what does that mean?

The most common monetising method for a CBAs is to find out peoples' monetary valuation for a non-monetary good by "willingness to pay" (WTP) approaches. There are several such techniques; they can either be based on revealed preferences (hedonic pricing methods, travel cost method or the avoided cost approach) or hypothetical markets (e.g., the contingent valuation method/CVM). These approaches are presented here in brief (see HANLEY 1993 for a more detailed discussion of each technique's shortcomings and advantages):

Hedonic pricing measures the value of say *air quality* or *quietness* by comparing, for example, the price difference of houses located in an area with high air quality and/or less noise with similar houses (comparable in other aspects) located in noisy and/or polluted areas. The travel cost method is mostly used to estimate the value of wilderness or recreational areas by measuring how much people invest to get to the place, while the avoided cost approach (in the climate change context) is useful when looking at defensive measures taken to avoid damage or negative influences (e.g. floods or noise). However, only a small number of climate change impacts are candidates for revealed preference evaluation and those where data is existent for many countries are even more limited.

Other impacts can be evaluated by CVM. In this approach people are surveyed to determine their willingness to pay for an environmental improvement, or what they would have to be paid to be willing to accept the loss of some aspect of environmental quality they already enjoy- the WTA "willingness to accept payment" approach. Alternatively, laboratory experiments are conducted where subjects are put into an artificial market where a non-market good is actually traded, and behaviour is observed in the search for underlying preferences (JACOBY 2004, the setting of WTA/WTP experiments have relevant influence on results, see HANLEY 1993 or HOROWITZ and MC CONNEL 2002 for more details).

WTP-approaches are very practical and useful methods to obtain money equivalent values for non-monetary goods; however, important objections against its validity exist. First of all, there are arguments against its fairness; WTP depends largely on people's *ability* to pay.

Poorer people can pay less (no to forget that future generations cannot express any WTP). Accordingly, the statistical value of a life in a rich country is higher than in a poor country. This problematic outcome was discussed when it appeared in the IPCC's Second Assessment Report (SAR- the respective study used was FANKHAUSER 1997, AZAR 1998 outlines the controversy). Similarly, NORDHAUS and BOYER (1999) estimate the value of a lost year of life (YLL) as two times the regional GDP per capita and year. Using equity weights to account for the higher relative value or utility of the dollar for different GDP levels can ease the problem (AZAR 1998:305 equity weighting is discussed in section 2.5.1).

In any case, WTP leaves the question open as regards whether or not a value somebody assigns to something adequately represents its true value (see SCHNEIDER and LANE 2005, LEIST 2005). When surveying the WTP of individuals for the preservation of a wilderness area, the result represents the valuations of individuals as consumers. As many environmental goods can be regarded as public goods, the same people's valuations as citizens could well differ. Generally, HANLEY (1993) sees a difference between what we are observed to do as consumers buying and selling in markets and what we want to happen as citizens, e.g. considering the interests of future generations, which is particularly relevant in the context of irreversible impacts. Further WTP approaches have difficulties representing the whole value of complex ecosystems in, for example, preserving watersheds, combating soil erosion, buffering sea level rise, pollinating crops, providing new medicines, etc. (WARREN ET. AL. 2006, HANLEY 1993).

Despite the above shortcomings, it is hard to imagine a CBA without using WTP approaches. As assessment criteria, I think that it is important that equity distortions are considered when WTP results are used and that the surveyed subjects have a reasonable understanding of what is at stake, illustrating not only the necessity of a better understanding of our environment, but also the importance of a public that is well-informed about climate change.

2.4. Avoiding Climate Change's Negative Impacts

There are two main options to address climate change and avoid its negative impacts: To arrange with its consequences by *adaptation* and to limit GHG emissions by *mitigation*. Both will alleviate climate change's negative consequences. In this section, modelling of both options will be elucidated (sections 2.4.1 and 2.4.2) and to conclude I will conduct a short discussion on their different characteristics (section 2.4.3).

2.4.1. Adaptation

Adaptation refers to adjustments in ecological or socio-economic systems in response to actual or expected climate changes and their impacts. It means changes in processes, practices and structures to moderate potential damages or to benefit from opportunities associated with climate change. Examples of adaptation are the building of dykes, the changing of crop types, or vaccinations. Adaptation can be private or public, anticipatory or reactive (DE BRUIN, DELLINK and TOL 2007). Additionally to mere adaptation costs, usually some cost of adjustment will occur, these are defined as "*the extra costs incurred relative to the (counterfactual) case of instantly adapting to changed circumstances*" (KELLY ET. AL. 2005:469).

Integrated assessment models mostly ignore adaptation; or at most consider it implicitly in the calibration process reflecting the adaptation assumptions of the underlying impact studies (WARREN ET. AL. 2006; DE BRUIN, DELLINK and TOL 2007). Adaptation is thus treated exogenously; modelled policy scenarios have no influence. Instead, the level of optimism exhibited by the author's assumptions on the adaptive behaviour of actors (individuals or governments) determines the degree of adaptation and its effectiveness (SCHNEIDER 1997:238ff accurately describes that aspect, also STERN 2006:61). PAGE2002 is no real exception in that, even though adaptation is a variable, its value (increasing the level where temperature increases have negative consequences) is exogenously set by the modeller.

Some adaptation will happen autonomously as climate changes; however, to what extent depends on the knowledge about changes, as well as on resources available to invest in adaptive measures (WEYANT 2000:25). In this regard, policy has an important role to play as "*the public lacks information on the effects of climate change and adaptation options and adaptation often entails big scale projects that the market cannot provide*" (DE BRUIN, DELLINK and TOL 2007:3). WARREN ET. AL. (2006:72) further summarise:

> "*Research has also drawn attention to the importance of actors at different levels (institutions, communities, individuals) in promoting/constraining adaptation (e.g. through knowledge transfer, support for measures and practices) […]. Some acknowledgement of their role [in IAM] would be helpful*"

This suggests that adaptation is an important policy option and that it should be depicted explicitly and with more detail in models.

Treating adaptation exogenously yet leads to another possibly important inaccuracy; it does not account for the interdependence (trade-offs or synergies) between mitigation and adaptation policy; models focus on the trade-off between damages due to climate change and mitigation costs only (DE BRUIN, DELLINK and TOL 2007:2).

In a recent approach, DE BRUIN, DELLINK and TOL (2007) add adaptation as a policy variable to the IAM DICE-99. Using the regular model's version, they add two terms to the damage function; one is a fraction subtracted from overall damage (limited to 80% of damages) and one is added to damage, accounting for adaptation costs. Marginal costs of adaptation are assumed to increase due to the fact that cheaper measures are exhausted eventually. The model is calibrated to yield the same results as the original model. Its results qualitatively show that adaptation pays particularly in the early periods, while mitigation has effects in the farer future (due to climate systems' inertia). Additionally, adaptation lowers the optimal level of mitigation, as mitigation can avoid fewer damages when adaptation takes place.

While this approach focuses quite strongly on trade offs between adaptation and mitigation, which I regard as doubtful (in section 2.4.3 and 3.2.2 it is argued that they can be supplemental as well), I think the important step taken is the explicit inclusion of adaptation into the model. This makes modelling more realistic and informative. However, the basis for estimating and modelling adaptation costs have to be improved as WILBANKS and SATAHYE (2007:959) indicate.

2.4.2. Mitigation

Orientating oneself on the concept of the *Kaya Identity* (named after the Japanese energy economist Yoichi KAYA), there are three main dynamics that determine the level of CO_2 emissions: overall output, energy intensity of output and carbon intensity of energy production (EDENHOFER, LESSMANN, KEMFERT, GRUBB and KÖHLER, 2007:82). Accordingly, cutbacks in economic output and lowering both the carbon intensity of energy generation and the energy intensity of production have to be considered when modelling mitigation of CO_2 emissions.

While cutbacks in output are the last resort when the other two mechanisms are insufficient to reach a certain climate target, the latter two are complex processes, closely related to technological change (TC). Modelling TC has ultimately progressed considerably. This section describes the progress and thereby gives an overview of the most important factors to be modelled. Thereupon, assessment criteria for mitigation modelling are developed.

Previously, many IAM focussed on one single factor to represent TC: the declining carbon intensity of economic output, expressed as the ratio of carbon emissions per unit GDP. This process - called "Autonomous Energy Efficiency Improvement" (AEEI) - was assumed to happen at a constant or declining rate based on empirical data (as for instance in DICE-99). The decoupling of GDP growth and energy consumption is, in this concept, taken as a merely external process (KELLY and KOLSTAD 1998).

There are many reasons why exogenous treatment of technological change, using the AEEI approach is not convincing. Neither the important influence that (climate) policy and relative prices have on innovations, nor the development process of low carbon energy alternatives, is represented. These dynamics can only be included when models treat TC as an endogenous process.

TC is largely driven by learning-by-doing (LBD) and research and development (R&D) in the private and public sectors (GRUBB, CARRARO and SCHELLNHUBER 2006). LBD in the energy sector means that initially high per unit costs of a new energy type are driven down when installed capacities increase. This can be modelled using learning curves whose slope depends on learning rates (the rate refers to the proportion of price decrease when installed capacity is doubled). As renewable, low-carbon energies are still installed at relatively low capacity levels, LBD implies considerable potential price improvement (HEDENUS, AZAR and LINDGREN 2006, WEYANT 2000). Of course, LBD also has potential for other energy generation processes. HEDENUS, AZAR and LINDGREN (2006:110) assume learning rates to be "*around 5% for mature technologies, such as power production from fossil fuels, and between 10% and 15% for more immature technologies such as carbon capture, wind power, fuel cells and solar PV*". However, the existence of LBD constitutes increasing returns of scale which "*can cause path dependency, with the possibility of lock-in to sub-optimal technologies*"(KÖHLER, GRUBB, POPP and EDENHOFER 2006:20). Policy that shifts investments into a wider range of technological options than *myopic* market actors do can avoid such lock-in risks (SHILPA, KEPPO and KEYWAN 2006:137)

R&D is another field to be included in modelling endogenous technological change (ETC); the private R&D sector is likely to react on increasing carbon prices (due to carbon tax or certificates); when more stringent policy is adopted, emission costs rise and more mitigation orientated R&D spending on behalf of firms is induced (KELLY and KOLSTAD 1998:23). Steering investment towards R&D and low carbon innovations was initially predicted to have negative outcomes, mainly due to crowding out of other investments (GOULDER and

SCHNEIDER 1999). However, there are good reasons to assume inefficiently low R&D investments in the market equilibrium due to the existence of knowledge spill-overs (GOULDER 2004:27 for the first-best – second-best discussion see IMCP 62; 102). Consequently, increasing public investments on renewable energy's R&D, as well as giving subsidies and warranting patent rights to foster private R&D investments, might not only drive down mitigation costs but also lead to an overall more efficient market situation. In any case, mitigation has positive external effects on the environment (GOULDER 2004:28). To model the effect of R&D, a stock of "knowledge capital" can be introduced; this stock grows with R&D investments and reduces a technology's per unit costs.

Another influence on mitigation costs are technological assumptions; particularly, the inclusion of carbon capture sequestration (CCS) and the availability of a *backstop technology* in the future (i.e. an "unlimited" carbon free energy source that becomes available at a certain energy price) are key factors for future development of mitigation costs (KÖHLER, GRUBB, POPP and EDENHOFER 2006).

The inclusion of ITC lowers the costs of reaching climate goals and makes more ambitious climate policy feasible. It highlights the importance of policy in the innovation process and shifts market imperfections into the scope of modelling. Concerning the timing of mitigation, there are two contradictory tendencies: while pronouncing the effect of LBD leads to early mitigation (the sooner capacity is built up the sooner learning takes place), estimating R&D as more important may result in delayed mitigation as technological development will be viewed as the first priority (GOULDER 2004:30).

Another factor that influences costs of mitigation is the flexibility that stakeholders are given to reduce emissions. Higher regional and sectoral flexibility results in more cost efficiency, as cheaper opportunities to mitigate CO_2 can be exploited first. But flexibility can also mean trading between different types of GHG gases. However, non-CO_2 gases are not included in the vast majority of modelling approaches (e.g. models in the Innovation Modelling Comparison Project- IMCP). If they are included, no coherent mitigation cost estimates are presented (e.g. V. VUREN ET. AL. 2006). In fact, for non-CO_2 gases, there seems to be only static mitigation cost estimates (i.e. defined potential of a particular GHG at a fixed price in a region or sector). This indicates potential improvement in the field.

Summarising the above information, to estimate mitigation costs in a dynamic CBA framework, the influence of different policies on mitigation cost has to be depicted; market imperfections have to be considered; assumptions concerning the availability of key technologies have to be tested. Additionally, it is worth estimating the potential importance of non-CO_2 gases. As there are many different modelling approaches to meet these exigencies, the use of different models is recommendable.

2.4.3. Comparing Adaptation and Mitigation

Adaptation and mitigation have the same goal; to decrease adverse climate induced impacts. However, they are not substitutes and feature important differences. Firstly "*Reducing emissions [i.e. mitigation] changes the climate and has the potential to reverse the impacts of climate change, while adaptation actions are simply adjustments to climate change and its associated impacts"* (CALLAWAY 2004:274). Accordingly, adaptation's effects will be limited to specific regions and sectors, while mitigation has global effects. There are also impacts that cannot be tackled by adaptation, for instance, those on unmanaged ecosystems (CALLAWAY 2004). On the other hand, adaptation has immediate effects and as considerable climate change is already irreversibly in progress, many impacts cannot be addressed by mitigation. Here adaptation is the only option and studies suggest it can decrease damages considerably. Thus, systematically, mitigation policy can be seen as a long term and international, while adaptation is rather short term and has to be addressed regionally.

None of the two can be the sole solution to the climate problem. As WILBANKS and SATAHYE (2007:958) explain "*mitigation is not going to unfold quickly enough to avoid most impacts; adaptation will be necessary. Adaptation cannot cope with many possible impacts associated with substantial climate change; so mitigation is necessary"*. However, policy might have to find the right mixture of adaptation and mitigation. TOL (2007), using sea level rise as an example, stresses how expenses on mitigation can lower GDP growth and consequentially leave countries more vulnerable to climate change.

The decision on the mixture of adaptation and mitigation also involves thoughts about inter-generational justice: A myopic policy maker will overestimate adaptation, ignoring its iniability to cut GHG emissions and its limitations when climate change reaches too severe levels in the future. Focussing too strongly on adaptation means valuing future generations little, especially when it comes to catastrophic risks as discussed in section 2.3.2. In this sense, the discussion on more or less adaptation or mitigation is similar to the one about discounting that is discussed in sections 2.5.2 and 3.3.

Besides these points, the financing of both options touches intra-generational justice; in the case of mitigation, the idea of fair burden sharing comes up, which could be discussed on a similar base as equity weighting in section 2.5.1. Correspondingly, one could argue that according to higher GDP levels, industrial countries should carry the major share of mitigation (the same could be argued with a polluter pays approach). Concerning adaptation, the responsibility of industrial nations to help poorer countries adapt to unavoidable climatic changes has to be defined. It is plausible that if global welfare maximisation is the aim, then fair burden sharing and strong support for adaptation in poorer, affected regions has to be discussed in a CBA of climate change policy. In fact, in the theoretic framework of CBA, compensations from climate winners to losers cannot be left aside (PEARCE 2006:47)

2.5. Two Central Aspects of Justice

As mentioned above, intra-generational equity is an important issue in the climate debate as people from varying socio-economic backgrounds will be affected. At the same time, climate change will have great influence on future generations, so besides the intra-generational, inter-generational equity concerns are a key issue. In this section, I discuss how both concerns can be integrated in dynamic CBA of climate policy.

2.5.1. Intra-generational Justice - Equity Weighting

Including equity concerns into a CBA (e.g. by equity weighting -EW), giving greater weight to poor people or regions/countries, is not a new idea exclusively within the climate change debate (for an overview see e.g. LOPDRUP and LYNGBY-PEDERSEN 2007). In fact, whenever there are considerable economic inequalities within a CBA's scope, equity concerns arise. PEARCE ET. AL. (2006) give three specific reasons for this:

- The marginal utility of income differs between rich and poor.
- Less income inequality could be a goal for society in itself.
- The ability to pay differs across individuals in WTP surveys, as richer people will have more *dollar votes* and thus their interests will be overrepresented.

For the estimation of climate impacts, the first and the last point are of particular importance. As outlined in section 2.3.3, impacts in regions with a lower ability to pay will likely be underrepresented in a conventional framework of CBA for climate policy, because people there have less money to demonstrate their preferences, i.e. they have less *dollar votes*. Because the developing world will probably be hit worst by climate change, this fact gains more relevance still. Climate change will most likely further increase existing inequalities among word regions. EW can help to avoid unjust assessment of climate impacts.

On these grounds, many economists argue for equity weighting. One prominent advocate is the British economist David PEARCE; he developed a method of equity weighting in relation to the quotient of GWP per capita (Y_{avg}) and regional average income (Y_i, PEARCE ET AL.2006). The quotient is denominated weighting factor a_i . The weighting factor a_i is powered by the elasticity of marginal utility of consumption "η", a measure for a society's aversion towards inequalities. If the income level is below average, a_i is bigger than one, if it is above average a_i is smaller than one. In the damage function, regional damage estimates are then multiplied by the weighting factor:

$a_i = (Y_{avg.}/Y_i)^\eta$ where: Y_{avg} worldwide per capita income; Y_i regional per capita income; η elasticity of marginal utility of consumption

Equation 1: Equity Weighting Factor

The relevance of EW in this manner is shown in PEARCE ET. AL. (2006:231) giving regional impact estimations of climate impacts with different values of "η" see Table 1 (note that $\eta = 0$ means no equity weighting as all resulting a_i are unity. The Table 1's impact values' source is not further explained in PEARCE ET.AL. 2006. However, for the purpose here, the focus is the changing relation in damages caused by EW)

Table 1: Climate Impacts equity weighted

	η = 0	**η = 0.5**	**η = 1**	**η = 2**
Poor countries	106	184	318	954
Rich countries	216	125	72	24
TOTAL	322	309	390	978

Source PEARCE ET. AL. (2006:231)

PEARCE ET. AL. (2006) argue that just as the impacts should be equity weighted, the same should be done with mitigation costs distribution. Poorer countries are to pay less accordingly. It will always remain a matter of opinion, whether CBA should account for income inequalities, or if it should be strictly orientated on monetary efficiency. However if one regards the actual income distribution as not optimal and accepts the assumption of decreasing marginal utility of consumption, distributional aspects have to play a central role in climate impact assessment. Equity weighting is one possibility to account for this.

Independently, mechanisms of redistribution and compensation for the strongly disadvantaged should be discussed along with a CBA of climate change (this can mean e.g. aid for adaptation as in 2.4.3 or international funds that finance reconstruction after extreme events as described in 2.3.2), which is the main criterion drawn from this section.

2.5.2. Inter-generational Justice – Discounting

As the bulk of negative climate impacts are likely to occur in 50 years or later, while the costs of climate policy occur now or in the near future, discounting becomes very important for climate policy assessment. WEITZMAN (2007a:18) states: „*The idea behind analyzing climate-change projects by converting future costs and benefits into present discounted values is that society has alternative investment opportunities, whose proxy rate of return is the discount rate*" To demonstrate the importance of the discount rate (DR), Table 2 shows the net present value (NPV) of 1000 € (this can be damages or benefits) in 50 and 100 years at different discount rates (the formula used is $\lambda_t = 1/(1+DR)^t$ where λ_t is the discount factor, i.e. the remaining fraction of the future value after discounting details e.g. in PEARCE, GROOME, HEPBURN and KOUNDOURI 2003:123).

Table 2: Net Present Value (NPV) of 1000 € at different Discount Rates 50 and 100 Years hence

Discount Rate	1000 € in 50 years	1000 € in 100 years
0.1%	950 €	905 €
1%	608 €	370 €
3%	228 €	52 €
5%	87 €	8 €
10%	9 €	0 € (0.07 €)

Source: Author

Table 2 clearly shows that if future impacts are discounted at low DR, they will be considered far more in CBA (and climate policy will be more rigid) than when discounted at high DR, as adverse effects in the future become much less relevant. Accordingly, IAM are very sensitive to the DR; for instance, marginal damage of one ton CO_2 in FUND increases from \$20 to \$42 and then to \$109, as the discount rate declines from rates of 5% to 3% to 1% respectively (PEARCE, GROOM, HEPBURN and KOUNDOURI 2003:123).

The standard way of determining the DR in an optimal growth model is based on RAMSEY (1928). It is calculated by the growth of consumption ($\dot{c}/c$), which is multiplied by the elasticity of marginal utility of consumption (η), meaning that to the degree that future generations are richer, their welfare is discounted. The value of η is a measure for a society's aversion against inequalities; the higher η, the smaller the additional welfare gained from an extra unit of consumption (*η* is also a measure for relative risk aversion, i.e. when an IAM averages many runs with varying parameters bad outcomes will count stronger, see section 3.3.3).

This is called *growth discounting,* the standard RAMSEY discounting scheme entails. Further another summand that represents a society's *pure rate of time preference* (PRTP- *δ*). The PRTP value is subject to much controversy (see section 3.3), as it devaluates future goods in favour of present ones just because they are posterior and thus it can be understood as a measure of discrimination of future generations. There are two competing approaches to determine the PRTP. One is *prescriptive,* meaning that a value is prescribed following ethical reasoning. The other is *descriptive* and implies observing and describing individuals' market behaviour and market interest rates to deduce the PRTP (see section 3.3.3 for a detailed discussion of the two approaches). A PRTP is commonly rationalised by *impatience* that leads individuals to prefer earlier consumption and by the possibility of extinction of the human species (AZAR and STERNER 1996:174). The DR (*ρ*) accordingly is determined by the following equation:

DR: $\rho = (\dot{c}/c)\,\eta + \delta$ where: $\dot{c}/c$ growth of consumption; η elasticity of marginal utility of consumption; δ pure rate of time preference

Equation 2: Discount Rate

There is a limiting empirical and an ethical condition to be fulfilled when a discounting scheme is designed. In a RAMSEY framework *δ* and *η* determine the investment behaviour (in the assumed perfect market conditions *δ* is equal to the market interest rate, TOTH 2000) with the equation:

$i = (a+n/\ \delta+a\eta)\beta$ where: i: investment rate; a: labour productivity increase; n: population growth; β: capital income share

Equation 3: Investment Rate

The investment rate should be in a range of about 10-30%, otherwise it cannot be reasoned empirically. Ethically, the choice of a low PRTP, just as the choice of a high rate of *η*, implies high aversion to inequalities. The choice of *δ* and *η* should thus be ethically contingent, meaning that low *δ* implies somewhat high *η*. To depict these two conditions, Table 3 presents combinations of δ and η with the corresponding investment rate i and its implied ethical statement illustrated by the arrows on the side:

Table 3: Investment Rate and ethical Duality

		Intergenerational Inequality →		
Inequality between rich and poor ↓		**$\delta = 0.1$ %**	**$\delta = 1\%$**	**$\delta = 5\%$**
	$\eta = 2$	18 %	16 %	12 %
	$\eta = 1$	36 %	30 %	18 %
	$\eta = 0.5$	70 %	51 %	24 %

Based on Equation 3 with a = 5 %, n = 1, $\beta = 30\%$

Source: Presentation by O. EDENHOFER at the ETH Zurich, download at www.ied.ethz.ch/news/publect/publect_old/Edenhofer_2007_04_18.pdf (last visit 8.5.2008)

The diagonal from the upper left to the bottom right are empirically and ethically contingent, with the red field corresponding to high preference for equity; the blue for low.

As assessment criteria that can be deduced from this section, a CBA's discounting scheme should be ethically and empirically contingent concerning the choice of δ and η. It should also be carefully reasoned, declaring explicitly if it is based on descriptive or prescriptive grounds. Further, due to its substantial influence, results are more solid when checked with varying discounting schemes.

2.6. Conclusions

Within this section, many important aspects of a dynamic CBA of climate policy were presented and discussed. Summarising the derived assessment criteria and requirements to analyse CBA approaches, as well as to discuss CBA in the climate context in general, we go back to the three categories named initially: Concerning methodology, the comparability of studies and a transparent, solid empirical foundation are especially important criteria, particularly as indicated by the discussion about baseline cases and scientific impact studies. In terms of modelling, methodology especially mitigation is challenging; a complex understanding of economic processes, such as investment behaviour and technological progress, is essential. However, modelling of extreme weather events also calls for better understanding (and modelling) of economies and their ability to recover from shocks.

Departing from perfect market assumptions and optimal growth models is promising in both cases. Due to limited knowledge and modelling experience, comprehensively capturing the uncertain impacts of section 2.3.2 in IAM is very challenging. However, these uncertain impacts can not be omitted when policy is evaluated, because of their potential importance. In terms of ethical criteria, this section has shown that varying value judgements leads to a considerable range of impact estimates at identical side conditions. Such value judgements, be it equity weighting, discounting or difficulties using WTP approaches have to be transparently discussed and exposed in a CBA.

Although many criteria have been derived here, most of them are not clear cut. This is particularly due to limited knowledge and predictability of impacts and future economic, social and technological development. Furthermore, many ethical questions (discounting, WTP, equity weighting) remain open for debate, as explained in the corresponding sections. Together these ambiguities lead to a tremendous variety of possible settings for modelling when dealing with climate policy design. Accordingly, a CBA of climate policy has to cover these ambiguities. Several points in this chapter already indicated how this could be done, e.g. by the use of various baseline scenarios and varying discount rates. Also, extensive sensitivity analysis varying several parameters simultaneously (e.g. by Monte Carlo Analysis) is necessary. Likewise, it seems important to take into account various different models which utilise different methodologies and assumptions.

3. Assessing the CBA Approach in the Stern Review

The Stern Review' report on the economics of climate change was published by the British HM Treasury in the end of 2006. The whole report and numerous commentaries and background information is available on the HM Treasuries' website (www.hm-treasury.gov.uk, last visit 8.5.2008).

The Review has quickly raised a lot of discussion and feedback. This is mainly because it predicts high climate change related damages and relatively low costs for stabilising GHG concentrations at levels that would avoid the worst consequences. The Review recommends early action as the best strategy. This is in contradiction with the so called *climate policy ramp* which has been the preferred strategy among many economists so far.

This part of the present work analyses the Stern Review to find out if its results, rejecting the *climate policy ramp,* are well founded. Bearing this issue in mind, I will lead a detailed discussion about the impact estimations that STERN presents. This is followed by investigating the treatment of mitigation and adaptation. The third important field that I want to regard is STERNs' idea of discounting, particularly the treatment of impacts that lie in the far future. The analysis is concluded presenting and discussing STERNs overall results. Whenever possible and useful I will refer to the good practice criteria derived in the former section and include important critiques by other economists'.

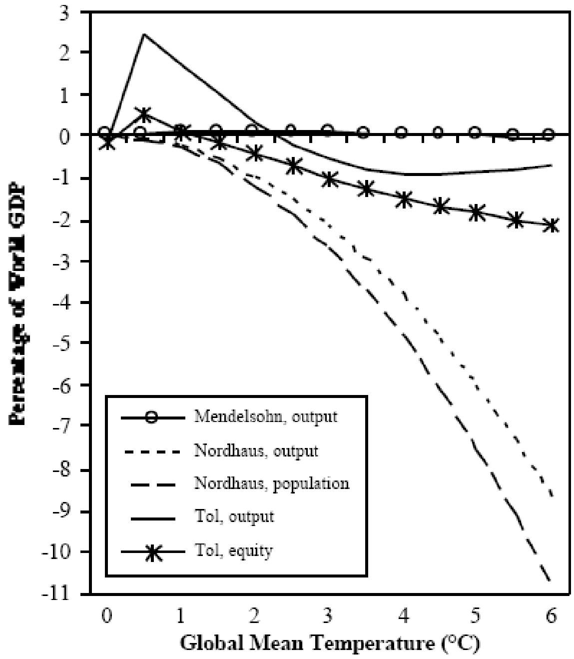
3.1. Impacts

The Stern Review addresses climate impacts in part two of the Review (chapters 3-6). Chapters 3-5 are devoted to separate analysis of particular regions and sectors that will be subject to impacts. These are not aggregated in a dynamic modelling framework, as they are *static* estimates. Therefore, I will focus on the modelling part in chapter 6, which STERN describes as follows: "*Chapter 6 aims to pull together the existing modelling work that has been done to estimate the monetary costs of climate change, and also sets out the detail of modelling work undertaken by the Review.*"I will follow this line and present STERN's overview of existing models first before discussing the Review's own modelling results.

3.1.1. Impact Assessment in the Stern Review

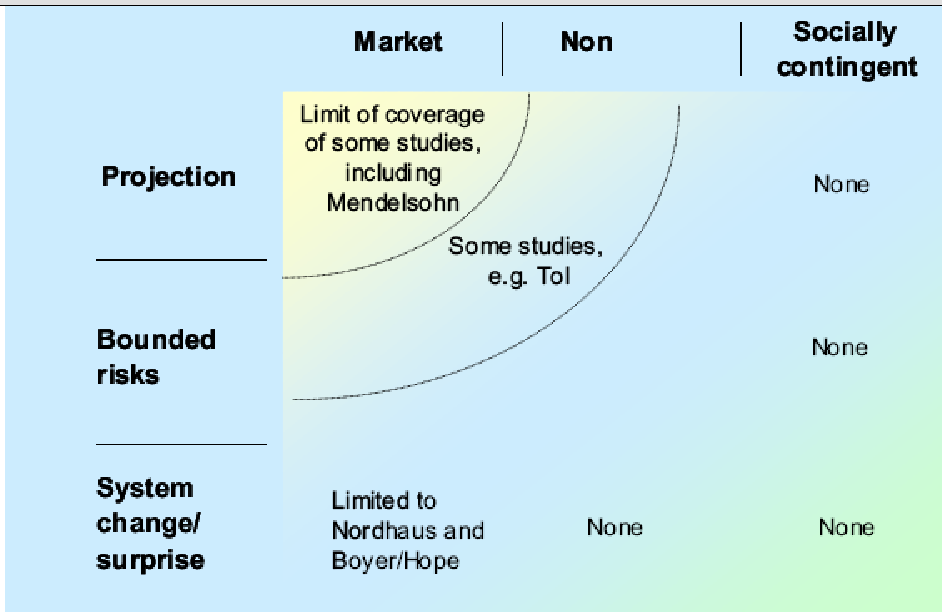
Following an introduction and critical remarks about IAM in general, STERN resumes modelling results from the IPCC's Third Assessment Report (IPCC 2001). The three IAM's (DICE, NORDHAUS 1999; FUND, TOL 2002 and MERGE, MENDELSOHN 1998) results for damages at certain levels of temperature rise are given in Figure 1 (Table 10 gives comparable results for PAGE2002). The models are ambiguous about the impact of global warming for lower temperature rises, but unambiguous that further warming will have negative consequences. All three models forecast stronger negative impacts on poor countries. Accordingly, using equity weights in FUND and DICE (the graphs *Nordhaus population* and *Tol equity*), their impact estimates become more adverse (see 2.5.1 for an explanation of equity weights).

Figure 1: Monetary Impacts at different Levels of temperature rise presented in TAR



Source: IPCC (2001:944)

Figure 2: Coverage of existing IAM



Source: STERN (2006:150)

The main point that STERN notes about the TAR models is that none of them capture all damages that are going to occur and thus that their impact estimates are too low. To illustrate that, he categorises damages in Figure 2 (originally taken from WATKISS and DOWNING 2005) and groups the models with respect to their impact depictions' totality:

In the figure, the impact categories on the horizontal axis are ordered with respect to the difficulty valuing them in monetary terms. The distinction between *market* and *non-market* impacts has been addressed in section 2.3.3 in detail. The third category, titled *socially contingent,* is described as „*'second-round' socio-economic responses to the impacts of climate change, such as conflict, migration and the flight of capital investment*" (STERN 2006:150). This category is not described in chapter 2.3, as there is currently no modelling approach to evaluate the considered processes. Including them will raise impact estimations (see WATKISS and DOWNING 2005:iii).

The categories on the vertical axis are ordered by the grade of scientific uncertainty related to each impact (STERN 2006:150). As an example, STERN refers to predictions of a rise in sea-level as *projection*. Alterations in precipitation schemes, which are less certain, are considered *bounded risks*, meaning that at least the upper and lower boundaries of their scale are defined. STERN also assigns *extreme weather events* (described in section 2.3.2) to that category. The third category, *system changes/surprise*, is what I referred to as *catastrophic events* in section 2.3.2.

After the overview of former IAM, STERN explains the Review's modelling approach, in which the IAM PAGE is used (version PAGE2002 as described in HOPE 2006). STERN reasons his choice, stressing several advantages of PAGE2002. The most important ones being that it

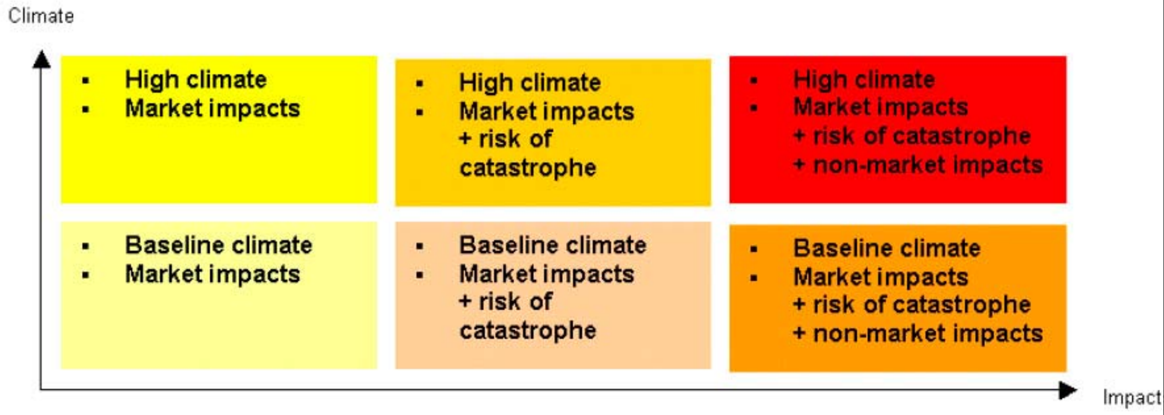
- is updated with recent science (see also WARREN ET. AL. 2006), the majority of its parameter ranges are orientated on various peer reviewed studies (STERN 2006:153),
- is capable of doing a Monte Carlo welfare analysis (meaning that several factors can be varied at a time, creating a probability distribution of possible outcomes after doing 1000 runs per scenario), and
- includes catastrophic events (HOPE 2006).

The model delivers results in the form of "*a probability distribution of future income under climate change, where climate-driven damage and the cost of adapting to climate change are subtracted from a baseline GDP growth projection*" (STERN 2006:153). Thus, impacts can be expressed in % of GWP lost.

PAGE2002 uses external data for central variables, such as GHG emissions, population trends and economic development (all taken from the SRES A2 scenario). Impacts in the model are differentiated as suggested in Figure 2; *non-market*, *market* and *catastrophic events*. For the categories market and non-market damages, PAGE2002 is calibrated to meet the standard literature at a doubling of GHG concentrations and it assumes accelerating damages as temperatures rise (the damage functions exponent varies from 1 to 3 probabilistically, 1.3 is the mode, see WARREN ET. AL. 2006:31). Catastrophic events are included with a rising occurrence probability as temperatures rise. The likelihood is projected to be zero until a threshold that lies between 1.5 and 7.5 Cº above 1990 temperatures (most likely at 5 Cº). From then on, each degree of further warming increases the occurrence probability of an extreme event by 1-20% (most likely 10%, HOPE 2006:26). WARREN ET. AL. (2006:31) summarises that in PAGE2002 catastrophic events "*comprise about 15% of today's social cost of carbon, a percentage that will rise in the future as we get closer to the time that discontinuities are likely to occur*". The model contains no explicit consideration of elevated frequency of extreme weather events as HALLEGATTE (2007, see section 2.3.2) suggests. By repeating each scenario in 1000 runs with parameters varying, the model can also account for uncertainty about climate sensitivity (as suggested in section 2.2.)

PAGE2002, in its *baseline* climate scenario (as in HOPE 2006), "*produces a mean warming of 3.9°C relative to pre-industrial in 2100 and a 90% confidence interval of 2.4 – 5.8°C*" (STERN 2006:154). Additionally, STERN introduces a *high* climate scenario. This considers two possible *feedback effects* (described in section 2.3.2); the weakening of carbon sinks and increased methane emissions due to thawing permafrost. The resulting higher GHG emissions increase the mean expected warming to 4,3°C and the 90% confidence interval to 2.6- 6.5°C (STERN 2006:154). With the three impact categories and the two baseline cases, STERN defines six possible scenarios for impact estimations; differing in the groups of impacts included and the assumed climate scenario (see Figure 3).

Figure 3: 2X3 Matrix of Scenarios used in the Stern Review



Source: STERN (2006:155)

Both scenarios are based on climate sensitivity being between 1.5-4.5°C, as suggested by the TAR. STERN additionally introduces a *high+* scenario (not included in Figure 3). The *high+* scenario is identical to the *high* scenario but based on higher climate sensitivity estimations by MURPHY ET.AL. (2004). They estimate climate sensitivities' 90% confidence interval to be between 2.4-5.4°C, (the mode is 3.5°C). For the *high+* scenario the expected warming until 2100 is not given. STERN described this scenario as rather speculative; however, the IPCC's FAR (IPCC 2007) has confirmed the possibility of such higher climate sensitivity (see section 2.2).

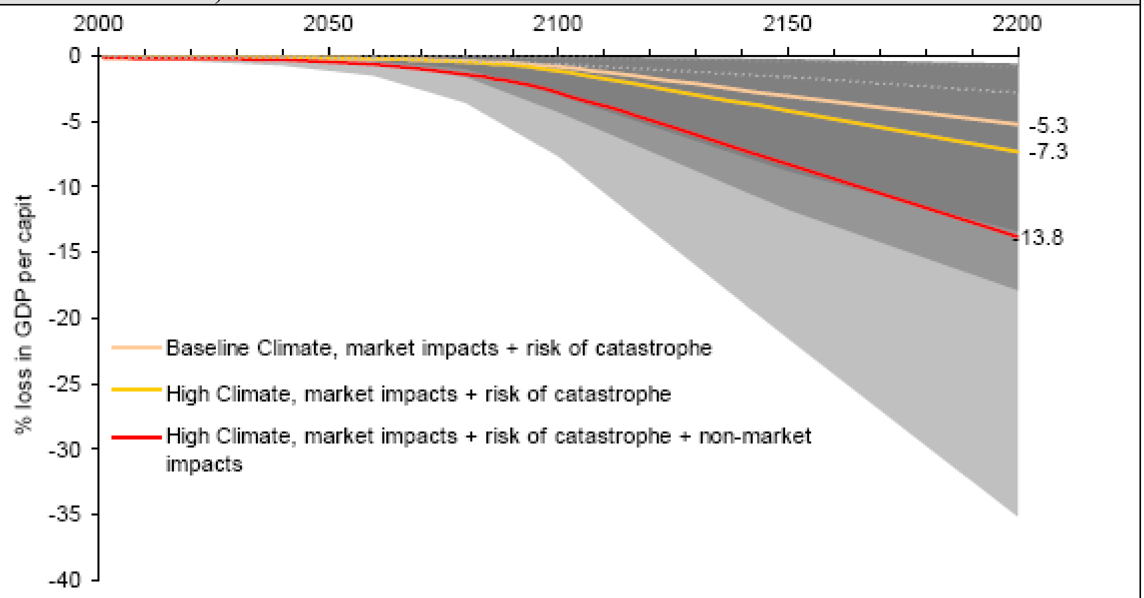
According to the temperature levels that each climate scenario produces, PAGE2002 calculates consequent impacts at certain time points for different combinations of the Figure 3 matrix. As an overview, all estimations named in the Review are summarised in Table 4 (there is no such overview in the Stern Review). Below that in Figure 4 four graphs from the Review depict impacts until 2200 related to different scenario-impact combinations.

Table 4: Time- Impact Estimates in different PAGE2002 Scenarios (Expressed in lost consumption percentages. In the boxes: *Mean value* (*lower - upper bound* of 90% confidence interval). Blank fields are not given in the Stern Review).

Scenario		**2060**	**2100**	**2200**
Baseline Climate	Market impacts+ risk of catastrophic events	0,2	0,9 (0,1 to 3)	5,3 (0,6 - 13,4)
	Market impacts + risk of catastrophic events + non-market impacts			11,3
High Climate	Market impacts+ risk of catastrophic events			7,3 (0,9 - 17,9)
	Market impacts + risk of catastrophic events + non-market impacts			13,8 (2,9 - 35,2)
High + Climate	Market impacts+ risk of catastrophic events	0,4	2,7	12,9
	Market impacts + risk of catastrophic events + non-market impacts	1.3	5.9	24.4

Source: Author based on STERN (2006)

Figure 4: Impacts until 2200 in three Scenarios (grey fields are the scenarios 90% confidence intervals)



Source: STERN (2006:157)

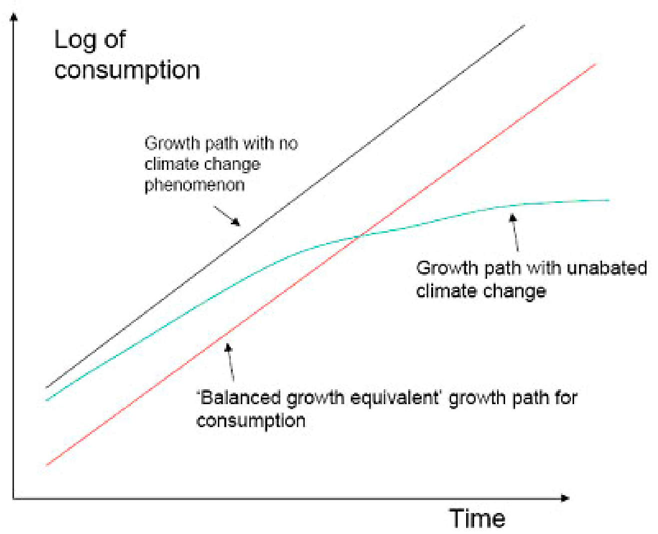
In a next step, STERN prolongs the model's time horizon from 2200 to infinity, assuming constant population and a consumption growth rate of 1.3% with no further climate damages from 2200 on. He explains:

"In other words, as a simplification, in each run the world instantaneously overcomes the problems of climate change in the year 2200 (zero damages and zero adaptation) and all runs grow at an arbitrary 1.3% into the far-off future. In this sense there is an underestimate of the costs of climate change." (STERN 2006:362)

STERN then aggregates consumption over the infinity time horizon and compares the results to the BAU case using *balanced growth equivalents* (BGE), which he defines as "*the BGE essentially measures the utility generated by a consumption path in terms of the consumption now that, if it grew at a constant rate, would generate the same utility*" (STERN 2006:160).

The BGE (developed by MIRRLEES and STERN 1972) is the rate of constant growth of consumption that leads to the same aggregated welfare level, as a given optimal path with changing levels of growth. The BGE's *averaged* optimal growth rate can then be compared to alternative paths (e.g. one that adapts a certain policy). Comparing the different paths, an *average constant growth loss* can be derived. As regards the climate, the optimal case is that of the BAU, assuming a future with no climate change, while the alternative paths assume climate impacts, based on different scenarios (see Figure 5)

Figure 5: The Concept of Balanced Growth Equivalents (BGE)



Source: Presetation for the Gurukul Chevening Lecture 7.11.2006, download at http://www.hm-treasury.gov.uk/media/5/7/stern_gurukulchevening_presentation.pdf (last visit 8.5.2008)

Averaging losses in the climate case is particularly relevant, as future impacts are projected to be much stronger than present ones. STERN describes the BGE values summarised in Table 5 as a *"tax levied on consumption now and forever, the proceeds of which are simply poured away"* (STERN 2006:160).

Table 5: BGE-Losses based on different PAGE2002 Scenarios (expressed in lost consumption percentages. In the boxes: *Mean value* (*lower - upper bound* of 90% confidence interval)		
Scenario		**BGE loss**
Baseline Climate	Market impacts	2.1 (0.3 - 5.9)
	Market impacts + risk of catastrophic events	5.0 (0.6 - 12.3)
	Market impacts + risk of catastrophic events + non- market impacts	10.9 (2.2 - 27.4)
High Climate	Market impacts	2.5 (0.3 - 7.5)
	Market impacts + risk of catastrophic events	6.9 (0.9 - 16.5)
	Market impacts + risk of catastrophic events + non- market impacts	14.4 (2.7 - 32.5)
Calculated with $\delta = 0.1\%$ and $\eta = 1$		
Source: STERN (2006:163)		

Referring to Table 5, he concludes that 5% BGE loss of consumption *now and forever* is the lower bound and 14.4% the upper bound of impact estimates. (STERN 2006:163/4) He adds that 14.4% would rise to around 20% BGE if equity weights were applied (this step is discussed in section 3.3.1)

3.1.2. Critique of Sterns Impact Estimation

To assess climate impacts in a dynamic modelling framework, STERN uses the IAM PAGE2002. The first important criticism is just this- the use of exclusively one model. The results of the Review would be more solid and fruitful if they were based on more models and different modelling approaches (as is the case for the mitigation cost estimations). Further, it is important to note that PAGE2002 is not more comprehensive than DICE-99 (see Figure 2); Just as the latter, it includes catastrophic events, however, both don't include extreme weather events or what was described as socially contingent impacts above. Both effects would increase impact estimates, other things being equal.

To me, the most relevant advantage of PAGE2002 is that its result is a probability distribution function (PDF) of 1000 runs per scenario instead of a single best guess estimate (based on parameters' most likely values) as in DICE-99. This way, parameter uncertainty is displayed and, as worst case runs' weights heavier due to decreasing marginal utility of consumption, risk aversion is accounted for in the results.

A second observation to be made in advance concerns the chosen discounting scheme. The central factors η and δ are set 0.1% and 1 respectively in all calculations. There is no sensitivity analysis of them, which limits the Reviews' results universality. Particularly setting η unity causes an important consequence: adjusting Equation 2

$$\text{DR: } \rho = (\dot{c}/c)\,\eta + \delta$$

shows that no matter what path of economic development g ($\dot{c}/c$ in the equation) is assumed, the sum $\rho - g$, which could be described as *growth adjusted discounting,* is always going to be δ, i.e. 0.1%. WEITZMAN (2007a:7) critically notes that *"The Review could have made life easier here […] by assuming δ = 0, which along with η =1 would make cost-benefit analysis really simple because a fixed fraction of GDP would then always be worth the same fixed fraction of GDP at any future time".* Most important for my critique here, is that the choice of η makes the value g irrelevant for discounting. Only in the underlying SRES scenarios, the projected growth path indirectly codetermines GHG emissions. Beyond 2100 though, GHG emissions are set constant, (i.e. independent of g) so then g is in fact totally irrelevant, making the difficult task of projecting growth perspectives obsolete. However, as soon as other values for η are discussed, as in STERN (2008), g is a key factor.

PAGE2002 uses an *extrapolated* version of SRES scenario A2 to get key external data. STERN adopts the A2 GDP average growth rates (about 1.9%, by 2100 GDP is 20 times that of 1990), its average population growth rate (about 0.6%, from 1990 to 2100 world population triples) and its overall GHG emissions (STERN 2006:161, for data of the SRES scenarios see http://sres.ciesin.org/final_data.html). As PAGE is run until 2200 but the SRES scenarios only project until 2100, the *extrapolation* suggests that projections for population and economic growth are prolonged until 2200. GHG emissions are set constant after 2100, as described in HOPE (2006, HOPE also uses data of the A2 scenario). Strikingly, there are few details to make the extrapolation process transparent. As population development and GHG emissions (and economic growth when η is not unity) are central variables when projecting climate impacts, assumptions about them should be altered. However STERN doesn't run PAGE with any other SRES scenario. The A2 scenarios' projections for population growth are relatively high; those for economic growth are in a medium range (see IPCC 2000:5). Particularly because of the high population projections, it is a scenario that produces a tendency towards somewhat higher impact estimations (see e.g. outcomes of different SRES-scenarios in the context of specific impact studies STERN 2006:66; 73; 78). As HOPE (2006:32) critically acknowledges "*it would probably be worthwhile to repeat the calculations at least for one other of the IPCC scenarios*".

Another aspect of criticism concerns the transparency of STERN's damage estimates, particularly the modelling of catastrophic events, which STERN describes as "*similar to the approach used by Nordhaus and Boyer"* (STERN 2006:153, NORDHAUS and BOYERs' base their estimates largely on an expert survey as described in section 2.3.2). TOL and YOHE (2007:158) argue that there is no source of estimates given to confirm that and that it is unclear from where estimations were derived. Also referring to transparency, COLE (2007:28) criticises that STERN is not explicit about valuations of non-market goods such as human lives. In fact, the Review does not give complete information about the PAGE's foundation. HOPE (2006) and WARREN ET. AL. (2006) give some further information, however, in comparison to DICE, PAGE is not so well documented.

Summarising so far, we can hold that STERN's calculations have a serious lack concerning variation of key parameters and developments. Additionally, there is a lack of transparency concerning the prolongation of the impact calculations' time horizon until 2200 and the valuation of some of the impacts.

Having this in mind, the next question is whether or not these flaws uniformly bias the results in a certain direction. TOL (2006) asserts that PAGE2002 tends towards higher damage estimates because of the specific model structure (particularly too little growth-induced adaptation along with less vulnerability and too little probability of positive effects of climate change). On the contrary, DIETZ ET. AL. (2007) states that the relatively high impact estimates in the Review are the result of the inclusion of catastrophic impacts and the discounting scheme.

To find out who is closer to the facts, NORDAHUS (2006:15) gives helpful insights. NORDHAUS adopts STERNs' values for discounting in DICE-99, which (as stated above) covers about the same amount of impacts as PAGE2002 and compares the outcome with his DICE-99 standard results. The standard setting delivers optimal CO_2 taxes for 2005 that are 18 times smaller that those of STERN while, using STERN's discounting scheme, this difference melts down to less than factor two! DIETZ ET. AL. (2007:320) also names PAGE's risk aversion, including PDF results as one more reason that its results are higher than those of DICE-99 (explained above). Thus the bottom line is that it is not the assumptions that the model is based on that lead to high impact values; it is more than anything the discounting method and risk aversion. The inclusion of catastrophic events is very relevant for both IAM (see sections 2.3.2 and 3.1.1).

Another key aspect that has surprisingly gained little attention in the numerous critiques of STERNs' work is the importance of prolonging the models' time horizon to infinity and averaging impacts by means of BGE. A comparing look at the values in Table 4 and Table 5 indicates the importance of this step. It is important to notice that STERN sees the results of the prolonged time horizon in Table 5 as the Reviews' *headline results* (STERN 2006:162). STERNs' prolongation technique underestimates the impacts of climate change, in so far that from 2200 no additional climate impacts are assumed and the economy uniformly grows at 1.3% per year. However, despite the constant growth after 2200, the utility loss reached in 2200 continues to exist in all following periods (DIETZ ET. AL. 2007:318). Accordingly, the 2200 value is superiorly important and very strongly influences the BGE values. In fact, its prevalence is only limited by low discounting at 0.1% PRTP. To illustrate, one can compare mean values of one scenario found in Table 4 and Table 5, e.g. the *baseline scenario* including *market impacts* and *catastrophic impacts.* The Table 4 values are 0.2% in 2060, 0.9% for 2100 and 5.3% for 2200. The BGE equivalent in Table 5 is 5% *now and forever*!

The reason for the high damage estimates in Table 5 is not STERN's "*dim view of human ingenuity",* as TOL suggests (2006:2), nor is it the "*large and speculative damages in the far-distant future*", as NORDHAUS (2006:12) states. The main reason why the averaged loss from a maximum of about 3% between now and 2200 (with values below 1% until 2100) results in a 5% average loss *now and forever* is the infinite extrapolation of the 2200 status combined with low discounting. My major concern with this is not so much the prolongation of the time horizon until infinity and the consequent dominance of future utility losses in present calculations, this is an ethical position that seems defensible. It is rather the fact that assumed values in the far future are ever more speculative: The least credible data and ballpark estimates dominate STERN's impact calculations. To me, it seems more attractive to refrain from long-term aggregation of utility and stick with time series as in Table 4 and Figure 4. The possible risk of disastrous climate risk in the far future can still be depicted like that and could still serve as a strong argument for strict climate policy. At the same time though, the argument would remain more transparent and credible.

3.1.3. Conclusions

Altogether, the critique of that STERN's damage estimates found two important methodological aspects: first the use of only one (albeit well suited) IAM and second, the missing variation of external data and key parameters of discounting. In addition to these points, there are some critics that claim that STERN's impact estimations lack transparency.

STERN's time path damage estimates are higher than those of previous studies mainly because of the discounting technique, the expected utility approach and the inclusion of more catastrophic risks in the calculations. Nonetheless, the estimated damages still don't include important *socially contingent* second round impacts. Finally, the aggregation over time by the use of balanced growth equivalents (BGE) is what pushes the STERN values so much above those of other studies.

3.2. Mitigation and Adaptation

Mitigation of GHG emissions is subject of chapters 8, 9 and 10 of the STERN review. STERN recommends a stabilisation of GHG concentrations at 550ppm CO_2e. Thus the three chapters mainly focus on that goal. As STERN does no proper modelling of mitigation costs, but relies on external studies, I will explain his argumentation and present the modelling results rather than focus on modelling details. In the critique I will express some general thoughts about mitigation modelling. As in the following sections I refer to CO_2 values in some cases and in others to CO_2e (depending on the context), Table 6 gives an overview of the relation between the two.

Table 6: Translating CO_2 to CO_2e

CO_2	**CO_2e**
450ppm CO_2	500-550 CO_2e
500ppm CO_2	550-650 CO_2e
550ppm CO_2	600-700 CO_2e

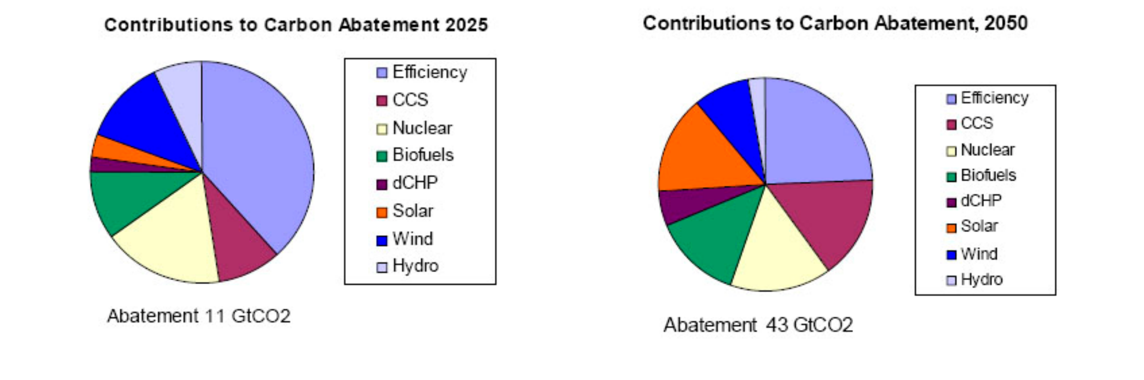
Source: Author based on STERN (2006)

The STERN Review uses no models that address adaptation explicitly, as was suggested in section 2.4. Still, adaptation is discussed in several chapters. I will outline the main findings first and then discuss why modelling adaptation explicitly could be fruitful to further work.

3.2.1. Mitigation in the Stern Review

STERN addresses the modelling of mitigation costs in chapter 10 of the analysis. The previous chapter of the Review gives quantitative information about different technologies' mitigation potentials and related costs, aiming at a 550ppm CO_2e target (STERN 2006:229ff, based on ANDERSON 2006). Figure 6 gives an overview of different technologies' abatement shares for that target in 2025 and 2050.

Figure 6: GHG Savings by Technology for 550ppm CO_2e Scenario in 2025 and 2050



Source: STERN (2006:230)

Chapter 10 is based on several external multi-model studies such as the Innovation Modelling Comparison Project (IMCP) and the Stanford Energy Modelling Forum (EMF). Further, to isolate key assumptions that drive results of mitigation modelling, a meta-analysis by BARKER ET.AL. (2006), mostly based on the IMCP models, is used. The IMCP investigates three different stabilisation goals: 450, 500, 550ppm CO_2 (500-700ppm CO_2e according to Table 6). More ambitious targets (400ppm CO_2) are not presented, as many IMCP models do not converge for such values, due to limited mitigation options and/or a missing backstop technology assumed in the models (EDENHOFER, LESSMANN, KEMFERT, GRUBB and KÖHLER, 2007:81). For each concentration target the average projected cost is expressed in % of GDP at different discount rates (see Table 7). The average costs of mitigation, consistent with an emission trajectory leading to stabilisation at 450ppm CO_2, are estimated below 1% of GDP by 2050. For longer time horizons, particularly after 2100, costs diverge further, reflecting the uncertain availability of alternative technologies (STERN 2006:247). The IMCP tries to minimise baseline effects by using data from the Common Poles-Image (CPI, V.VUUREN 2003, see section 2.1) for development of GWP and GHG emissions. If these factors where modelled endogenously, the modelling teams tried to calibrate models to match CPI values (EDENHOFER, LESSMANN, KEMFERT, GRUBB and KÖHLER, 2007:69).

Table 7: Average discounted Abatement Costs of Concentration Targets, expressed in %GWP					
Target	**Discount Rate**				
	5 %	**Declining Rate***	**2 %**	**1 %**	**Undiscounted**
450ppm CO_2	0.41	0.64	0.71	0.83	0.95
500ppm CO_2	0.16	0.25	0.28	0.32	0.37
550ppm CO_2	0.10	0.14	0.16	0.18	0.19
*The Declining Rate is adopted from the "Green Book" (HM Treasury 2003), starting at 3.5% for the first 30 years, then dropping to 3.0% until year 75, and 2.0% until year 125					
Source: EDENHOFER, LESSMANN, KEMFERT, GRUBB and KÖHLER (2006:69)					

However, the spread of results behind these average values is considerable; for the 450ppm CO_2, models deliver a cost range of +3.9 to – 3.4% of GDP (STERN 2005:240). BARKER ET.AL. (2006:32) list the model-characteristics that cause this wide range (see Table 8):

Table 8: Average Impact of Model Assumptions on GWP in 2030 for stabilisation at 450ppm CO_2, relative to BAU costs.	
Assumption	**Potential Impact**
1 Use of active recycling of government revenues	1.9
2 Adoption of static CGE models	1.5
3 Introduction of ITC	1.3
4 Allowing for non-climate benefits	1.0
5 Use of the Kyoto Mechanism	0.7
6 Introduction of a backstop technology	0.6
7 Allowing for climate benefits	0.2
Total variance caused by all model assumptions	**7.3**
Worst case	- 3.4
Best Case	+ 3.9
Source: BARKER ET.AL. (2006:32)	

The deduced main drivers in Table 8 largely confirm what was described as central determinants for mitigation costs in section 2.4.2. As stated above, targets that are more ambitious than 450ppm CO_2 are out of models' scope in many cases; STERN finds that "*cost of stabilising emissions at 500- 550pmm CO_2e would be around a third of doing so at 450-*

500ppm CO_2e."(STERN 2006:247). Thus, there is a disproportionate increase related to more ambitious policy goals than what STERN favours. The same disproportionate increase happens when the pace of reductions is raised. This implies that it will be costly to wait with abatement and then tighten emission goals on the short term (STERN 2006:247, STERN 2008:17).

Deriving implications for policy from models' outcomes, STERN strongly emphasises the importance of flexibility in mitigation policy. This flexibility aims to allow mitigation at lowest marginal cost referring to CO_2-equivalents. He distinguishes three different dimensions of flexibility (*what, where* and *when* flexibility, see STERN 2006:244-6). Summarised this means: A wide portfolio of technological options should be considered, mitigation of all relevant GHG should be included in the calculations (the EMF-21 suggests 30-40% cost reductions when including non-CO_2 gases; see WEYANT ET AL. 2004, VAN VUUREN ET AL. 2006), mitigation should be pursued in whatever sector and place it is cheapest and to the extent that mitigation is likely to be cheaper in the future delaying mitigation lowers costs.

3.2.2. Adaptation Modelling

As stated above, the STERN analysis does not present modelling results for CBA of adaptation measures. Adaptation is implicitly included in the impact modelling with PAGE2002 (within the assumptions of the underlying sector studies). However, STERN expresses that IAM reporting explicit results for adaptation would be favourable:

> *"adaptation is an important component of integrated assessment models that estimate the economy-wide cost of climate change […]. However, these models are currently of limited use in quantifying the costs and benefits of adaptation, because the assumptions made about adaptation are largely implicit. Adaptation costs and benefits are rarely reported separately."* (STERN 2006:410).

Explicit modelling could particularly help to alleviate the lack of understanding of potential autonomous adaptation and help to understand processes like knowledge transfer (e.g. by modelling the effects of programs like the Climate Impact Program in the U.K.-UKICP), the effectiveness of financial insurances and help funds to support affected people and regions that do not have the resources to adapt (e.g. for development of resistant crops). In addition, it could analyse the effects of long term policy on investments or change of land use. As suggested in chapter 2.4.3, modelling could also assess synergies and/or (financial) resource conflicts between mitigation and adaptation, potentially considering different preferences concerning discounting (for further such considerations e.g. WILBANKS and SATHAYE 2007 or chapters 18-20 of the Stern Review).

The STERN Review does not leave adaptation aside though- it is dealt with in chapters 18, 19 and 20 (chapter 18 is a general methodological overview, while chapters 19 and 20 examine adaptation strategies in industrialised and developing countries respectively). STERN stresses that, in analysing adaptation strategies, it is important to use CBA. For that purpose, there is a very rudimentary concept of a CBA approach outlined (STERN 2006:406ff). It compares costs of adaptation and remaining climate impacts with altered climate to climate impacts with no adaptation. In a second step, the uncertainty about the use of adaptation measures is introduced (STERN 2006:409 Box 18.2).

Very roughly spoken, on a global scale, STERN identifies three key constraints that hinder effective adaptation:

- information deficits, i.e. to adapt agents need access to information,
- market imperfections, i.e. sometimes rational individual behaviour causes negative overall effects
- financial constraints, i.e. developing nations or poorer inner groups of a society will have more trouble to adapt

To overcome those constraints is the key for successful adaptation policy according to STERN. While TOL tends to see a competition between adaptation and mitigation (see section 2.4.1), STERN presents them as complementary using an argumentation that is similar to that of section 2.4.3 (see STERN 2006:306). Further, he highlights the many common goals that conventional development aid and adaptation policy have, e.g. the concept that economic development most effectively lowers vulnerability towards climate change.

3.2.3. Critique of Sterns Mitigation Modelling

The critiques of the STERN Review mostly focus on the discounting issue and impact modelling. There is little well grounded criticism to be found about mitigation. Several authors, such as WEITZMAN (2007a), LOMBORG (2006) or TOL (2006), claim that the Review's estimates are too optimistic. However, they fail to deliver facts to prove it.

I think that there are two main reasons for that scarce criticism. First, mitigation modelling in general and modelling induced technological change ITC in particular has made considerable progress recently; as BARKER ET.AL. (2006:1) suggest: "*induced technological change is a relatively new topic in economic modelling and results are often experimental and* *controversial.*" As the Review reports results from a variety of different, innovative approaches, it sure is hard work to assess its quality in a comprehensive way. Secondly, the mitigation work presented in the Review corresponds to a large degree to what was developed as criteria in section 2.4; the IMCP which is the most important base of the Review's estimates considers many different types of models. There is a meta-analysis conducted to isolate effects of specific assumptions (Table 8), the results are confirmed with varying discounting rates (Table 7) and the modellers of the IMCP tried to minimise baseline effects. In this sense, mitigation in the Stern Review stands on a quite sophisticated base.

However, I find that the wide mitigation cost range presented in Table 8 could become more narrowly defined discussing the listed assumptions' plausibility. There are some highly plausible assumptions; particularly that *active CO_2 tax revenue recycling*, *ITC* and *non-climate benefits* (e.g. less air pollution) are likely to occur to some degree, due to mitigation policy. On the other hand, when we want to use mitigation cost estimates for CBA of climate policy, it seems counterintuitive to count *climate benefits* as reduction of mitigation costs- they would already be counted within correspondent lower climate impact estimations. The other three assumptions (existence of a backstop technology, existence of efficient international trading mechanisms and the influence of the chosen model type, i.e. CGE, optimal growth or econometric models) seem less clear. Of course, this qualitative argument leaves open *how* for instance ITC or tax revenue recycling is assumed to happen, which will still vary results. However, at a first glance, there seems to be a promising potential to reduce the range of mitigation cost estimates

More in general, I see a risk of one-sidedness in the mitigation discourse. Climate change is driven by several GHG's; the IMCP studies are exclusively focussed on CO_2. As non CO_2-GHG's represent a considerable warming potential too, it would be an important progress to include them in formal models (in fact this would correspond to STERN's call for flexibility between GHG). Further, some of the most important techniques reducing CO_2 in the atmosphere (see overview in Figure 6) cause considerable adverse effects in other fields. For instance, carbon capture sequestration (CCS) causes long term risks of leakage (see BAUER 2005). Also, nuclear energy is very problematic not only at the power plant level but also when dealing with radioactive waste. Other mitigation options may have less adverse effects. For my concern, it is important to evaluate mitigation options not only by their direct costs and potential to decrease GHG emissions, but to see mitigation as part of an integral sustainable development strategy assessing all its consequences.

3.2.4. Conclusions

STERN's treatment of mitigation is technically well done, while adaptation remains without explicit modelling in the Review. Including other GHG gases and trying to focus more on associated risks of low CO_2 technologies could be further steps in mitigation modelling. As many models did not converge for concentration targets below 400ppm CO_2, it may be worthwhile to prove if the models' assumptions that cause the non-convergences are justified and perhaps try to find more precise estimations for lower targets.

3.3. Intra- and Intergenerational Justice

This chapter will begin to describe STERN's discounting approach to assess climate impacts. After this, there will be a discussion of important critiques of STERN's approach. To do that, I will go further into the main debates that drive the discussion of discounting. First, however, STERN's consideration of equity weighting will be briefly described.

3.3.1. The Role of Equity Weighting in the Review

Although STERN doesn't use equity weights (EW) in his modelling approach, several statements emphasise that he regards it as legitimate (e.g. STERN 2006:149). STERN stresses that the sole reason for not including EW in the Review was lack of time and team capacity "*Calculating the BGE cost of climate change after including value judgements for regional distribution is beyond the scope of this Review, given our limited time*" (STERN 2006:163).
However, he uses EW as an argument to increase his upper end impact estimates (that is 14.4% BGE losses according to Table 5): "*if we take as an indication of how much estimates might increase the results of Nordhaus and Boyer, then estimates might be one quarter higher*" (STERN 2006:163). 14.4% adding a quarter gives 18%. Further, STERN adds "*because their deterministic approach could not take into account the valuation of risk, there is good reason to believe that the weighting would in our model increase estimates still further […] the global cost of climate change would probably be equivalent to around a 20%*" (STERN 2006:163). In this way, EW adds up to an increase of around 5.6% (39% of 14.4%).
STERN's argument that accounting for equity weights would increase estimates is credible. However, guesstimating that 25% from NORDHAUS and BOYER would rise to 39% because of PAGE's probabilistic approach looks as if STERN wanted to get to 20% impacts. These 20% appear many times in the Review, as well as in critiques of it. While it is not clear

that STERN overvalues the importance of EW, the calculation presented is unscientific and I find it unfortunate that it is often cited without mentioning its context and foundation.

3.3.2. Discounting in the Stern Review

Sterns approach to discounting is treated in chapter 2 and the associated Annex 2.A of the Review. It is based on the RAMSEY framework presented in section 2.5.2. Accordingly the central variables are the growth of consumption (*g* in the Review), the pure rate of time preference (PRTP, δ) and the elasticity of marginal consumption (*μ*). Consumption growth *g* is determined externally according to SRES scenario A2 and its extrapolation. The two other values δ and μ are set 0.1% and 1 in the Review. There is no sensitivity analysis of the two included. Thus, to calculate the discount rate ρ, g replaces $\dot{c}/c$ in Equation 1, which results in:

$$\rho = g * \eta + \delta$$

When looking at a development path following from a certain scenario, the amount of welfare that comes from a certain amount of consumption; and the discounted welfare, aggregated over time are decisive. These two values are given by the Utility function:

$$u(c) = c^{1-\eta}/1-\eta$$

Equation 4:Standard Utility Function

Which is u(c) = ln(c), for η = 1. Discounted welfare (time bounds need to be added to the integral) over time is

$$W = \int u(c)\, e^{-\delta t}\, dt$$

Equation 5: Welfare over Time

As stated in chapter 2.5.2, *η* is a measure for aversion against inequalities. In STERN's modelling framework, *η* also captures a societies' *relative risk aversion*. This is because for positive *η*, of the 1000 runs per scenario, low growth runs will have stronger influence on the scenarios' welfare average than runs that reach high consumption levels. This effect of *η* favours scenarios that produce little variation in outcome. The higher *η* is, the stronger the effect. Setting *η* = 1 means rather little relative risk aversion and little aversion against distributional inequalities. To legitimate his choice, STERN states: *"In our main case, we take η to be 1, in line with recent empirical estimates"* without further discussion (STERN 2006:161, in fact the only estimate he refers to is that of PEARCE and ULPH 1999).

In contrast to the missing discussion on η, there is considerable reasoning for the choice of the PRTP. Here STERN is unambiguous: "*if a future generation will be present, we suppose that it has the same claim on our ethical attention as the current one*" (STERN 2006:31). This means that there are no reasons for pure time discounting, except the possibility of extinction of the human race. Following this STERN sets $\delta = 0.1\%$ per year (which in this sense is high). With consumption growth of 1.3%-1.9% (see section 3.1), a discount rate of 1.4%-2% results for the calculations of the Review.

STERN's position *prescribes* the PRTP. Based on an ethical argumentation, it doesn't take into account empirical market observations that *descriptive* approaches would refer to. His *prescriptive* approach is in line with numerous well known economists such as Robert SOLOW, Amartya SEN, Arthur C. PIGOU and Frank RAMSEY. The controversy between economists favouring *descriptive* or *prescriptive* approaches is one key issue in the discounting discussion. It will be further elucidated in section 3.3.3.

It has to be noted though, that STERN makes a difference between discounting in the context of long-term path comparison and short-term project decisions:

> "*If a projects costs and benefits affect only this generation then it is reasonable to argue that the revealed relative valuations across periods has strong relevance (as it does across goods). On the other hand as we have emphasised allocations across generations and centuries is an ethical issue for which the arguments for low pure time discount rates are strong*." (STERN 2006:47/48)

To evaluate such projects, STERN refers to the position of the HM Treasury's "Green Book" (HM TREASURY 2003), which uses higher PRTP (STERN 2006:47).

3.3.3. Critique of Sterns Intra- and Intergenerational Aggregation

STERN's discounting approach has been in the focus of most critiques of other economists. I will try to order their discussion, splitting the critiques in two parts. The first is focussed on STERN's discounting methodology and its consistency. The second is more of a discourse analysis; it deals with the objection of the *prescriptive* approach as such and discusses the implications of using a *descriptive* approach, for which many economists argue.

STERN himself expresses the importance and his (methodological) exigencies for different fields of aggregation as follows: "*How policy-makers aggregate over consequences (i) within generations, (ii) over time, and (iii) according to risk will be crucial to policy design […]. The Review pays special attention to all three forms of aggregation*." (STERN 2006:29) And

"*It* [a welfare analysis of climate change] *should carry out these three types of aggregation consistently."* (STERN 2006:158)

Arguably, the exigency of paying *special attention* to aggregation is contradicted by the fact that STERN gives no reasoning for the choice of *η,* which accounts for aggregation of consequences *according to risk* and *within generations,* and the missing sensitivity analysis of both the parameters *η* and *δ*.

Another aspect of critique follows directly from STERN's second citation, which was explicated in section 2.5.2. The choice of *δ* and *η* cause such a high saving rate (36%, see Table 3), which demands high consumption abandonment for current generations. This is not coherent with STERN's egalitarian intergenerational position, as the present generation is poorer than its followers and thus it is contradictory to demand them to save 36% in favour of their successors. A value of η=2 results in a savings rate of 18% which seems more realistic and ethically contingent. It is not evident though, that changing STERN's discounting approach to be ethically contingent would result in less stringent climate policy: Higher risk aversion leads to more stringent policy, while at the same time aversion to welfare inequalities would bring the focus more on the present generations' welfare instead of avoiding climate change on their cost (DASGUPTA 2006:8).

There has also been a controversy about calculating the saving rate related to STERN's $\eta = 1$ and $\delta = 0.1\%$; in contrast to the 36% saving rate Reviewed in Table 3, DASGUPTA (2006:6) cites a rate of 97.5%. It is worth having a look into how DASGUPTA calculated this; his approach starts rearranging Equation 2 to:

$$g(C) = (\rho - \delta)/ \eta; \dot{c}/c = g(C)$$

DASGUPTA assumes constant population and sets the discount rate *ρ* (which in his argument is equal to the rate of return on investment *r*) at 4%, which means a consumption growth of 3.9%. Now in a steady state, the growth of consumption equals overall economic growth *g(Y)*. Following a HAIG-SIMONS output equation the relation between economic growth, investment and consumption is:

$$g(Y) = r\,(1\text{-}C/Y)$$

Equation 6: HAIG-SIMMONS Output Investment Relation

From here demanding *g(Y)* to be 3.9% forces consumption C/Y down to 2.5% which confirms DASGUPTAs 97.5% saving rate. However, this conception assumes that economic growth only stems from investment; including technological progress, the picture changes considerably as DE LONG demonstrates in an entry in his internet blog (http://delong.vox.com/library/post/haigsimons-income-vs-gdp.html, last visited 8.5.2008). With technological progress (*g(A)*) the saving rate is given by:

$$g(Y) = r\,(1-C/Y) + g(A)$$

Setting *g(A)* = 3% per year, the saving rate drops to 22.5% (leaving 77.5% of economic output for consumption). A *g(A)* of one or two percent delivers saving rates of 72.5% and 47.5% respectively. This shows that DASGUPTA's alarming 97.5% saving rate depends on the omissions of technological progress and stems from a simple economic concept. I think that Equation 3. (which considers the competitive share of capital β) upon which Table 3 is based, is the more adequate way and, accordingly, the numbers presented in Table 3 are more credible than DASGUPTA's. In any case, DASGUPTA did clearly state that his calculations were "*classroom exercises*" and thus they were not meant literally, but to show how easy it is to produce extreme outcomes handling the ethical parameters η and δ (this is what he stresses in his response to DE LONG's calculations in his blog)

To get back to STERN, I do not think that he meets his above cited requirements, as his discounting parameters δ and η are not varied. Particularly, η is not soundly reasoned for and is set too low to be ethically consistent. However, it is important to note that STERN himself has accepted these flaws and addressed them; in STERN (2008:49) he considers higher values of .η.

An interesting other approach of criticism is found in NORDHAUS (2006). He argues for alternative prescriptive concepts than demanding equal treatment of future generations. Particularly, he names a *Rawlsian* approach that would maximise the welfare of the worst-off generation or demand (at least) constant overall *societal capital*; consisting of *"tangible, natural, human, and technological"* components (NORDHAUS 2006:9). To calculate the societal capital described above would demand a multi dimensional approach instead of a one dimensional monetarian one. This is certainly not trivial, but maybe worth considering if one believes that incommensurability exists within the impacts of climate change. On the contrary, to pursue a *Rawlsian* approach in the climate context would prevent any climate action as long as economic growth rates are positive (any present generation will always be worst off which impedes policy in favour of future generations). This "*devil-may-care*" attitude doesn't seem attractive in the climate context for my concern. Without further discussing NORDHAUS' proposals here, we can hold that there are alternative prescriptive conceptions to the one of STERN.

Economists that favour a *descriptive* approach often focus on the contradiction between a prescribed ethical position and market realities, i.e. market agents behaviour concerning e.g. saving rates, development aid or future investments. TOLs' fierce argument in an internet-blog shows this exemplary:

> "*It has been long known that if the discount rate were low, or equity were important, then we should really do quite a lot about climate change. More generally, the world would be a much better place if people were nice to each other. Reality is different, though. […]If you argue that there should be global, inequity-averse dictator for climate change, the same should hold for everything else. A large part of the meagre […] income that you do not save, would go to Africa. If you are willing to do that, I would be willing to believe that your pure rate of time preference is 0.1% and your rate of risk aversion is unity. Somehow, I don't think that you put your money where your mouth is*."
>
> (see: http://johnquiggin.com/index.php/archives/2006/12/19/reviewing-the-stern-review-again/#comments)

Even though TOL's statement is quite polemic, its argumentation is representative of many critiques of STERN's approach. Now, can such argumentation disprove STERN? I think for one main reason it cannot: STERN doesn't orientate on observed reality; his position is based on ethical conviction. Confusing this is like saying that rejecting the death penalty as ethically indefensible can be disproved by the fact that it is practiced.

Now, what is behind the two approaches? In the climate case, the dispute behind *prescriptive* and *descriptive* approaches is to what degree markets produce optimal results and whether or not they represent people's preferences. If one believes that markets are the best representation of people's preferences, then it is logical to demand markets to guide policy. A policy maker should thus do (or *describe*) what the market indicates. However, if one thinks that markets are potentially defective and that they do not necessarily represent people's preferences, then a policy maker that follows ethical standards rather than market outcomes is preferable. For instance, it is quite possible that a majority of the world's population would prefer higher development aid to Africa than what is fact today, or they would consider their countries' income distribution unfair. Strictly following TOL's argumentation means to ignore such possible misbalances and to give up policy's capacity to alleviate market failures.

This contradictory conception of a policy maker's role exist in other political fields as well e.g. in the economics of welfare states where it corresponds roughly to conceptions of economic liberalism with a laissez-faire state on the one hand and such of more paternalistic social welfare states on the other.

For deciding between *prescriptive* or *descriptive* approaches, it should thus be considered if there are good reasons to believe that market outcomes differ from people's preferences in the discounting case. Some authors have tried to find out about people's preferences in long term discounting by surveying them. HEAL (1997:338) names an implied PRTP of 2% for investment decisions with a horizon of about a hundred years. He found that people discount lower the longer the time horizon of an investment decision is (this is called *declining* or *hyperbolic* discounting). SHERWOOD (2007:209) comes to a still lower result referring to a bayesian analysis by LAYTON and LEVINE (2003):

> *"Layton and Levine (2003) analyzed the results of a survey explicitly asking respondents to compare different investment and environmental change scenarios reaching into the far future, […]. The authors report that results implied a discount rate of less than 1%, indicating that despite their strong instinct to discount in everyday situations, most people reject long-term discounting of human welfare."*

These results indicate that, in long-term discounting, it is reasonable to assume that conventional market discount rates differ from people's preferences. There are several other arguments that can be taken as reasons for rejecting *descriptive* discounting e.g. the fact, that future generations' preferences are not represented in today's markets. However, it will finally remain a matter of taste if policy makers should be entitled to apply ethical judgments rather than market observations to guide policy. Seeing this another question comes in the focus: Is the discussion really as important as it seems, i.e. are the results of the two approaches really going to be that different?

Usually, modellers of IAM that argue for *descriptive* discounting suppose a PRTP of around 3% (MERGE has discount rate of 5% including GDP growth WARREN ET. AL. 2006:22; PAGE2002 uses a PRTP of 3% in the version of HOPE 2006; FUND uses 1%, WARREN ET. AL. 2006:52; DICE uses a rate that declines from 3% to 1% in 300 years, NORDHAUS 2006:13). When this is combined with medium to high growth projections, the rate can easily be in the range of MERGE's 5%. From this point of view, the difference to STERN's 1.4%-2% is in deed tremendous (Table 2 gives an idea). But it is worth taking a step back to see how an adequate *descriptive* rate could be found. WEITZMAN (2007a) (an ardent opponent of *prescriptive* approaches) gives very interesting insights on that issue. He stresses that there is uncertainty about the degree to which climate change's negative impacts on utility (or utility benefits from climate policy respectively) are directly linked to economic growth. If parts of what generates human utility don't grow with the economy, but stagnate or even decrease, than these components should lower the discount rate (alternatively one could argue for differential discount rates as explained in BROOME 1994). WEITZMAN opts for a factor *β* to represent this *utility-economy* linkage. *β* lies between 1 and 0, lower values meaning that utility is less linked to economic growth. To further define the rationale behind *β*, WEITZMAN distinguishes *outdoor* activities (agriculture, coastal recreational areas, and natural landscapes, also including the existence value of ecosystems) that are likely to be strongly influenced by climate change and are rather decoupled from economic growth and technological progress and *indoor* activities that are strongly linked to future technological progress (e.g. increase of computational power) and are probably less hit by climate change. The uncertainty about the correct value of *β* produces uncertainty about the discount rate. Additionally, WEITZMAN stresses that when there is uncertainty about the correct discount rate, a tendency towards the lower estimate is the result:

> *"A 0.5 chance of r = 6% and a 0.5 chance of r = 1.4% are not at all the same thing as splitting the difference by selecting the average r = 3.7%. It is not discount rates that need to be averaged but discount factors. A 0.5 chance of a discount factor of* e^{-6} *a century hence and a 0.5 chance of a discount factor of* $e^{-1.4}$ *a century hence make an expected discount factor of* $0.5e^{-6} + 0.5e^{-1.4}$ *a century hence, which, when you do the math, is equivalent to an effective interest rate of r =2%."* WEITZMAN (2007a:9)

He sees a future tendency towards lower *β,* with growing wealth as the income elasticity for environmental goods is high. This argument could become more relevant still, as scarcity of environmental goods is likely to increase, which will cause their relative importance for utility to rise further (see HOEL and STERNER 2007). WEITZMAN concludes that *"the Stern value may end up being more right than wrong when full accounting is made for the uncertainty of the discount rate."* (WEITZMAN 2007a:9).

Considering the above arguments, discount rates well above 2% referring to *descriptive* reasoning is doubtful and at the same time the difference between *descriptive* and *prescriptive* discounting becomes smaller than often assumed in climate literature.

3.3.4. Conclusions

To summarise we can draw three important conclusions from this section: first, that STERN's discounting can be criticised on a technical level, second, that *descriptive* and *prescriptive* argumentations cannot outcast each other as they are placed in different spheres and third, we have seen that the uncertainty about the nature of climate change's impacts on human utility can drive a *descriptive* discount rate below conventional market rates and into a similar range as the one that STERN uses. This final conclusion is particularly important from my point of view: it shows that there are good arguments for low discounting of climate impacts no matter if one prefers a *descriptive* or a *prescriptive* approach. Maybe instead of focussing so much on the controversy about discounting, it is more important to turn to other critical issues related to CBA in the climate issue (e.g. the treatment of risk and uncertainty).

3.4. Results

In this section, the results of the Review are presented. In the critique there will be a discussion on STERN's central reasoning. The main question here is if the results soundly represent the gathered modelling information from the previous chapters. The section is concluded by assessing the meaning of STERN's results for climate policy, in particular, for the *climate policy ramp*.

3.4.1. The Review's Results

While the previous chapter on mitigation presented feasible targets for climate policy, in chapter 13, STERN discusses them with cost and benefit criterions (I will focus on the model based approach, chapter 13 also discusses a bottom up and a marginal approach). He defines a range of GHG concentrations as climate policy targets. The lower boundary is where mitigation efforts become prohibitively expensive or unfeasible. The range's upper boundary is where concentrations provoke a rapidly growing occurrence probability of catastrophic climate change but would still be appropriate if impacts result lower than expected and mitigation costs tend towards upper estimates. According to these guidelines, STERN suggests an upper boundary of 550ppm CO_2e (STERN 2006:299, 295).

Table 9: Concentration Targets and consequent equilibrium Temperature Rise Probabilities in Percent						
	2°C	**3°C**	**4°C**	**5°C**	**6°C**	**7°C**
450ppm CO_2e	78	18	3	1	0	0
500ppm CO_2e	96	44	11	3	1	0
550ppm CO_2e	99	69	24	7	2	1
650ppm CO_2e	100	94	58	24	9	4
750ppm CO_2e	100	99	82	47	22	9
Source: STERN (2008:13)						

Table 10: Estimates of the Costs of Climate Change by Temperature Increase, as a Proportion of Gross World Product, from PAGE2002 (expressed in lost consumption percentages. In the boxes: *Mean value* (*lower - upper bound* of 90% confidence interval)	
2°C	0.6 (0.2 - 4.0)
3°C	1.4 (0.3 – 9.1)
4°C	2.6 (0.4 – 15.5)
5°C	4.5 (0.6 – 23.3)
Source: STERN (2006:295)	

Concerning the lower boundary, STERN finds that, until 550-600ppm CO_2e, "*the benefits of choosing a lower stabilisation goal clearly outweigh the costs*" (STERN 2006:299) but that below that, cost benefit calculations are less clear cut: "*The incremental mitigation costs of choosing 500 – 550ppm instead of 550 – 600ppm CO_2e are three to four times as much as the incremental costs of choosing 550 – 600ppm instead of 600 – 650ppm* CO_2*e*" (STERN 2006:299, see Table 11). Nevertheless, aiming somewhere 500ppm CO_2e is still possible. To stabilise GHG concentrations at 450ppm CO_2e or below that is "*likely to be very difficult and costly*" as the world is already at 430ppm CO_2e concentration, currently growing at 2.5ppm CO_2e per year (STERN 2006:299).

Table 11: Cost of shifting up Concentration Targets, expressed in %GWP					
Target	**Discount Rate**				
	5 %	**Declining Rate***	**2 %**	**1 %**	**Undiscounted**
Moving from 500ppm to 450ppm CO_2	0.25	0.39	0.43	0.51	0.58
Moving from 550ppm to 5000ppm CO_2	0.06	0.11	0.12	0.14	0.18
*The Declining Rate is adopted from the "Green Book" (HM TREASURY 2003), starting at 3.5% for the first 30 years, then dropping to 3.0% until year 75, and 2.0% until year 125					
Source: STERN (2006:296) based on Table 7					

In concrete numbers, STERN argues that compared to the nearly 11% damages projected for that BAU case (see Table 5), stabilising at 550ppm CO_2e could reduce damages to about 1.1% (about 90% reduction) at costs below 1% GWP. Reducing to 450ppm CO_2e would lower damages by further 0.5% to 0.6% though causing much higher mitigation efforts (STERN 2006:295). The Review gives no details how the damages related to 450 and 550ppm CO_2e are calculated. However, Table 9 shows that most likely the stabilisation temperature at 550ppm CO_2e (450ppm CO_2e) lies between 2-4 C° (2-3 C°) above pre industrial levels. From Table 10 we find damages between 0.6%-2.6% (0.6%-1.4%) of GWP, which roughly confirms the results. Consequently, STERN defines 450-550ppm CO_2e as the range of adequate climate policy targets and states:

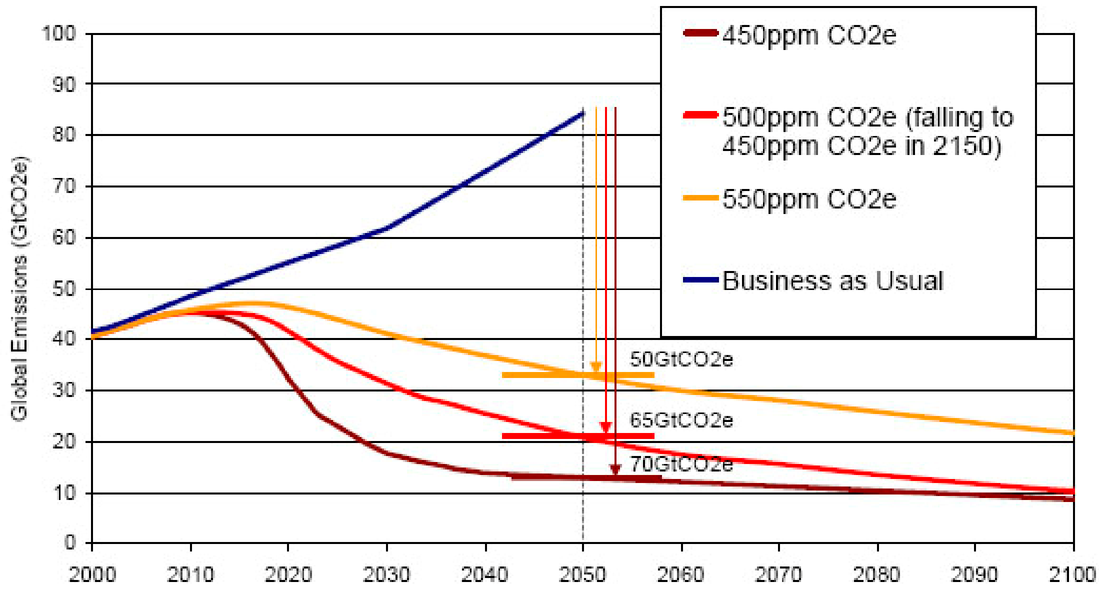
> *"Anything higher would substantially increase risks of very harmful impacts but would only reduce the expected costs of mitigation by comparatively little. Anything lower would impose very high adjustment costs in the near term for relatively small gains and might not even be feasible, not least because of past delays in taking strong action"* (STERN 2006:284)

Despite of the important amount of damages avoided, concentration level at 550ppm CO_2e still involves the possibility of high stabilising temperatures; Table 9 shows a 24% risk of equilibrium temperatures exceeding 4 C° and still of 7% for 5 C° (550ppm CO_2e is about a doubling of pre industrial concentrations so the resulting temperature increases correspond closely to the climate sensitivity range in section 2.2). However, there is a considerable difference to what a development with no climate policy would imply; the PAGE2002 BAU case (baseline climate) calculates a mean temperature increase of 7.4 C° above pre industrial levels (STERN 2006:158). The BAU 2200 concentration level is not given in the Review, but can be estimated; starting in 2100 the range in PAGE2002 is given to be 700-900ppm CO_2

(HOPE 2006:26). From 2100 to 2200 emissions are set constant at 30Gt CO_2/year (the SRES A2 value in 2100). Applying the Reviews' estimation – that per emission of 15-20GtC02, CO_2 concentration rises by about 1ppm (STERN 2006:196) – yields a further increase of 150-200ppm CO_2 in the 22nd century. This implies concentrations in the region of 850-1100ppm CO_2 in 2200.

It is important to note that the used mitigation models refer to 2000 as base year, which makes targets already harder to reach (STERN 2006:297). Further, the Review states "*weak action over the next 20 to 30 years, by which time GHG concentrations could already be around 500ppm CO_2e, would make it very costly or even impossible to stabilise at 550ppm CO_2e*" (STERN 2006:298). In a later lecture, STERN specifies "*waiting for 30 years before strong action would take us to around 530ppm CO_2e, from which point the cost of stabilising at 550ppm CO_2e would likely be similar to stabilising at 450ppm CO_2e starting from now*" (STERN 2008:17/8). This indicates little time for delay. Starting now, in rough terms, reaching a 550ppm CO_2e (500/450ppm CO_2e) goal means cuts of about 30% (50%/70%) in 2050 relative to year 2000 levels (STERN 2006:200). Figure 7 shows exemplary emissions trajectories (mitigation initiating now) leading to different targets.

Figure 7: Emission Trajectories for specific Concentration Targets



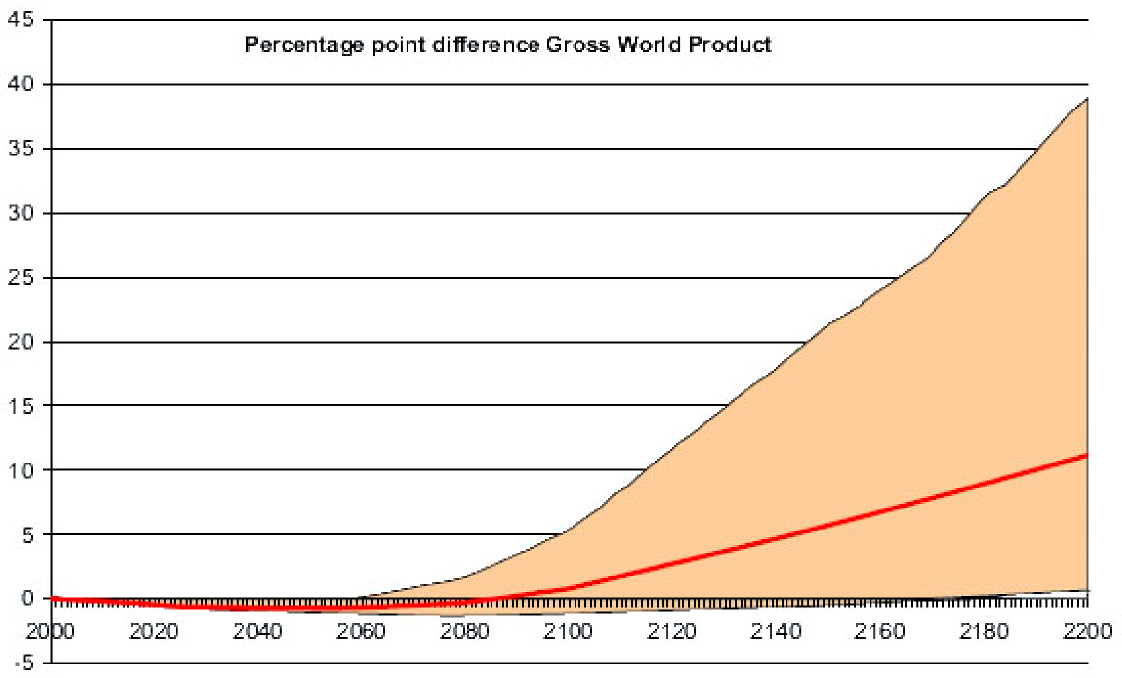
Source: STERN (2006:206)

3.4.2. Critique of the Review's Results

The results presented in chapter 13 of the review are based on several pillars; the data from the Reviews modelling which was the focus of this work, bottom up approaches (that were also mentioned in the beginning of correspondent sections of this work) and maybe the most important contribution of chapter 13, an explicit consideration of risks related to climate targets.

However, STERN's argumentation is misleading in one case, resulting in some sharp criticism. Figure 8 (Figure 13.1 in the Review) is a mixing of a PAGE2002 BAU impacts (*high climate* with all impact categories- the red line in Figure 4) with mitigation costs of 1% (in the Review there is the same figure also with costs at 4% GWP).

Figure 8: "Output Gap" at 1% Mitigation Costs



Source: STERN (2006:285)

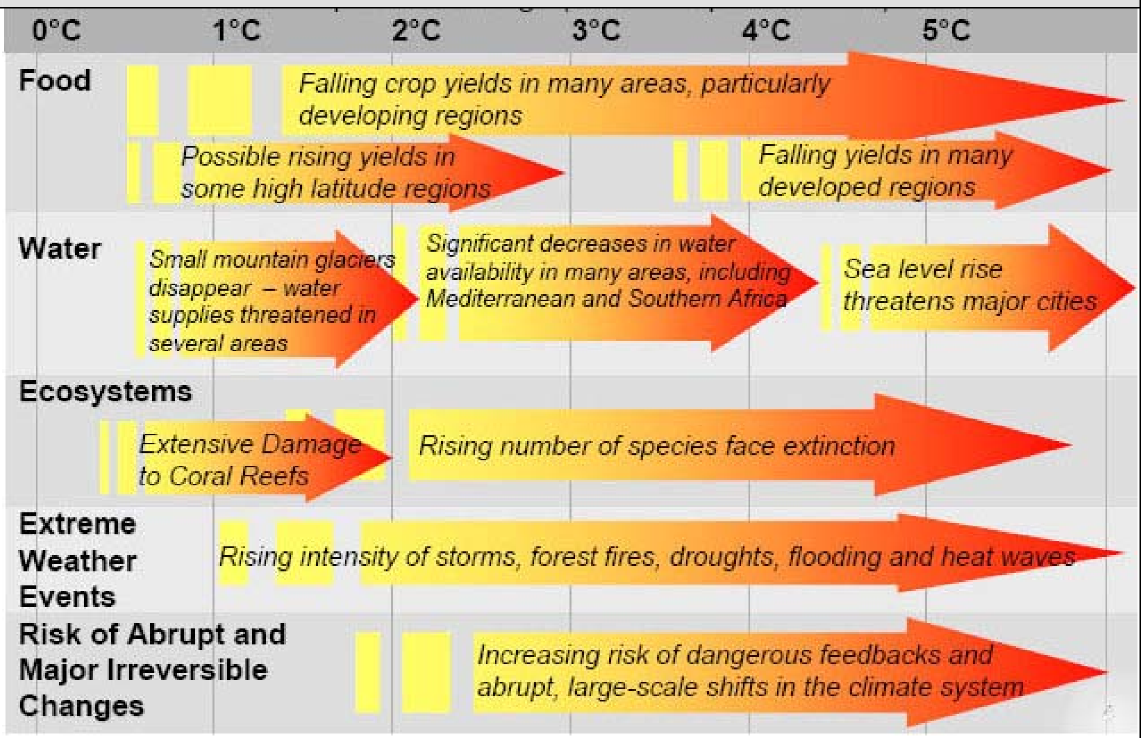
The resulting curve is titled *output gap* between mitigation costs and the BAU scenario. The figure suggests that at one percent GWP all climate damage could be avoided. Apparently this is what TOL (2006) refers to concluding „*The Stern Review does not include a cost-benefit analysis, apart from a ranking of two projects. It compares the magnitudes of the costs of abatement [...] to the costs of climate change [...] and concludes that the latter justifies the former*". He correctly criticises that *"the benefits of emission reduction are smaller than the costs of climate change*"- there will always be residual climate change and thus resulting damages. A world without climate change is not an option. As cited above though, STERN does a specific comparison of the costs of stabilising at 550ppm CO_2, with the related averted damages. While TOL could have read the Review a little more accurately, the informational benefit of Figure 8 *is* dubious.

All the same, the key novelty of the Review's results is the rejection of the so called *climate policy ramp* in favour of immediate mitigation efforts. The *climate policy ramp*, common position among economic climate scientists, means moderate climate policy now, tightening emissions slowly in the beginning and faster in the far future (see e.g. NORDHAUS 2007). NORDHAUS (2006:21) affirms that the rejection of the policy ramp is merely due to STERN's low impact discounting. In addition, as was discussed in section 3.1.2, the particular choice of the discount rate in PAGE2002 is important for STERN's impact results. However, in my view, STERN's argumentation is not mainly focussed on the averaged results of impact modelling. The more important reason to reject the *climate policy ramp* is the assessment of uncertainty and risk in climate policy, particularly considering *option values* (see e.g. WEITZMANN 2007a:22ff for a brief and informing of option values and uncertainty in climate policy). Works that support the policy ramp stress that waiting for both more information about the exact structure of the climate problem and for technological process to bring down abatement costs is favourable (however as argued in section 2.4.2 abating early will also initiate necessary learning-by-doing lowering the costs of alternative technologies and give signals for long term investment to shift away from carbon intense technologies). As KELLY and KOLSTAD (1998:7) put it, the main question concerning uncertainty is then "*Do we know enough to control the problem or should we wait until more is known about climate change?*" Too hasty (and thus costly) mitigation is seen as the major problem in this reasoning; waiting is related to a high *option value*.

STERN (2006:246; 292) doesn't disagree with that logic. However, he argues that waiting for information will take too long. If the uncertainties about the climate system's reaction on higher GHG concentrations (particularly uncertain impacts in section 2.3.2 and the upper ends of climate sensitivity estimations are relevant in this sense) resolve in negative surprises, then, as argued in the previous section, shifting to lower emissions goals will probably be impossible. On the other hand, if climate change results are less grave, then too strict policy can still be relaxed. STERN sees this latter argumentation more important than pro *climate policy ramp* reasons. It is the uncertainty about the climate system's reaction towards GHG emissions that is the key reason for demanding early and decided mitigation policy. The *option value* of maintaining flexibility to react on bad surprises is higher than the one of waiting for better technologies.

To illustrate the difference between the two approaches, it is useful to compare STERN's results to NORDHAUS' orientating in a *climate policy ramp.* NORDHAUS (2007:90), using his DICE model, advocates for concentrations of 586ppm CO_2e in 2100 and 658ppm CO_2e in 2200 in the *optimal control case*. Additionally, DICE's BAU case assumes lower emissions than PAGE's: 686ppm CO_2e in 2100 and 1183ppm CO_2e in 2200, compared to 700-900ppm CO_2e and 850- 1100ppm CO_2e with PAGE2002. Thus, the difference in the mitigation gap (the total GHG emissions to be mitigated) is even bigger. Leaving aside which BAU case is more realistic; what would-be risk is present at NORDHAUS' optimal GHG concentration? Table 9 shows that at 650ppm CO_2e we would face a 24% chance of equilibrium temperatures exceeding 5C°, compared to 7% at 550ppm CO_2e. Almost certainly temperatures would rise above 3C° and there would be a 9% chance of even passing 6C°. A further look at Figure 9 shows the projected consequences that follow temperature rises of 5C° above industrial levels.

Figure 9: Projected Impacts at different equilibrium Temperatures



Source: STERN (2006:294)

Even though the depiction is illustrative, when overlooking the possible consequences it becomes strikingly clear that from equilibrium temperature rises of 4C° on, and clearly passing 5C°, consequences are likely to be disastrous (see STERN 2008:14-17 for further detailed description of such temperature's consequences).

In this sense, I think that STERN's precautionary approach is comprehensible. The lowered likelihood of extreme temperatures *bought* (to get from the BAU case and the 550ppm CO_2e target) for less than 1% GWP is justified. It even seems desirable to maintain targets well below 550ppm CO_2e possible. To say it in STERN's own words:

> *„A concentration in the region of 550ppm CO_2e is clearly itself a fairly dangerous place to be and the danger posed by even higher concentrations looks unambiguously unacceptable. For this reason I find it remarkable that some economists continue to argue that stabilisation levels around 650ppm CO_2e or even higher are preferable to 550ppm, or even optimal […]. It is important to be clear that the "climate policy ramp" […]) advocated by some economists involves a real possibility of devastating climatic changes*." STERN (2008:17).

3.4.3. Conclusions

The above discussion of the Stern Review's results and its reasoning showed that, besides a cost benefit examination, risk analysis plays a major role for STERN. The presented information suggests that the risks related to a less stringent policy target than STERN's upper limit for GHG concentration will, in fact, cause a very high chance of disastrous outcomes. Considering this, STERN's rejection of the *climate policy ramp* and his call for immediate strong mitigation policy seems justified. Moreover, for future discourse it would be interesting to examine targets in a range of 500-550ppm CO_2e.

4. Conclusions and Outlook

The main question of this work was whether or not the Review presented sound reasoning for its call for immediate action. This implied checking the adequateness of impact and mitigation modelling and for the coherency of the ethical judgements underlying. Two major results from the discussion can be noted: First, there were a number of methodical objections in different sections, these particularly concerned missing sensitivity analysis and little variance of external data inputs assessing climate impacts. Methodologically, I find the dominance of far future values on overall impact estimates problematic, as these are scientifically the most speculative. Further, the way STERN uses equity weighting as an argument to increase his (non equity weighted) impact results is unsatisfactory, in my view. Some of these flaws are explainable by time pressure releasing the Review and they have been addressed in the meantime, namely in STERN's Ely Lecture (STERN 2008). Nonetheless, particularly concerning impact estimations, I find that the Review has a tendency to enforce unambiguous results at the cost of scientific accuracy. There is one statement that makes this tendency tangible; in favour of using BGE (instead of time-damage paths) as main results, STERN curtly argues "*If the result is to guide policy, it must be easily understandable*" (STERN 2006:160). I would argue that problems as complex as climate change cause somewhat complex results.

Notwithstanding the above criticisms, the flaws do not imply a uniform bias of the Reviews results. Second and central for the main question of this work, mitigation and impacts are adequately enough modelled and assessed to back up STERN's policy recommendations. Further, the low discounting rate is not so far from standard economics, when the particular nature of climate change's impacts is considered.

In short, the Stern Review's call for early and strong action is well founded and is not disentitled by its critiques, although some methodical objections hold.

For future improvement of models used for climate policy assessment, I find there are some particularly important fields. Firstly, harmonising impact modelling to improve comparability among different approaches seems promising. Also, if impact modelling referred to impacts at specific GHG concentration levels, just as mitigation cost models, results would be easier to compare. Another model improving step would be to integrate endogenous adaptation.

Potential improvement also exists concerning the genesis of units compared in Stern's CBA approach; while e.g. climate impact estimation includes non-market damages and risk of catastrophic events, this is not the case for BAU utility from which damages are subtracted. BAU utility stems from (GWP-) consumption only. There is no consideration of aspects like *utility from non-market goods* or a positive value of *life with less fear of catastrophes*. Thus, impacts and utility do not refer to the same main unit. This is a conceptual deficit; it could, for instance, cause impacts that exceed utility, i.e. damages above 100% of utility. At the same time, it has influence on the argument concerning descriptive discounting. In section 3.3.3, I have argued for a low rate, because many climate impacts are not linked to economic growth (implying low β). On the other hand, what we discount is the residual future BAU utility, which depends merely on GWP growth, in this sense β should be one. A broader concept of utility could not only resolve this inconsistency, it could also be a more realistic representation of human preferences. In a similar vein, secondary benefits of mitigation options (e.g. on air pollution or health) as well as risks of technical mitigation options, such as nuclear energy, could be integrated as secondary effects in mitigation modelling.

In my view, despite the important critique against STERN's modelling, his approach takes a big step forward compared to previous studies. It takes into account (some of) the uncertainty related to climate change, showing that it is misleading to argue about the optimal path of emissions, as if this was a determinable option. In the Review's terms, climate policy is more than anything a matter of risk assessment; it is about what future risk we are willing to accept (and in a second step, how we can avoid too big of risks in a cost effective way). This approach is backed up by the fact that best- and worst-case impact estimates differ by several orders (see Table 5). The fact that STERN does not account for uncertainties about future GHG emissions by using different SRES scenarios and that he doesn't consider the recent upper extremes of climate sensitivity estimates (e.g. by using the *high+ climate* scenario) implies that the range of results could arguably be even bigger. In fact, the presence of uncertainty has led some economists to argue that CBA might not be adequate to assess climate policy (WEITZMAN 2008, TOL 2003).

It seems very likely that the trend in climate policy assessment following the Stern Review will prescribe what STERN initiated: A risk analysis concerning the impacts of climate change finding maximum tolerable levels of GHG concentrations and following this an analysis of cost effective ways to get there.

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