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Climate Policy: Costs and Design

A survey of some recent numerical studies

Michael Hoel, Mads Greaker, Christian Grorud,
Ingeborg Rasmussen

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Nordic Council of Ministers
Store Strandstræde 18
DK-1255 Copenhagen K
Phone (+45) 3396 0200
Fax (+45) 3396 0202

Nordic Council
Store Strandstræde 18
DK-1255 Copenhagen K
Phone (+45) 3396 0400
Fax (+45) 3311 1870

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Content

Preface

This report gives results from a project financed by the Working Group on Environment and Economics under the Nordic Council of Ministers. The aim of the project has been to give a thorough discussion of some recent studies on economic issues related to climate change and climate policies. The focus is on various numerical analyses and not on the purely theoretical studies.

The leader the project was Michael Hoel, University of Oslo. The report was written jointly by Michael Hoel and Mads Greaker (Statistics Norway), Christian Grorud (Vista Analyse) and Ingeborg Rasmussen (Vista Analyse).

Many of the studies we considered report costs for stabilizing CO_2 emissions at about 450 ppm CO_2, corresponding roughly to 500-550 CO_2-e. The long-term temperature increase for such a concentration target will be about 2.5-3^{o}C. The cost estimates vary considerably. For approximately the same climate targets, the total costs are in the range of 1-5% of GDP.

The marginal cost of mitigation, often called the carbon price, tells us how strict climate policy must be in order to achieve the climate target. Under an efficient climate policy, the carbon price should increase over time at a rate below the discount rate. This holds in most of the studies, but in some of them the carbon price grows considerably faster.

The predicted carbon price necessary to achieve a climate goal of the type above differs strongly between studies. Most of the studies predict a carbon price in 2050 in the range of 100-400 US $ per ton of CO_2.

1 Introduction/Summary

There is a large and growing literature focusing on economic issues related to climate change and climate policies. This report presents a discussion of some of the recent studies. Our focus has been on various numerical analyses and not on the purely theoretical studies.

Among the important issues in the studies we discuss are the following:

a.) What will the development of greenhouse gas emissions be and what climate changes will follow if no new policies are introduced?
b.) What can economic analyses tell us about climate policy goals?
c.) What are the costs of reducing emissions?
d.) What types of policies should be used to reduce emissions?
e.) For a given climate goal, what are the additional costs of using sub-optimal policies?

Each of the studies considered in this report address some or all of these questions. In the present section we give both a non-technical discussion of the methodologies used to answer these questions and a summary of the most significant results.

a) Emissions under BaU

Projections of greenhouse gas (GHG) emissions and climate development without any change of policies are often called ‘business as usual” (BaU) predictions. These will be strongly influenced by assumptions made about population growth and the growth of per capita GDP. The latter is to a large extent determined by what is assumed about total factor productivity growth. Assumptions about population growth and total factor productivity growth are in most analyses taken as exogenous from various sources. Since these variables are highly uncertain for the time perspectives relevant for studying climate change (at least 100 years into the future), many studies consider several alternatives.

The development of GDP follows from the assumptions made about population growth and the development of GDP per capita. Total GHG emissions are often measured in CO_2-equivalents (CO_2-e) and split into three components. The most important (currently approximately 60% of total emissions) is energy-related CO_2 (sometimes called industrial CO_2), which include all fossil-fuel emissions plus CO_2 emissions from industrial processes. The other two components are other CO_2 emissions (mostly from deforestation) and other GHG emissions. Predictions for these last two components are often made exogenously, while energy-related CO_2 is usually modelled endogenously. The simplest way to model this is to assume some exogenous development of energy-related CO_2 per unit GDP. For instance, the study using the DICE model (discussed in section 3.1) assumes, based on historical trends and predictions of the future composition of GDP between regions, that industrial carbon emission per unit GDP will decline by 0.6% per year for the rest of this century (under BaU). A more satisfactory way of modelling industrial carbon emissions is to have an explicit modelling of various types of energy and other inputs in a production function explaining the development of GDP. This is the procedure used in the studies discussed in sections 3.2 and 3.4 (ENTICE, WITCH).

Predictions about BaU emissions differ quite a lot between different studies. For instance, in 2050 industrial CO_2 emissions in the study using the ENTICE model reported in section 3.2 are about 11 Gt carbon under BaU, while they are about 16 Gt in the study using the WITCH model reported in section 3.4, in spite of the models being relatively similar. The latter prediction is roughly in line with what is assumed in the Stern Review (discussed in section 4.2). Incomplete reporting in several of the studies means it is in many cases not clear whether differences in CO_2 emissions are due to differences in GDP predictions or in predictions of emissions per unit of GDP.

Different predictions of CO_2 emissions give different predictions for concentration levels of GHGs in the future, and therefore also for temperature changes. In the most recent IPCC report (discussed in section 4.1), emission trends are based on a set of scenarios developed by the IPCC in a ”Special Report on Emission Scenarios” (SRES). These should be interpreted as BaU scenarios. Basically there are four main families of scenario, A1, A2, B1 and B2, each with a number of sub-scenarios. The parameters of the scenarios differ in four ways: size of economic growth, regional difference in economic growth, degree of global technology diffusion and success of less polluting technology. Together they cover a range of possible emission time paths which, according to the IPCC, will lead to a concentration of GHGs in the atmosphere in the year 2100 of between 855 and 1,130 ppm CO_2-e. Concentration levels in most of the studies we have considered in this report fall within this range: see table 4.6 in section 4.6. There are, however, two exceptions. In the DICE study (section 3.1) BaU concentration of CO_2 in 2100 is only 685 ppm (even adding other GHGs not reported in the study would probably keep the number below 800 ppm). The second exception is the Australian study reported in section 4.5, which gives a BaU concentration in 2100 of 1,560 ppm CO_2-e. This study also assumes much more rapid growth in GDP per capita than other studies and we suspect that this is the reason for the high long-term concentrations of CO_2 in the atmosphere.

Predicted climate change under BaU obviously depends on the predicted development of GHG concentration in the atmosphere. The relationship between atmospheric concentration and climate change is often characterized by so-called climate sensitivity, which tells us by how much the global average temperature will ultimately increase as a response to a doubling of the atmospheric concentration of CO_2-e. According to IPCC (2007), climate sensitivity is “likely to be in the range 2^oC to 4.5^oC with a best estimate of 3^oC, and is very unlikely to be less than 1.5^oC. Values substantially higher than 4.5^oC cannot be excluded, but agreement of models with observations is not as good for those values.” Almost all studies use the point estimate of 3^oC, implying that stabilization of atmospheric concentrations at 550 ppm CO_2-e will give a long-term temperature increase of 3^oC (and that, e.g., 450 ppm CO_2-e will give a long-term temperature increase of about 2^oC). However, due to the uncertainty about the parameter characterizing climate sensitivity, there is roughly a 50% chance that the long-term temperature increase will be higher than 3^oC even if one succeeds in stabilizing atmospheric concentration at 550 ppm CO_2-e.

b) Optimal development of emissions

Uncorrected climate change may give large future costs, in particular in the next century. Mitigating emissions also have costs and these will occur immediately (and in the future). A sensible climate policy goal needs to find the right balance between present mitigation costs and future climate change costs. Ideally, one should aim at minimizing the discounted sum of mitigation costs and climate change costs. This type of optimization is discussed in detail in section 2.1. In addition to giving the optimal time path for emissions, optimization of this type will give a time path for the marginal mitigation cost, often called the carbon price. This price tells us how emissions should be reduced: any emission reduction that costs less than this price should be carried out, while potential emission reductions that would cost more than the carbon price should not be carried out. As shown in section 2.1, the carbon price will typically grow over time at a rate less than the discount rate.[1]

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[1] Strictly speaking, less than the sum of the discount rate and a rate reflecting how carbon depreciates from the atmosphere. However, this latter term is low – less than 1%.

The resulting climate goal, emission development and carbon price will depend on three factors: (i) mitigations costs, (ii) climate change costs and (iii) the discount rate (for translating all costs into a present value). The optimization performed in the studies discussed in sections 3.1-3.3 all suggest that optimal climate policies should be quite moderate: according to the optimization with DICE, it is optimal to let CO_2 concentrations increase to 659 ppm in the end of the next century, implying a temperature increase of 3.5 degrees[2]. The study using ENTICE gives about the same result for emissions, while the study discussed in section 3.3 gives even higher GHG concentrations than the previous two. All these studies use roughly the same estimates for the costs of climate change. In particular, in the analysis with DICE the total costs for the world of a temperature of 3, 4 and 6 degrees are assumed to be 2.5%, 4.5% and 10% respectively. It is difficult to judge whether these numbers are ‘low” or ‘high”. The assumed cost of a 4-degree temperature increase is well within the bounds suggested by the IPCC report, and considerably higher than the mean cost suggested in the Stern Review.[3]

As already mentioned, the assumed discount rate is important for the result of an optimization, since most of the climate change costs occur in the distant future. The studies above use discount rates of the magnitude of 4–5%. The Stern Review argues for a much lower discount rate and uses 1.4%. The Stern Review does not give a formal optimization in order to find an optimal emission path. However, it discusses the costs of stabilizing GHGs at levels between 500 and 550 ppm CO_2-e: i.e. at the high end, about twice the pre-industrial level. Due to very high costs of adopting a target below 500 ppm, the Review recommends a target between 500 and 550 ppm CO_2-e. Given a climate sensitivity of 3 (the ‘best guess” of the IPCC), this would limit the global mean temperature increase to 3 degrees Celsius (while it would increase to 7–9 degrees by 2200 under the BaU scenario of the Stern Review).

A lot of the debate in the literature regarding the optimal climate goal focuses on what is assumed about the discount rate. We address this issue in section 2.2. The question of determining the ‘correct” size of the discount rate in dynamic optimization problems has been discussed at length for many decades in the economics literature, one of the issues being the extent to which observations of market data can give us useful information. There is relatively broad agreement that observed market rates of return are important for determining the discount rate to be used in public decision-making about projects with a time horizon up to about 20 years. However, for projects giving costs and/or benefits further into the future it is not clear that there are any good market data. Moreover, even if such data exist, it is not obvious that they should be used for analyses with a

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[2] Throughout the report, temperature changes are given in degrees Celcius.

[3] Table 13.2 in the Stern Review gives the mean cost of a 4–degree temperature increase as 2.6% of world GDP, but with a range from 0.4% to 15.5%.

very long time horizon. Put very simply, there are two camps in this discussion: one argues that the discount rate should reflect ethical considerations regarding equity across generations; the other argues that the discount rate should be roughly equal to expected rates of return on other investments.

While the discount rate clearly is important, and explains the difference between the results of the Stern Review and the DICE model, it is not the only important factor. Some costs of climate change will come in the form of reductions in non-market goods, such as loss of biodiversity, effects on human well-being (health, amenities), various forms of extreme weather events, risk of conflicts etc. Non-market goods of this type grow only slowly over time, and might even decline. If, simultaneously, the number of produced market goods increases rapidly, we should expect an increased marginal valuation of non-market goods as time passes. This suggests that climate change costs might be much higher in the future than is assumed in most analyses. In section 3.6 we discuss a study that incorporates issues of this type into a model that in other respects is practically identical to Nordhaus"s DICE model. With this modification of the DICE model, the optimal climate policy is much stricter than Nordhaus suggests. Even with the high discount rate used by Nordhaus (4.1%), optimal emissions decline sharply in the second half of this century, implying that CO_2 concentrations reach about 450 ppm in 2100 and then decline. This is an even stricter goal than that suggested by the Stern Review.

We mentioned above that there is a considerable degree of uncertainty with regard to the parameter for climate sensitivity. In section 3.7 we discuss an important contribution by Martin Weitzman (2009), who focuses on the possibility of ‘values substantially higher than 4.5^{o}C”. Based on the scientific literature on this topic, he argues that there is a 5% probability of climate sensitivity higher than 7 degrees Celsius and a 1% probability of climate sensitivity higher than 10 degrees Celsius. He combines this with a model in which climate costs become very high for large temperature increases. Moreover, the probability distribution of temperature increases is ‘fat-tailed” in the sense that, as we move towards higher temperature increases, the probabilities decrease less rapidly than the damages increase. As a consequence, he finds that expected climate costs will be ‘infinitely high”. This is of course not meant literally, but it implies that actual expected climate costs will be very sensitive to both details of the probability distribution of the climate sensitivity and the exact costs of very large temperature increases. Weitzman argues that most analyses of optimal climate policy (such as the studies discussed in sections 3.1-3.3) ignore this important feature and may therefore give very misleading results.

The studies reported in sections 3.6 and 3.7 indicate that by introducing some quite small and not implausible changes into DICE and other optimization models, major numerical conclusions may change dramatically. We should therefore be very cautious about claims stating that long-term concentration limits of, e.g., 450 ppm CO_2 are too ambitious.

The studies in sections 3.1 and 3.3 also solve constrained optimization problems, where there is a limit on the atmospheric concentration of CO_2 or on temperature increase. These studies thus take some climate goals as given and calculate the optimum given these goals (see section 2.1 for a theoretical discussion of this type of optimization). In table 3.9 of section 3.9 we have summarized the results from the studies for such a constrained optimization. The climate goal is similar across the studies. Nevertheless, there are large differences in the time paths of the carbon price, which is an indicator of how difficult it is to achieve the goal. This table indicates how the results of the analyses depend heavily on details about the assumptions made.

c) The costs of reducing emissions

For a given climate goal, the costs of reducing emissions are higher

- the stricter the climate goal;
- the higher the BaU emissions;
- the higher the mitigation costs.

Many of the studies we consider report costs for stabilizing CO_2 emissions at about 450 ppm CO_2, corresponding roughly to 500–550 CO_2-e. The long-term temperature increase for such a concentration target will be about 2.5–3 degrees. There are two relevant concepts of costs, namely *absolute* costs and *marginal* costs. The absolute costs should in principle be reported as a present value of all future costs. However, this way of reporting makes costs depend on the discount rate used and may therefore make comparisons across studies with different discount rates difficult. A more usual way is to report costs in a particular year, often as a percentage of GDP.

Table 1 below gives such costs for some of our studies. We can see that the cost estimates vary considerably, in spite of the climate targets being similar. Some studies give costs for stabilizing emissions at or below 550 ppm CO_2-e well below 2% of GDP. Some other studies, in particular one of the OECD studies discussed in section 4.3, suggest that costs might be considerably higher. We suspect the reason for these high costs is that this study considers a mitigation path with very little mitigation in the near future, therefore making large emission reductions necessary in 2050 (see also the discussion below).

The Australian study also reports relatively high costs and we think the reason in this case is the high emissions under BaU here. It is also interesting to note that the costs of stabilization at 450 ppm CO_2-e in this study are not much higher than the costs of stabilization at 550 ppm CO_2-e. We believe that there are two important reasons why the Australian study suggests that 450 ppm costs are closer to the 550 ppm costs compared to the Stern Review:

- Carbon capture and storage (CCS) technology is included, becoming very important and widespread, and there are developments in other technologies as well. In other words, the possibilities for technological development seem more optimistic in the Australian scenarios.
- The 450 ppm stabilization scenario involves overshooting, so a majority of the costs of reaching the 450 ppm level are pushed into the future, where they are then more heavily discounted.

The marginal cost of mitigation, often called the carbon price, tells us how strict climate policy must be in order to achieve the climate target. If there were no other distortions in the economy than the climate externality, a carbon tax or a carbon quota price equal to this price would give an efficient outcome. The carbon price is therefore a good measure of how strict the climate policy must be. For a given climate target, minimizing the present value of mitigation costs gives a carbon price that increases at a rate equal to the sum of the discount rate and the depreciation rate of carbon in the atmosphere.[4] If we also care about when the upper limit on concentration is reached (later is better), the carbon price should grow at a slower rate. For the two OECD studies and the IEA study "World Energy Outlook", the carbon price increases much faster than any reasonable value of the discount rate (see table 1) This indicates that the assumed emission path does not minimize costs of keeping GHGs under the concentration limits assumed. If we have understood these studies correctly, the emission paths are designed taking into account what is politically feasible, and this need not minimize discounted mitigation costs. In any case, the fact that the carbon price is too low at an early stage implies that emissions are 'too high" at an early stage. To keep CO_2 concentration under the imposed limit, emissions in 2050 must therefore be cut back quite sharply, implying a high carbon price in 2050 and also a high absolute mitigation cost.

From table 1 we can see that there are very large differences in the long-term carbon price (2050), even for comparable climate goals. Some of the differences have been explained above and in the discussion in section 3.9. In any case, the tables indicate how the results of the analyses depend heavily on details about the assumptions made.

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[4] The depreciation term is of the magnitude 0.5–1%. Note that this rule for the price development holds only as long as the concentration level is below the exogenous limit: see section 2.1 for further discussion.

Table 1: Carbon prices (US $ per ton CO_2) and costs (% of GDP)

Study	Stabilization target	Carbon price[5] 2010-2015	Carbon price[6] 2050-2055	Costs as % of GDP (2050)
Nordhaus, Dice	Maximum 2°C temperature increase	US $ 20	US $ 83	0.6%[7]
Nordhaus, Dice	420 ppm CO_2	US $ 67	US $ 189	1.4%
ENTICE	Constant 1995 emissions	US $ 182	US $ 491	1.6%
Grimaud et al.	450 ppm CO_2	US $ 48	US $ 200	
WITCH	450 ppm CO_2	US $ 20	US $ 350	3.9%
Stern Report	550 ppm CO_2-e			1% (-0.6-3.5%)
IPCC, 2007	445-535 ppm CO_2-e			< 5.5%
IPCC, 2007	535-590 ppm CO_2-e	US $ 20-80 (in 2030)	US $ 30-150	0.1-4%
OECD, Env. Outlook 2008	450 ppm CO_2-e	US $ 5	US $ 177	2.5%
OECD, 2008b	550 ppm CO_2-e	US $ 5	US $ 400	4.8%
IEA, World Energy Outlook	550 ppm CO_2-e	US $ 40 (in 2020)	US $ 90 (in 2030)	
IEA, Energy Technology Perspectives 2008	450 ppm CO_2-e		US $ 200	
Australia's LPF, Garneau	550 ppm CO_2-e	US $ 20	US $ 91	2.7-3.2%
Australia's LPF, Garneau	450 ppm CO_2-e	US $ 34	US $ 158	4.2-4.3%

d) What types of policies should be used to reduce emissions?

Whether an emission path is derived from optimization or is simply given as an exogenous policy target, we need to use policy instruments to achieve the desired emission level. It is well known that a key instrument is a correct price of emission, either as a carbon tax or as a price on tradable emission quotas. An important question is whether any policy instruments in addition to a correct emission price are needed. If climate externality was the only externality in the economy and all markets were perfect, and if there were no regulatory failures, there would be no need for any policy instruments in addition to a price of emission. However, the real world is more complicated than such an ideal. Failures exist in most markets, including markets of particular relevance for climate is-

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[5] The exact date within the period 2010–2015 varies across studies

[6] The exact date within the period 2050–2055 varies across studies

[7] The DICE studies give the present value of costs as percent of present value of output.

sues, such as energy markets and markets for technological development. There may also be regulatory failures. In particular, it is not possible for any government to commit to a carbon price path far into the future. Since many decisions in the present have long-term consequences for emissions, assessments of carbon price development will be important for current emissions. If market agents believe in a slower increase in the carbon price than policymakers intend, this will typically lead to decisions in the present that make future mitigation costs higher than they would be in an efficient outcome.

In addition to a correct carbon price, policy instruments should ideally be designed to correct whatever market and regulatory failures exist. Various types of subsidies and regulations can be part of such a policy package. It is in any case important to be clear about exactly what type of market or regulatory failure we are trying to correct when a carbon price is supplemented with other policies.

Future technological development will be important for the costs of achieving whatever emission goal we have. A correct carbon price will give market agents strong incentives to use resources in order develop new climate-friendly technologies. However, there is little doubt that the outcome of unregulated markets is far from perfect with respect to the development of new technologies. An important reason why unregulated markets give an inefficient outcome is that the benefits of new knowledge will, to a large extent, go to others than those who created the new knowledge. This positive knowledge externality implies that unregulated markets tend to put too little effort into creating new technologies. The patent system to some extent addresses this issue. However, since the marginal cost of knowledge is close to zero once the knowledge has been created, the patent system must not be too strict if the new knowledge is to be used to a sufficient extent. Even with a patent system there will therefore typically be positive externalities associated with the creation of new knowledge. This is a key argument for letting public institutions participate in knowledge creation (typically basic research) and for giving various types of public support to knowledge creation in the private sector. These issues are treated in more detail in section 2.4.

In several of the numerical studies in chapter 3 technological development is endogenous and depends on both the carbon price and other policy instruments. Some of these studies derive only what the optimal R&D levels should be (sections 3.1 and 3.2), while others discuss how policy instruments in addition to a carbon tax should be used in order to achieve the optimal outcome (sections 3.3 and 3.8). These latter studies show that subsidies towards R&D and the use of new technologies may play an important role in the design of climate policy.

e) For a given climate goal, what are the additional costs of using sub-optimal policies?

No matter how abatement costs (or benefits from emissions) are modelled, aggregate abatement costs will depend not only on total emissions but also on how emissions are allocated across sources and sectors. The cost-minimizing allocation is often called the cost-effective allocation. An important output from several analyses is to compare the costs of the policies giving the cost-effective allocation of emissions with other policies giving the same aggregate emissions. Deviating from cost-effective policies typically gives quite large cost increases. This is discussed theoretically in section 2.3 and is also shown in several of the numerical analyses in this report.

In section 3.1 we consider two examples using the DICE model. First, under the Kyoto Agreement only countries accounting for about 33% of global emissions in 2010 are given quantitative commitments. The cost of reaching the Kyoto limits is calculated to be 7.4 times higher than the costs of the same global emission reduction with full participation. The second example concerns an agreement between the USA, EU and eight other large countries: China, Russia, India, Brazil, Canada, Japan, Mexico and South Africa. Between them, they accounted for 75% of global emissions in 2004. Reducing emissions in these countries, without imposing any restrictions on emissions from the remaining countries, gives total costs that are 68% higher than the costs of the same global emissions reduction with all countries participating in a cost-effective agreement. These numerical illustrations show very clearly how important it is to achieve an international climate agreement with the broadest possible participation.

The OECD and IEA studies discuss several scenarios of international cooperation on climate policies. The results are similar to what the analysis with the DICE model indicates: costs are substantially higher with limited participation than with full participation. For example, the OECD (2008b) study shows that GHG concentration targets below 750 ppm are out of reach if Annex 1 countries act alone. These studies also consider restrictions on the use of some ways of reducing emissions. In particular, one of the reasons why the costs are relatively high in the OECD (2008b) study is that the mitigation options of halted deforestation and reforestation as well as CCS are ruled out. The same study shows that exempting energy-intensive industries from policy action increases the cost of achieving the 550 ppm concentration target by 50%. Likewise, not including all GHGs, but focusing only on CO_2, increases the cost of reaching the target by almost 100%.

A similar illustration is presented in section 3.4. In this analysis the WITCH model is run with restrictions on nuclear power (no increase from present capacity), not allowing CCS, and restrictions on the size of solar and wind energy (max. 30% of total electricity). By imposing these restrictions, mitigation costs in 2050 are increased from 3.9% of GDP to more than 7%.

We have already briefly discussed why it could be desirable to supplement the correct carbon price with other policy instruments. In policy debates the view is sometimes put forward that other policies should be an *alternative* rather than a *supplement* to the correct price: i.e. ‘a carrot is better than a stick”. Economists are reasonably unanimous that the correct price is crucial in order to get an efficient outcome. There is, however, no guarantee that this type of policy recommendation will be followed. It is therefore interesting to see numerical studies indicating how large the efficiency loss may be if we try to achieve an emission goal with policies other than a suitable emission price. One example of such a study is Fischer and Newell (2008), which we discuss in section 3.8. Fischer and Newell consider a model of the US electricity sector. Due to imperfections in the markets for technological development, the optimal policy package is a carbon tax combined with a production subsidy for renewable energy and subsidies for R&D. For the same emission target, there is a modest efficiency loss if one uses only a carbon tax and not the other two policy instruments as well. The efficiency loss is considerably higher if one uses only a subsidy of renewable energy and/or an R&D subsidy and not a carbon tax.

* * * * *

All of these issues are considered in more detail in the subsequent chapters. We start with a thorough theoretical discussion in chapter 2. While we believe this chapter gives a useful background for understanding issues treated in later chapters, it is also possible to skip it and move directly to chapters 3 and 4. Chapter 3 discusses numerical analyses that focus mainly on optimization. Most of these studies are based on relatively simple aggregate models of the world economy. The studies covered in chapter 4 are mostly large ones that treat a broad range of issues and often consider quite complex and disaggregated models of the world economy. These models usually have no optimization, but instead typically identify a policy that is consistent with a specific emission target and then calculate the costs of such a policy.

In some places we have given a brief mathematical description of key features of the models used. However, we believe that the main points will be easily understood by those not familiar with this type of formal model discussion.

Throughout, we have presented costs in US$. We have not always been explicit about what year these prices refer to (e.g. 2005 US$ versus 2007 US$) as the amounts can only be regarded as very crude estimates because of all the uncertainties involved.

2 Theoretical background

This chapter presents a theoretical discussion of the ways in which the results of various types of analysis depend on the assumptions that have been made.

2.1 Optimization

The simplest possible optimization problem for the climate problem is to maximize the net present value of benefits minus the costs of greenhouse gas emissions. If we restrict our attention to CO_2 from burning fossil fuels, the benefits of emissions are simply the benefits of using fossil fuels. If carbon capture and storage (CCS) is a relevant alternative to CO_2 emissions, the benefits of emissions are the costs saved by not using CCS. The costs of CO_2 emissions go via the stock of CO_2 in the atmosphere, which affects the climate. Using $e(t)$ and $S(t)$ to denote carbon emissions at time t and the stock of carbon in the atmosphere at time t respectively, a very simple representation of the present value of benefits minus costs at an initial date 0 is

$$(2.1) \qquad V = \int_0^\infty e^{-rt}\left[B(e(t),t) - D(S(t),t)\right]dt$$

Here $B(e,t)$ denotes benefits of fossil fuel use (or costs saved by not using CCS) and D denotes costs from climate change. Benefits are assumed to depend on carbon emissions as well as time, the latter reflecting factors such as increased income, which raises the demand for fossil fuels, and energy-specific technological development, which reduces carbon emissions. In this section we make the simplifying assumption that these two effects are of the same magnitude, so that the net effect is zero. We thus disregard time as an argument in the benefit function, so that it can simply be written as $B(e)$.

In several analyses the benefits of fossil fuel use are modelled in considerable detail, often linked to a detailed description of the production technology of the economy.

The term $D(S,t)$ denotes costs from climate change. These costs depend on the stock of carbon in the atmosphere (S), since this stock affects climate development (the exact relationship between S and the climate is not explicitly considered here, but it is included in most numerical analyses). The costs of climate change may also depend directly on time, as a given climate change may have a greater monetary impact the higher the GDP, and the valuation of non-market effects of climate change may also increase as a result of higher income (see, e.g., Hoel and Sterner, 2007). The discount rate r is exogenous in this simple optimization problem. However, in several of the analyses that derive an optimal emission path, the discount rate is endogenous. In this case it will depend on exogenous parameters, reflecting preferences as well as technology. We will return to this in section 2.2.

The simplest way to model the relationship between carbon emissions and the stock of carbon in the atmosphere is

$$\dot{S}(t) = e(t) - \delta S(t) \tag{2.2}$$

where a dot over a variable denotes its derivative w.r.t. time, and δ is a depreciation factor telling us how CO_2 is gradually moved from the atmosphere to other sinks (in particular the ocean). In this formulation, S measures the concentration in the atmosphere in excess of the natural concentration, so that if emissions become zero S will gradually decline to zero. In reality, the relationship between emissions and the development of the stock of carbon in the atmosphere is more complex than (2.2). A more realistic description of this relationship is given in many of the numerical analyses of these issues.

Before discussing the solution to this dynamic optimization problem, it is useful to consider its static counterpart. The flow pollution problem, with similar notation as above, is to maximize $B(e) - D(e)$. The optimal emissions e^* and corresponding emission price q^* are given by $B'(e^*) = D'(e^*) = q^*$.

This optimum is illustrated in Figure 2.1, where e^0 is the BaU level of emissions.

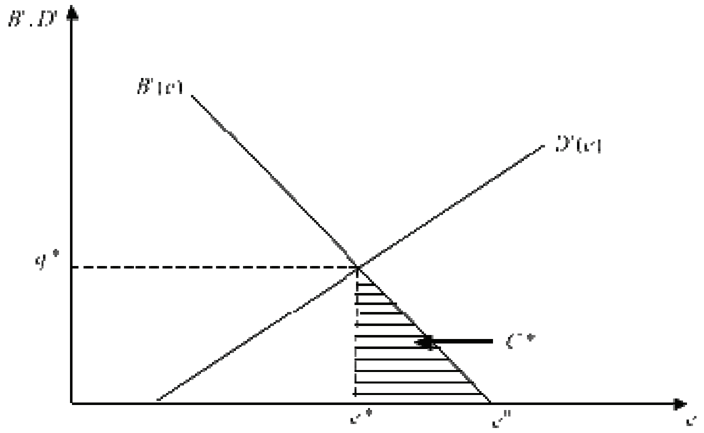

Fig. 2.1

While q^* is the marginal cost of emission reductions (at the optimal level), total costs are given by the shaded area C* in Figure 2.1. Obviously, e^*, q^* and C^* all depend on the functions *B* and *D* representing technology and preferences. In particular, it is straightforward to see from Figure 2.1 that an upward shift in the marginal damage costs (*D*”) will reduce emissions e^* and increase the emission price q^* and total costs C^*. An upward shift in marginal abatement costs (*B*”) will increase emissions e^* and increase the emission price q^*. However, it is not obvious how total costs will be affected. If *D*” is sufficiently steep, total costs C^* will increase, while they may decline if *D*” is sufficiently flat and e^0 does not increase as a response to the shift in *B*”.

Turning now to our dynamic optimization problem, maximizing *V* subject to (2.2) gives the following well-known result (see the Appendix to this section for details):

$$(2.3) \qquad B'(e(t)) = q(t)$$

$$(2.4) \qquad q(t) = \int_t^{\infty} e^{-(r+\delta)(\tau-t)} D_S(S(\tau),\tau)\,d\tau$$

The variable *q*(*t*) defined by (2.4) is often called the social cost of carbon. Equation (2.4) has a straightforward interpretation: the emission of one ton of carbon into the atmosphere at time *t* gives an addition to the carbon stock in the atmosphere at a future time τ equal to $e^{-\delta(\tau-t)}$. The marginal damage of this addition to the stock is at time τ equal to $D_S(S(\tau),\tau)$, so that the marginal damage of the one ton emitted at *t* is $e^{-\delta(\tau-t)}D_S(S(\tau),\tau)$ at time τ, which discounted to *t* gives $e^{-(r+\delta)(\tau-t)}D_S(S(\tau),\tau)$. The sum of these terms over all dates $\tau \geq t$ is the marginal cost of one ton of emissions at *t* and is given by (2.4).

In the optimal outcome the marginal benefits of carbon emissions (often termed the marginal costs of reducing carbon emissions) are equal to the social cost of carbon: see (2.3). This implies that emissions are given as a declining function of the carbon price *q*.[8]

The optimization problem above is discussed in more detail in the Appendix to this chapter. Here we derive the following relatively well-known results:

- If *D* is proportional to *S*, implying D_S is constant, $q(t)$ will be constant.
- If D_S is rising for all $\tau > t$, $q(t)$ will be rising at time *t*.[9]
- Whenever $D_S > 0$, the growth rate of *q* is less than $r + \delta$.
- Whenever $D_S = 0$ (which could be the case for low values of *S*), the growth rate of *q* will be equal to $r + \delta$.

It is often assumed, and seems reasonable, that both total and marginal climate damage, i.e. *D* and D_s, is quite small for relatively small values of *S*. As *S* increases, *D* and D_s eventually increase quite rapidly. If D_S rises rapidly enough, it is almost as if there is an absolute upper limit on *S*. In the Appendix to this chapter we therefore consider an approximation to this situation, by assuming that $D(S,t) = m(t)S$ for values of *S* up to S^*, and that S^* is an upper limit for *S*. In a diagram where the horizontal axis measures *S* and the vertical axis measures the marginal damage D_S, the curve for D_s will be horizontal up to S^* and become vertical at S^*. Moreover, if $m(t)$ is increasing in *t*, the horizontal portion of this curve will gradually move upwards as time passes.

An alternative interpretation of the case described above is that the damage cost is simply given by $D(S,t) = m(t)S$, but in the optimization problem we add the constraint that $S \leq S^*$. With this interpretation our problem is a mixture of restricted and unrestricted optimization, since $S \leq S^*$ is an exogenous constraint.

In the Appendix we derive the following properties of the optimal solution for the case in which the constraint $S(t) \leq S^*$ is binding from some date *T* onwards. Prior to *T*, $q(t)$ rises at a rate less than $r + \delta$. The value

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[8] If benefits depend on *t* for a given *q* (cf. the discussion above) the relationship between emissions and the carbon price is more complicated. In this case a constant carbon price will generally not give constant emissions; emissions will increase or decline over time depending on whether or not the increase in demand as a result of income growth exceeds the decline in demand resulting from energy-specific technological development.

[9] There are two reasons why D_S might be increasing over time. First, there will be a direct effect if $D_\tau > 0$. Second, if $D_{SS} > 0$, which is often assumed, an increase in *S* will make D_S increase. If the optimal outcome implies that *S* never overshoots its long-term stationary value, D_S will therefore increase over time if $D_{SS} > 0$.

of *q*(*t*) reaches a value q^* at *T* and remains constant at this level after *T*.[10] This value is the carbon price making emissions exactly equal to δS^*, so that carbon in the atmosphere remains constant equal to δS^* after *T* (formally, q^* is defined by $q^* = B'(\delta S^*)$: see (2.4)).

The time path of *q*(*t*) is illustrated in Figure 2.2. In this figure $\tilde{q}(t)$ is the price path that would have been optimal without the constraint $S(t) \leq S^*$: i.e. the price path given by (2.8). When the constraint $S(t) \leq S^*$ is binding for some values of *t*, the optimal price path q(t) lies above $\tilde{q}(t)$. The exact position of the curve for *q*(*t*) in Figure 2.2 will of course depend on all exogenous variables as well as on the function $B'(e(t))$. We will discuss the effects of changes in some important variables.

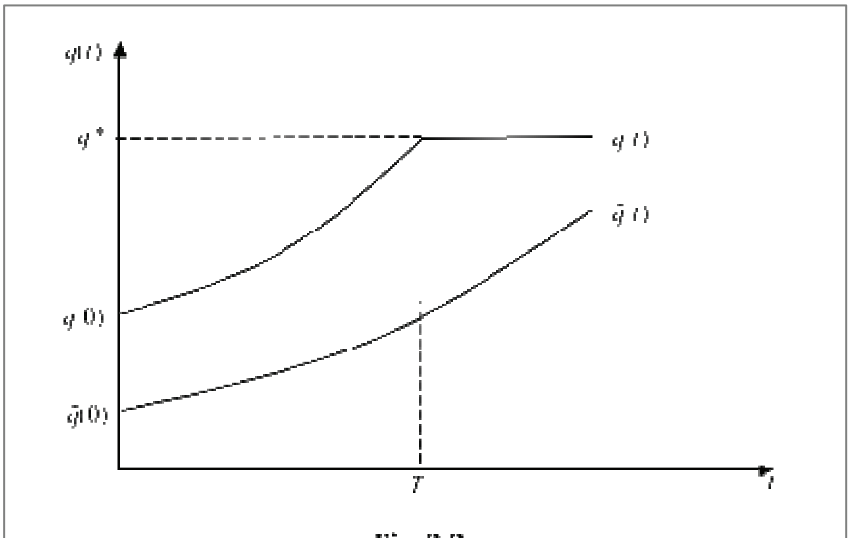

Fig. 2.2

Consider an increase in the marginal damage costs *m*(*t*). This will shift the initial carbon price *q*(0) upwards. However, it will also reduce the growth rate given by (2.9), so the whole price path will become flatter, and the new price path will at some date intersect the old price path. The price q^* remains unchanged but will now be increased at a later date. Total abatement costs associated with the optimal climate policy will increase as a consequence of the increase in *m*(*t*): i.e. the present value of $B(e(t))$ will go down.

A reduction in the limit S^* will imply an increase in q^*. The whole path of *q*(*t*) will in this case move upwards. Just as with an increase in *m*(*t*), a reduction in S^* will increase total abatement costs: i.e. reduce the present value of $B(e(t))$.

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[10] As shown in the Appendix, *q*(*t*) may start to increase again at a date later than *T* if *m*(*t*) continues to increase after *T*.

An increase in the interest rate r will make the path of $q(t)$ steeper. Since q^* remains unchanged, the new price path will at some date intersect the old path, and $q(t)$ will reach q^* at an earlier date than before.

Finally, consider the effect of the assumptions about technology. A more favourable technology in relation to reducing emissions means a lower value of $B'(e(t))$ for any given value of e: i.e. the carbon price necessary to achieve a particular emission level is lower the better the technology is. Better technology will give a lower path for $q(t)$, so that q^* will be reached at a later date. Just as in the static case described earlier, it is not obvious that total costs go down if marginal abatement costs $B'(e(t))$ go down. The reason is that the improvement in technology gives us a reduction in climate costs through lower emissions and a lower time path of the stock of carbon in the atmosphere, implying that the limit S^* is reached at a later date. Overall, welfare is increased by the technological improvement, but this welfare increase can come as an increase in abatement costs that is more than compensated for by the decrease in climate costs.

The discussion above gives a rough picture of how various factors influence the development of the optimal carbon price in numerical optimization models. However, the detailed results of these models may differ slightly from the analysis above, as this was based on several simplifying assumptions.

2.2 The discount rate

In all analyses involving some kind of optimization, the size of the discount rate is important. It follows from the discussion in section 2.1 that the discount rate is important even if we have a constrained optimization problem where we have imposed an upper limit on CO_2 in the atmosphere (or an upper limit on temperature change). We will therefore briefly discuss some of the issues related to the discount rate.

The question of the ‘correct” size of the discount rate in dynamic optimization problems has been discussed at length for many decades in the economics literature. In the last five to ten years this discussion has intensified because of the increased focus on the climate problem, which by its nature has a very long time horizon.[11]

One of the issues in this discussion has been the extent to which observations of market data can give us useful information for determining the ‘correct” discount rate. There is relatively broad agreement that observed market rates of return are important for determining the discount rate to be used in public decision-making about projects with a time hori-

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[11] Important contributions include Arrow et al. (1996), Cline (1992), Dasgupta (2001), Hasselmann (1999), Heal (1997), Horowitz (1996), Lind (1982), Nordhaus (1997), Portney and Weyant (1999), Schelling (1995), Shogren (2000), Weitzman (1994, 1998, 2001) and Zerbe (2004).

zon up to about 20 years. However, for projects giving costs and/or benefits further in the future it is not clear that there are any good market data.

A related issue is whether there are reasons why the discount rate should be lower for analyses involving a long time horizon (such as the climate problem with a horizon of more than a century) than for analyses with horizons up to only a couple of decades.[12] An example of a declining discount rate is given in the 'Green Book" from HM Treasury in the UK (see HM Treasury, 2003), where the discount rate over time is as in Table 2.1.

Table 2.1 Example of a declining discount rate (from HM Treasury, 2003)

Year	0–30	31–75	76–125	126–200	201–300	301+
Discount rate (%)	3.5	3.0	2.5	2.0	1.5	1.0

Note that a correct interpretation of this table is *not* that one should use a constant discount rate throughout the calculation period for projects lasting from 31 to 75 years.[13] What is *does* mean is that for a project lasting, say, 50 years, costs and benefits incurred during the first 30 years should be discounted at a rate equal to 3.5%, and that costs and benefits for the remaining years first should be discounted back to year 30 at the rate 3% per year, then to year 0 (the initial date) at the rate 3.5% per year.

In economic models of dynamic optimization and cost-benefit analysis, a frequently used objective function is of the type

$$W = \int_0^T e^{-\rho t} N(t) U(c(t)) dt, \tag{2.5}$$

where $N(t)$ and $c(t)$ denote population and per capita consumption at time t. The function U can be interpreted as a measure of well-being or utility, and T is the time horizon. The trade-offs between consumption at different points of time are given partly by the utility discount rate ρ and partly by the utility function U. The larger ρ is, the more weight is given to the present relative to the future. The function U is assumed to be strictly concave, so that it increases less than proportionately with consumption. The more concave U is, the more weight is given to periods with low consumption relative to periods with high consumption. In most analyses it is assumed that the elasticity of the marginal utility U" is constant, denoted $-\omega$ (where concavity of U implies $\omega > 0$).

For issues with a time perspective of a century or longer (such as the climate problem), it is natural to interpret the function (2.5) as a representation of society"s preferences over distributions of consumption across

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[12] See, e.g., Weitzman (1998, 2001) and Gollier et al. (2008).

[13] To see that this would be meaningless consider two projects, A and B, that are identical for the first 30 years, with an initial investment and then positive benefits for 30 years. In project A there are zero costs and benefits after the first 30 years, while B has a small closing cost at year 31. Clearly, A is better than B. But if one uses a 3% discount rate for B (since it lasts 31 years) and a 3.5% discount rate for A (since it lasts only 30 years), the present value of B will be higher than for A if the closing costs are sufficiently small!

generations. An assumption of $\rho > 0$ means that society gives the current generation more weight than it gives future generations, and that society gives future generations lower weight the more distant they are. In the economics literature, there has been extensive discussion about whether a positive value of ρ can be given an ethical justification.

When the function (2.5) is interpreted as a representation of society”s preferences over distributions of consumption across generations, the concavity of *U* measures inequality aversion: the more concave *U* is – i.e. the higher ω is – the more weight is given to generations with low consumption relative to generations with high consumption. In a situation with economic growth (rising c(t)), the future is thus given lower weight the higher ω is. In a situation with economic decline, however, the value of future consumption might even be given a higher weight than current consumption. We would thus have a negative discount rate if the rate of economic decline was sufficient to outweigh the effect of utility discounting ρ: see equation (2.6) below.

The appropriate interest rate *r* for discounting consumption when preferences are given by (2.5) is found by differentiating (2.5) w.r.t. consumption and time to see how the marginal utility of consumption changes. It is well known that this gives the following ‘Ramsey equation (see, e.g., Dasgupta and Heal, 1979)

$$(2.6) \qquad r(t) = \rho + \omega g(t),$$

where $g(t)$ is the relative growth rate of consumption. If, e.g., $\rho = 0.01$, $\alpha = 1.5$ and $g(t) = 0.02$, we find *r* = 0.04: i.e. a discount rate of 4%.

Notice that this discount rate will be constant over time only if the growth rate of consumption is constant over time. During the last 50 years the average growth in consumption per capita has been about 2.5% per year (world average). This is unusually high in a long time perspective and there may be several reasons to believe that it will not be so high the next 100 years. If, e.g., the consumption growth rate gradually declines towards 1% per year, this will give a gradually declining discount rate.

To determine a numerical value of the discount rate *r*, we need values of the parameters ρ and ω. A major controversy in the literature is how these parameters should be determined. Put very simply, there are two camps in this discussion: one (e.g. Cline, Stern) argues that the parameters should reflect ethical considerations regarding equity across generations; the other (e.g. Nordhaus) argues that the parameters should be set so that historical values of r calculated from (2.6) should be (at least roughly) equal to historical rates of return.[14]

The interest rate given by (2.6) is usually defined as the appropriate discount rate to be used for investments for which there is no uncertainty. From standard economics literature we know that for a project giving a return that is positively (negatively) correlated with the general future consumption level (or, more generally, welfare level) a discount rate that is higher (lower) than the risk-free discount rate should be used. What does this mean for the discount rate to be used for analyses of the climate problem? The answer to this is not obvious. For example, consider the simple case in which we have a constraint on the accepted global average temperature increase (e.g. 2 degrees Celsius) and ignore climate costs for temperatures below this limit. The economic issue is thus to choose among all possible emission paths satisfying the constraint on temperature increase. Typically we thus have choices between more abatement in the near future (next couple of decades) versus abatement in the more distant future (second half of this century). The investment project of abating in the near future thus has a pay-off equal to the implied lower abatement costs in the more distant future. This pay-off is uncertain, for at least three reasons:

i.) uncertain total factor productivity growth;
ii.) uncertain carbon-reducing technological progress;
iii.) uncertain climate sensitivity.

With regard to i), the higher total factor productivity growth is, the higher BaU emissions are. Higher total factor productivity growth therefore gives a higher abatement requirement in the future and thus higher marginal abatement costs in the future. This means that the pay-off of abating now instead of waiting until some time in the future has a higher pay-off the higher the total factor productivity growth. Since future consumption is higher the higher the total factor productivity growth, the returns on abatement in the near future are positively correlated with the future consumption level. For this type of uncertainty, the appropriate discount rate should therefore be higher than the risk-free discount rate.

With regard to ii), a favourable development of technologies for low-carbon energy sources will imply lower marginal abatement costs in the future, implying a lower return on abatement in the near future. Such a favourable technological development will also give a yield in terms of higher future consumption. Returns on abatement in the near future are thus in this case negatively correlated with the future consumption level.

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[14] Even if one accepts this second approach, it is not obvious what the parameters in (2.6) should be, since historical rates of return vary across different types of investment.

For this type of uncertainty, the appropriate discount rate should therefore be lower than the risk-free discount rate.

With regard to iii), the long-term concentration of carbon in the atmosphere that is consistent with a given temperature target is lower the higher the climate sensitivity. This means that future abatement and hence future marginal abatement costs are higher the higher the climate sensitivity turns out to be. The returns on abatement in the near future are therefore higher the higher the climate sensitivity turns out to be. Moreover, higher required future abatement implies lower future consumption. Also, for this type of uncertainty, the appropriate discount rate should therefore be lower than the risk-free discount rate.

From the examples above, it is clearly not obvious which discount rate to use in analyses of the climate problem; the choice depends on which of the three sources of uncertainty is believed to be most important.

2.3 Simulation

As mentioned in chapter 1, many economic analyses make no attempt to optimize emissions. These analyses instead do simulations of various types. The most common type of simulation is to analyse consequences, including costs, of some particular policy package: e.g. some combination of carbon taxes, subsidies to R&D and/or renewable energy. A closely related analysis is to identify a policy that is consistent with a specific emission target and then calculate the costs of such a policy. There is no sharp distinction between these two types of analysis, as in the latter case the policy necessary to achieve an exogenous emission target is often derived through an iteration process.

A wide range of models may be used for analyses of this sort, from relatively simple and aggregated models to large-scale numerical general equilibrium models with a detailed sector disaggregation covering many regions of the world. In these models, the costs of climate change are not usually included, but the costs of reducing emissions will always play a crucial role. Just as with optimization analyses, the actual modelling of these costs may be done in several ways. The most detailed and micro-based approach is to link CO_2 emissions to the use of fossil fuels as inputs in production functions.

No matter how abatement costs (or benefits from emissions) are modelled, aggregate abatement costs will depend not only on total emissions but also on how emissions are allocated across sources and sectors. The cost-minimizing allocation is often called the cost-effective allocation. An important output from several analyses is to compare the costs of the policies giving the cost-effective allocation of emissions with other policies giving the same aggregate emissions. Deviating from cost-effective policies typically gives quite large cost increases. To illustrate, consider a case of n identical emission sources, each with a strictly convex abatement cost function $c(a)$, where a is abatement. If total abatement is given by A, the cost-minimizing allocation of abatement is for abatement to be equal at each source, giving a total abatement cost equal to $nc(A/n)$. Consider instead a policy that exempts half of the sources from having any abatement, so that abatement at the remaining sources must be $2A/n$. This gives a total abatement cost equal to $(n/2)c(2A/n)$, which will be higher than $nc(A/n)$ when the abatement costs are strictly convex: i.e. when marginal abatement costs are increasing in abatement. The size of this difference will of course depend on the detailed properties of the abatement cost functions. If, e.g., these are quadratic with marginal costs being zero at a=0, it is straightforward to verify that $(n/2)c(2A/n)$ will be exactly twice as large as $nc(A/n)$. In other words, this particular deviation from the cost-effective allocation of abatement will, in this example, make total abatement costs twice as high as they need to be.

2.4 Policy instruments

Whether an emission path is derived from an optimization or is simply given as an exogenous policy target, we need to use policy instruments to achieve the desired emission level. It is well known that a key instrument is a correct price of emission, either as a carbon tax or as a price on tradable emission quotas. An important question is whether any policy instruments in addition to a correct emission price is needed. If the climate externality were the only externality in the economy and all markets were perfect, and there were no regulatory failures, there would be no need for any policy instruments in addition to a price of emission. However, the real world is more complicated than such an ideal. Failures exist in most markets, including markets of particular relevance for climate issues, such as energy markets and markets for technological development. There may also be regulatory failures. In particular, it is not possible for any government to commit to a carbon price path far into the future. Since many decisions in the present have long-term consequences for emissions, assessments of carbon price development will be important for current emissions. If market agents believe in a slower increase in the carbon price than policymakers intend, this will typically lead to decisions in the present that make future mitigation costs higher than they would be in an efficient outcome.

In addition to a correct carbon price, policy instruments should ideally be designed to correct whatever market and regulatory failures exist. Various types of subsidies and regulations can be part of such a policy package. It is in any case important to be clear about exactly what type of market or regulatory failure we are trying to correct when a carbon price is supplemented with other policies.

Future technological development will be important for the costs of achieving whatever emission goal we have. A correct carbon price will give market agents strong incentives to use resources in order develop new climate-friendly technologies. However, there is little doubt that the outcome of unregulated markets is far from perfect with respect to the development of new technologies. An important reason why unregulated markets give an inefficient outcome is that the benefits of new knowledge will, to a large extent, go to others than those who have created the new knowledge. This positive knowledge externality implies that unregulated markets tend to put too little effort into creating new technologies. The patent system to some extent addresses this issue. However, since the marginal cost of knowledge is close to zero once the knowledge has been created, the patent system must not be to strict if the new knowledge is to be used to a sufficient extent. Even with a patent system there will therefore typically be positive externalities associated with the creation of new knowledge. This is a key argument for letting public institutions participate in knowledge creation (typically basic research) and for giving various types of public support to knowledge creation in the private sector.

It is beyond the scope of the present study to analyse the concrete design of policies to promote technological development. We will nevertheless briefly discuss what role technology considerations play in the determination of the optimal development of the carbon price. This issue has been extensively discussed in the literature, both for environmental taxes in general and for the particular case of a carbon price.[15] Distinctions are often made between knowledge derived from experience (so-called ‘learning by doing”, or LbD) and knowledge based explicitly on research and development (R&D), although the distinction in practice is not so clear. Goulder and Mathai (2000) show that with LbD the optimal outcome under reasonable conditions will be characterized by the marginal mitigation costs exceeding the social cost of carbon: i.e. exceeding the carbon price given by (2.4). This does not necessarily imply that the appropriate carbon price should exceed the social cost of carbon. If all the benefits of the learning that results from the activities of a market agent go to this same agent, the agent will in self-interest choose its activities so that the optimum conditions are satisfied. It is only to the extent that the benefits of the learning also go to others that this type of learning is an argument for the carbon price to exceed the social cost of carbon: see, e.g., Rosendahl (2004).

Goulder and Mathai also show that if there are sufficiently good policy instruments to influence R&D, the optimal carbon price should be equal to the social cost of carbon. However, if there are limited possibilities of influencing R&D directly, it may also for the case of R&D be op-

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[15] See Jaffe et al. (2002), Löschel (2002) and Requate (2005) for general surveys of environmental policy instruments under endogenous technological development. The optimal rate of an environmental tax is explicitly analysed by, e.g., Biglaiser and Horowitz (1995) and Parry (1995).

timal to let the carbon price exceed the social cost of carbon: see, e.g., Gerlagh et al. (2008) and Hart (2008).

If the carbon price is set correctly – i.e. according to the principles discussed in section 2.1 – there is in principle no difference between the imperfections associated with developing climate-friendly technologies and the imperfections associated with technological development elsewhere in the economy. There are therefore no good reasons for policies to differ in the area of climate-friendly technology development from those in other areas of the economy. Market imperfections may, however, be larger in the climate area than elsewhere, in which case it could be argued that a correct policy design in this area is more important than in other areas of the economy.

A point related is that if one gives various forms of economic support to R&D in the climate area, this might crowd out other forms of R&D. If this occurs, the benefits of such support are weakened if other types of R&D are lower than what is socially optimal. This point is made by Popp (2004), who assumes that the social returns on climate-friendly R&D are four times higher than the private returns (in the absence of any subsidies). This can justify subsidizing this type of R&D. However, the increase in this type of R&D following such a subsidy will partly come at the expense of a decline in other types of R&D, which also are assumed to have social returns that are four times higher than private returns. The social benefits of subsidizing climate-friendly R&D are therefore lower than they would have been had other R&D been unaffected by this subsidy.

2.5 Fossil Fuels as Non-renewable Resources

The most important contribution to the climate problem is CO_2 from the combustion of fossil fuels. The climate problem is thus to a large extent caused by extracting carbon resources and transferring them to the atmosphere. Logically, any discussion of the climate problem therefore ought to be intimately linked to a discussion of the extraction of carbon resources. In spite of this obvious fact, surprisingly little of the literature makes this link. However, there are important exceptions, such as the early contributions by Sinclair (1992), Ulph and Ulph (1994) and Withagen (1994), and more recent contributions, such as Hoel and Kverndokk (1996), Tahvonen (1997), Chakravorty et al. (2006), Strand (2007) and Sinn (2008).

One of the insights from this literature is that the principles for setting an optimal carbon tax (or price of carbon quotas) are the same as those derived in section 2.1. The literature shows what such an optimal climate policy implies for issues such as the time path of resource extraction, the transition to non-carbon substitutes, and the magnitude and timing of

CCS. Some of it also discusses the consequences of non-optimal climate policies when we explicitly consider the link between climate policies and the market for fossil fuel resources. We will outline some of the main insights below.

The conventional wisdom is that CO_2 emissions will be lower at any time the higher the carbon tax. If the supply side of the markets for fossil fuels is taken into account this is not so obvious. To understand this, consider the simplest possible case of one aggregate of fossil fuels that exists in a known total supply and has zero extraction costs. The Hotelling rule tells us that in this case the producer price of the fuel must increase at the rate of interest, denoted r. The price at any date t is thus $p(t) = p_0 e^{rt}$ where p_0 is the initial price. The *level* of this price path – i.e. p_0 – is determined so that total demand over the whole future is exactly equal to the total available fuel resource. Without any carbon tax, the demand at any time is given as a declining function of $p(t)$: i.e. lower the lower is p_0. The equilibrium $p(t) = p_0 e^{rt}$ is the value of p_0 that makes total demand over the whole future exactly equal to the total available fuel resource. We now introduce a carbon tax $q(t)$. Consider first the case in which it increases at the rate r and that $q_0 < p_0$. The price to consumers is now $\tilde{p}(t) + q(t) = (\tilde{p}_0 + q_0)e^{rt}$ where $\tilde{p}(t)$ is the producer price after the carbon tax has been introduced (which as before must rise at the rate r due to the Hotelling rule). Since the consumer price rises at the same rate as without a tax, the requirement that total demand over the whole future is exactly equal to the total available fuel resource must require the same initial price as before, implying $\tilde{p}_0 + q_0 = p_0$ and thus $\tilde{p}(t) + q(t) = p(t)$ for all t. The consumer price path is thus unaffected by the carbon tax, so the extraction path is also unaffected. In the absence of CCS, the level of the carbon tax therefore has no effect on CO_2 emissions. The only effect of the carbon tax is to transfer some of the resource rent from the resource owners to the government that sets the tax.

In the reasoning just outlined we assumed that the carbon tax rose at a rate equal to the interest rate r. It is straightforward to show (along the lines above) that if the carbon tax rises with a rate *higher* than r, the pace of extracting the fuel will be *increased* compared with the case of no carbon tax, so that CO_2 emissions will *increase* in the immediate and near future (in the absence of CCS). Conversely, if the carbon tax rises with a rate *lower* than r, the pace of extracting the fuel will be reduced compared with the case of no carbon tax and CO_2 emissions will therefore decline in the immediate and near future.

Finally, consider the case in which the carbon tax path is so high that, even with a zero producer price of fuel, total demand over the whole future is less than the total available fuel resource. Here the equilibrium producer price of fuel will be zero and some of the fuel will never be extracted. In this case the simple conventional wisdom holds: CO_2 emissions will be lower at any time the higher the carbon tax.

This reasoning is based on the assumption that extraction costs were zero. However, as shown by, e.g., Long and Sinn (1985) and Sinn (2008), similar results hold when extraction costs are positive and rise with increased extraction. The details differ, but the main message remains the same: it is not only the level but also the whole time profile of the carbon tax that is important for CO_2 emissions.

Another piece of conventional wisdom regarding climate policies is that a reduction in the price of non-carbon substitutes (as a result of either technological improvements or subsidies) will reduce CO_2 emissions. This is not necessarily true when we take the supply side of the market for fossil fuels into consideration. For instance, Jon Strand (2007) has shown that a technology agreement that will make carbon redundant in the future may increase present carbon emissions. Less dramatically, Hoel (2008) assumes that although technological improvement will lower the costs of renewable energy, carbon resources will still have lower costs than the substitute. The consequences of such a technological improvement are analysed for a situation where different countries (or groups of countries) have climate policies with differing levels of ambition, but where there is no efficient global climate agreement. In particular, each country is assumed to have some willingness to pay (WTP) for reducing carbon emissions and sets a carbon tax equal to its WTP. There will thus be a distribution of carbon taxes across countries. Moreover, there exists a perfect substitute for fossil fuels, with a constant unit cost. This substitute will be adopted by countries for which the fuel price plus the carbon tax exceeds the cost of producing the substitute. However, in countries that have a lower WTP the fuel price including the carbon tax will be lower than the cost of the substitute and these countries will not adopt the substitute.

Consider an improvement of the technology for producing the substitute, thus lowering its cost. If the fossil fuel price were unaffected, this cost reduction would induce some countries to switch from fossil fuels to the substitute, so that global carbon emissions would decline. However, fossil fuels are non-renewable and the competitive supply gives a price path of the fuel which depends on both present and future demand. When this ‘Hotelling feature” is taken into consideration, the whole price path of the fuel will shift downwards as a response to the reduced cost of the substitute. An implication of this is that it is no longer obvious that greenhouse gas emissions decline in the near future.

An important policy implication of the paper”s results is that technological improvement in the production of renewable energy cannot in itself be trusted as a good mechanism to reduce greenhouse gases. While technological improvement may be a significant feature of international climate cooperation, it is important that this cooperation also focuses directly on emissions reduction.

3. Articles with a main focus on optimization

This chapter presents articles containing numerical analyses that focus mainly on optimization.

3.1 Analyses with the DICE Model

In his book *A Question of Balance* (Nordhaus, 2008), William Nordhaus describes the most recent version of the integrated assessment model DICE (Dynamic Integrated model of Climate and the Economy),[16] using this to analyse a number of key issues:

i.) the calculation of emission path and climate change under BaU;
ii.) the derivation of the optimal emission path and associated climate change;
iii.) as ii) but with the addition of various exogenous constraints, such as a limit on the atmospheric concentration of carbon;
iv.) the consequences and costs of various climate policies that have been suggested;
v.) the consequences and costs of limited participation in an international climate agreement.

We will start by giving a very brief description of the DICE model before going on to discuss these issues.

DICE is an aggregate model for the world economy. Total world output at any time is assumed to be given by the following output function (omitting time references):

$$Q = \Omega(T)\left(1 - \theta_1 \mu^{\theta_2}\right) F(K, L) \tag{3.1}$$

In the absence of climate change costs and mitigation costs, output would simply be $F(K, L)$, which is a Cobb-Douglas function of capital

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[16] The first version of DICE was presented in Nordhaus (1979).

(*K*) and labour (*L*).[17] Technological progress is also assumed, so that *F* increases over time for given values of *K* and *L*. Climate change costs are given by $\Omega(T)$, which is declining in global mean temperature (above pre-industrial level), with $\Omega(0)=1$. The term $\left(1-\theta_1\mu^{\theta_2}\right)$ gives the output loss due to mitigation of CO$_2$, where μ is the control rate of emission, telling us how much emissions are reduced below BaU emissions. BaU emissions are proportional to potential output *F*, but lower the higher the control rate μ is. Total emissions are thus:

$$(3.2) \qquad E=(1-\mu)\left[\sigma F(K,L)\right]$$

The proportionality factor σ is assumed to decline exogenously, but the growth in *F* nevertheless implies that uncontrolled $\left[\sigma F(K,L)\right]$ emissions grow over time.

In addition to various standard economic equations (such as output equalling consumption plus investment, labour being determined by population) the model contains equations determining the climate variable *T*. These equations give *T* as a lagged variable in the stock of carbon in the atmosphere, the development of which depends on the path of emissions *E*.

The choice of all parameters in the model is based on estimates taken from various sources. In particular, in the mitigation cost function it is assumed that $\theta_2=2.8$, implying that a doubling of the control rate (e.g. from 10% to 20% or from 50% to 100%) increases the output loss by a factor of (approximately) 7. *Marginal* mitigation costs increase by a factor of about 3.5 when the control rate is doubled, so that marginal mitigation cost at a control rate of 0.5 is about 30% of what it is if the control rate is 1. Moreover, the parameter θ_1 (which is assumed to decline exogenously over time) is set so that the marginal cost of completely eliminating emissions ($\mu=1$) at the end of this century is approximately US$260 per ton of CO$_2$. This assumption implies that a 50% reduction in emissions relative to BaU – i.e. $\mu=0.5$ – at the end of this century will give a marginal mitigation cost of about US$75 per ton of CO$_2$ (but higher in, e.g., 2050 since mitigation costs are assumed to decline over time).

BaU predictions for emissions from DICE are on disaggregated numbers from 12 regions of the world. Total population is assumed to reach about 8.5 billon, while per capita consumption is assumed to have an average growth rate of 1.3% per year in this century (i.e., considerably lower than the growth rate from 1960-2000, which was 2.5% per year). Carbon emissions per unit of GDP fell by 1.7% per year during 1960-2000, but due to a changing composition of output the decline is expected to be only 0.6% during the present century.

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[17] See section 3.5 for an explanation and discussion of types of production functions.

Under BaU the predicted temperature increase is about 3 degrees in the end of 2100 and more than 5 degrees in 2200. Aggregate climate costs for the world are assumed to be about 4.5% of world GDP for a temperature increase of 4 degrees, and about 10% for a temperature increase of 6 degrees.

The discount rate in the DICE model is reached by using the Ramsey equation (2.6), with parameters ρ and ω of 0.015% and 2 respectively. With a growth rate of per capita consumption of 1.3% this gives $r(t) = 0.041$ – i.e. 4.1%.

The DICE model is used to calculate the optimal climate policy. The objective function is an inter-temporal welfare function of the type (3.5) discussed in section 3.3, with the parameters given above. Consumption is equal to output (given by 3.1) minus investment, which is endogenous and chosen together with the climate policy in order to maximize social welfare. The full optimum is summarized in Table 3.1. Perhaps the most striking result is that the optimum gives quite modest emission reductions, in particular in the near future. This implies that CO_2 concentrations will continue to rise during the next couple of hundred years to quite high levels, with a correspondingly high temperature increase. These results are closely linked to the assumptions made about the discount rate and the assumed costs of climate change. With either a lower discount rate or higher estimates of climate change costs, the optimal time path of emissions, CO_2 concentrations and temperature increases would be lower.

In addition to calculating the full optimum, various constrained optima are calculated. A particularly interesting case is the one in which an upper limit of 2 degrees Celsius temperature increase is imposed on the optimization. The results of this are given in Table 3.1. Also for this case the optimal policy in the near future is quite modest: the carbon price in 2015 is only US$20 per ton of CO_2. However, it rises rapidly, by 3.6% per year from 2015 to 2055, so that it reaches US$83 in 2055. It also continues to rise after 2055 and is US$220 per ton of CO_2 in 2105. Note that the time path of the carbon tax and of emissions in this case is not strongly influenced by the costs of climate change. The assumed discount rate is, however, of some importance. With a lower discount rate it would be optimal to reduce emissions more in the near future and less towards the end of this century, implying a higher initial level and flatter time path in the price of carbon.

Although the price of carbon rises rapidly in the case with the temperature limit of 2 degrees Celsius, the level of the price path is quite low compared with several other studies (see, e.g., chapter 4). With an upper limit on the acceptable temperature increase, the main factor that affects the level of this price path is the assumption made about present and future technology for reducing emissions. As mentioned previously, the DICE model assumes that the marginal cost of completely eliminating emissions at the end of this century is approximately US$260 per ton of

CO_2. Compared with several other studies, this seems to be very optimistic. With the higher costs of very large reductions of emissions (which are necessary to limit the temperature increase to 2 degrees Celsius), the whole time path of the carbon price would be shifted upwards.

In section 2.3 we showed that aggregate abatement costs depend strongly on how a given amount of emissions is allocated across sources and sectors. The cost-minimizing allocation is often called the cost-effective allocation and deviations from cost-effective policies typically give quite large cost increases. This is examined in chapter 6 of Nordhaus”s book. Of the several examples given there, we will look at two here. First, under the Kyoto Agreement only countries accounting for about 33% of global emissions in 2010 are given quantitative commitments. The cost of reaching the Kyoto limits is calculated to be 7.4 times higher than the costs of the same global emission reduction with full participation. The second example concerns an agreement between the USA, EU and eight other large countries: China, Russia, India, Brazil, Canada, Japan, Mexico and South Africa. Between them, they accounted for 75% of global emissions in 2004. Reducing emissions in these countries, without imposing any restrictions on emissions from the remaining countries, gives total costs that are 68% higher than the costs of the same global emission reduction with all countries participating in a cost-effective agreement. These numerical illustrations show very clearly how important it is to achieve an international climate agreement with the broadest possible participation.

Table 3.1 Major variables for three cases analysed with DICE

		2015	2055	2105	2200
Industrial CO_2 emissions, Gt carbon	BaU	8.74	13.47	19.75	
	Optimum	7.37	9.93	11.31	
	2ºC limit	6.88	6.72	1.64	
Emission reduction as percentage of BaU emissions	BaU	0	0	0	
	Optimum	16	27	44	
	2ºC limit	22	50	92	
Carbon price, US$ per ton CO_2	BaU	0	0	0	
	Optimum	11	27	59	
	2ºC limit	20	83	220	
CO_2 in atmosphere, ppm	BaU	405	508	686	1183
	Optimum	405	481	586	659
	2ºC limit	405	466	465	442
Mean global temperature increase, degrees Celsius	BaU	0.96	1.82	3.06	5.30
	Optimum	0.95	1.68	2.61	3.45
	2ºC limit	0.95	1.61	2.00	2.00

3.2 Analyses with the ENTICE Model

We have pointed out previously that assumptions about future technological development are important for:

- what the optimal emission path is;
- the total cost of achieving any given emission path;
- the carbon price needed to achieve any given emission path.

During the last five to ten years there have been many economic analyses that explicitly incorporate endogenous technology development. This literature includes both purely theoretical models and numerical models of various types. An example of the latter is ENTICE[18], which was developed by David Popp (2004, 2006). This model is very similar to the DICE model discussed in section 3.1, the main difference being that technology development is explicitly modelled instead of being exogenous.

Like DICE, ENTICE is an aggregate model for the world economy. It is an optimization model with the same type of objective function as DICE: i.e. an inter-temporal welfare function of the type (3.5) discussed in section 3.3. The main difference between DICE and ENTICE is the modelling of the production side of the economy. Below we present the version in Popp (2006) that includes a backstop technology, i.e. a non-carbon energy input, which has a cost that declines over time as a response to R&D.

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[18] The DICE modell extended with Endogenous Technological change.

Instead of (3.1) and (3.2), the present model assumes that net output is given by[19]

$$Q = \Omega(T)F(K, L, E) - p_e e - p_n(H_n)n \tag{3.3}$$

where climate change costs are, as in DICE, given by $\Omega(T)$. In the absence of climate change costs and mitigation costs, gross output would simply be $F(K, L, E)$, which in ENTICE is a Cobb-Douglas function of capital (*K*), labour (*L*) and an input *E*, which is 'effective energy".
Effective energy is produced by a composite of fossil energy, which by choice of units is equal to emissions *e*, and non-fossil energy (*n*), as well as a technology or knowledge variable H_E

$$E = E(H_E, \phi(e,n)) \tag{3.4}$$

where the functions *E* and ϕ are CES production functions. The elasticity of substitution between the two inputs in *E* is assumed to be 1.6. Popp considers several alternatives for the elasticity of substitution between *e* and *n*. In the results presented below we restrict ourselves to what Popp considers to be the 'base case", which has an elasticity of substitution of 2.2.

To get net output we must subtract the cost of using fossil energy ($p_e e$) and the cost of using non-fossil energy $p_n(H_n)n$. The variable H_n is knowledge; the higher it is, the lower the cost of the non-carbon energy source. There are thus two knowledge variables, H_E and H_n, in the ENTICE model. An increase in H_E can be interpreted as increased energy efficiency, implying that more output can be produced for the same input of energy and other items. An increase in H_n can be interpreted as improved technology in the production of non-carbon energy, thus lowering the cost of such energy.

The knowledge variables H_E and H_n depend on knowledge creation, which in turn depends on R&D investments and current knowledge. In continuous time the relationships take the form (omitting subscripts for the two types of knowledge)

$$\begin{aligned} \dot{H} &= Z - \delta H \\ Z &= aI^b H^c \end{aligned} \tag{3.5}$$

where *I* is R&D. Finally, output can be used for consumption, investment in real capital (*K*) or the two types of R&D, I_E and I_n.[20]

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[19] See section 3.5 for an explanation and discussion of types of production functions and the concept of the elasticity of substitution.

[20] Popp assumes that some of the I_E and I_n types of R&D crowd out other R&D that is assumed to have a higher return than other investments. Technically, this is modelled so that one unit increase in I_E or I_n, gives more than one unit reduction in investment of physical capital.

In Popp (2004, 2006) several exercises are done using the ENTICE model(s), many of them comparisons of different specifications of the model and of the sensitivity of various parameters. We will stick to what we interpret as the main version of the model: i.e. one with a backstop technology, endogenous R&D and the ‘base case” parameters of Popp (see section 3.1 in Popp, 2006).

Three optimization exercises are of particular interest:

i.) BaU;
ii.) optimal policy;
iii.) constant emissions.

In all cases, optimization is with respect to the three types of investment (physical capital and two types of R&D) and the two types of energy. Under i) there is no concern for the climate and the carbon price is therefore zero. However, there will be investment in both types of R&D. The reason for this is that energy efficiency and low costs of non-carbon energy are socially valuable even if there is no concern for the climate. Under ii) the climate effects are taken into account in the optimization. Finally, iii) gives a constrained optimum, the constraint being that emissions (and thus the use of fossil energy) are held constant at their 1995 level.

To demonstrate the importance of policy-induced R&D, the optimization cases ii) and iii) are also undertaken holding R&D levels equal to what they were under BaU.

Results for key variables are summarized in Table 3.2. From this we can see the following:

- The optimal climate policy is very modest, emissions continue to grow during all of this century and the difference from the BaU emissions is quite small. This result of course depends crucially on the assumed climate change costs, as well as on the discount rate.
- Given the moderate reduction of emissions under the optimal climate policy, it is not surprising that R&D in energy efficiency and in the production of non-carbon energy is only a little higher than under BaU.
- The carbon tax necessary to keep emissions at their 1995 level is very high – e.g. much higher than the DICE model gave for a limit of 2 degrees Celsius, despite the fact that this constraint requires lower emissions in the long run than the 1995 level. This result makes it clear how important the details of the production specification are for the results that are reached.
- When emissions are required to be constant, optimal R&D levels are significantly larger than they are under BaU, in particular for R&D aimed at improving the technology of non-carbon energy.

As mentioned above, the case with constant emissions is studied holding R&D levels equal to what they were under BaU: i.e. at lower R&D levels (see Table 3.2). Intuitively, we might expect that lower R&D would imply that the carbon price necessary to keep emissions constant would be higher. This is true for the version of the model without a non-carbon energy input (although the difference in carbon price is very small). However, in the full model with non-carbon energy we get the opposite result: i.e. the carbon price is slightly higher for the case with low R&D than for the case with high R&D. While this result might seem counterintuitive, the idea that increased energy efficiency and/or lower costs of non-carbon energy result in lower use of carbon energy is based on an implicit assumption that output is unaffected. However, output may increase as a consequence of increased energy efficiency and/or lower costs of non-carbon energy, implying that the intuition may be wrong. To illustrate this more formally, we insert (3.4) into (3.3) so that we may write the output as follows:

$$Q = Q(T, K, L, e, n, H_E) - p_e e - p_n(H_n)n$$

The optimal choices of e and n are (where subscripts to Q represent partial derivatives):

$$Q_e(T, K, L, e, n, H_E) = p_e$$

$$Q_n(T, K, L, e, n, H_E) = p_n(H_n)$$

From standard micro theory we know that if $p_n(H_n)$ goes down, n will increase, while e will go down if the cross-derivative Q_{en} is negative, but increase if the cross-derivative Q_{en} is positive. If H_E increases, whether e increases or decreases will depend on the sign and size of all cross-derivatives Q_{eHE} , Q_{nHE} and Q_{en} . All of these cross-derivatives depend on the properties of the underlying functions F and E and on the size of the variables entering the functions.

Table 3.2 Major variables for three cases analysed by Popp (2006, tables 4 and 6)

		2015	2055	2105
Industrial CO_2 emissions, Gt carbon	BaU	7.19	10.98	14.13
	Optimum	7.66	9.81	11.59
	Constant emissions	6.19	6.19	6.19
Emission reduction as percentage of BaU emissions	BaU	0	0	0
	Optimum	5	11	18
	Constant emissions	23	44	56
Carbon price, US$ per ton CO_2	BaU	0	0	0
	Optimum	4	10	20
	Constant emissions	182	491	801
Energy efficiency R&D (I_E) as percentage of BaU	BaU	100	100	100
	Optimum	101	102	102
	Constant emissions	106	109	109
Non-carbon energy R&D (I_n) as percentage of BaU	BaU	100	100	100
	Optimum	107	107	105
	Constant emissions	133	161	177

3.3 Market Equilibria with Endogenous Technological Development

Grimaud et al. (2008) have extended the ENTICE model in three important directions: first, carbon capture and storage (CCS) is added; secondly, the model is designed so that, in addition to the optimal outcome, various sub-optimal market outcomes can be studied; thirdly, the market for fossil fuels is modelled along the principles described in section 2.5. In other respects their model is roughly in line with the ENTICE model. However, emissions *e* are no longer equal to the use of fossil energy, denoted by *F* in this chapter. Instead we have $e = F - S$, where *S* is the amount of CCS. In the net output function corresponding to (10.1), we must now also subtract the cost of CCS, which is $p_S(H_S, \frac{S}{F})S$. The unit cost of CCS, $p_S(H_S, \frac{S}{F})$, is assumed to be increasing in the proportion of carbon captured – i.e. *S/F* – and declining in a knowledge variable H_S. The knowledge variable is assumed to develop endogenously over time, just like the two other knowledge variables in the ENTICE model (for energy efficiency and non-carbon energy production).

The Grimaud et al. model thus has three knowledge variables. Unlike ENTICE, markets for knowledge – i.e. for innovations – are explicitly modelled. It is assumed that only a share γ_i (with $0<\gamma_i<1$) of the social value of an innovation of type i is paid to the innovator (in the absence of subsidies). The unregulated market outcome therefore gives too few innovations of all three types. This market imperfection can be corrected through subsidizing the R&D sectors, and if the subsidies are equal to $1-\gamma_i$ the market values of innovations will be identical to the social values.

The emissions under BaU are not reported directly. However, the concentration of CO_2 in the atmosphere reaches about 1000 ppm in 2105 under BaU (see Figure 8 in the paper), which is much higher than in the analysis with DICE reported in section 3.1 (686 ppm). This means that emissions under BaU are considerably higher in this study than in the DICE study.

There are four policy variables in the model: a carbon tax and subsidy rates for the three types of R&D. With appropriate time paths for these four policy instruments, the full social optimum is achieved. This full optimum is derived using a climate cost function of a similar type as in DICE. It is also derived when a constraint on atmospheric concentration of CO_2 is added, the two constraints considered being 550 ppm and 450 ppm CO_2. The latter is roughly in line with the limit of 2 degrees Celsius analysed by Nordhaus (see section 3.1).

The carbon tax associated with the optimal outcomes is somewhat higher than Nordhaus”s results, in particular for the case of stabilization at 450 ppm. Here the carbon tax in 2015 is US$48 per ton CO_2, rising to

US$200 in 2055.[21] After 2055 (which is roughly when the limit of 450 ppm is reached) the carbon tax declines. The reason for the decline after 2055 is the improvement of the three knowledge variables (see section 3.1 for a general discussion of this).

In the study various sub-optimal cases are considered. This is done by keeping some policy variables equal to their values at the full optimum and setting other variables equal to zero. For example, if we set the carbon tax equal to zero but keep the subsidy rates at their optimal values, there is hardly any reduction of emissions compared with the BaU case. If we depart from the full optimum with the 450 ppm limit by setting the subsidy of either CCS or non-carbon energy equal to zero, CO_2 concentrations will continue to rise after 2050 and reach about 550 ppm at the end of this century.

The exercise of setting one or several policy instruments equal to zero and keeping the rest at their full optimum values gives some useful insights. In our opinion an alternative exercise would be at least as interesting. This would be to set, say, the R&D subsidy rates equal to zero and recalculate the second-best optimal carbon tax with this constraint. Similarly, we could constrain the carbon tax to not be ‘too high” – i.e. under some limit that may increase over time – and reoptimize with respect to R&D subsidies. The model seems well suited to this type of exercise, which would be worth pursuing in a later version of the paper.

3.4 Analyses with the WITCH Model

WITCH (World Induced Technical Change Hybrid) is a model developed at FEEM (the Fondazione Eni Enrico Matei) in Milan and Venice. A hybrid, it is a global model with a neoclassical optimal growth structure (top-down) and a detailed energy input component (bottom-up). The top-down part of the model is very similar to both DICE (see section 3.1) and in particular ENTICE (see section 3.2). The main difference is that WITCH is a multiregional model, with the world divided into 12 regions. Although the energy sector is similar to ENTICE in the way technology change is endogenized, it is modelled in much more detail than in ENTICE and most other integrated assessment models.

We will start with a brief description of the main version of the model as described in FEEM WP 10.2007 (Bosetti et al., 2007a). In several applications the model has been slightly modified to cope better with the issues.

The welfare function of each region is of the ‘standard” type described earlier, in particular in section 2.2: i.e.

$$W = \int_0^T e^{-\rho t} N(t) u(c(t)) dt$$

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[21] The corresponding carbon taxes for the case of the limit of 2 degrees Celsius analysed by Nordhaus are US$20 and US$83 respectively (see Table 3.1).

where u is a utility function of per capita consumption $c(t)$, while $N(t)$ is population. For all regions $u(c) = Lnc$, and ρ and T are identical across regions. T is equal to 150 years, while ρ is not constant but starts at 3% and declines gradually to 2% during the 150-year period. Using $\rho = 0.03$ and consumption growth rates from 2002 to 2032 from Table 1 of WP 95.2007[22] we find interest rates from (according to the Ramsey formula: (2.6)) for OECD and non-OECD equal to 5.1% and 7.5% respectively.

Consumption is equal to total output minus investments of various types, extraction or import costs of fuels, various operation costs of energy and costs associated with carbon capture and storage (CCS). Total output for each region depends on exogenous total factor productivity growth and the development of labour, capital and energy services in a similar way to ENTICE. Total output for each region is also assumed to be affected by future climate change in the same way as described in section 3.1 for DICE.

The gross output function corresponding to $F(K,L,E)$ in ENTICE (3.3) is a constant returns to scale nested CES (constant elasticity of substitution) function. As in ENTICE, the elasticity of substitution between K and L is assumed to be 1. While the substitution of elasticity between energy services and a composite of labour and capital was assumed to be 1 in ENTICE, the elasticity is assumed to be only 0.5 in WITCH.[23]

Energy services in each region are modelled in a similar way to that described in section 3.2 for ENTICE: i.e.

$$E_s = \phi(E_n, H)$$

where E_n is energy and H is knowledge. The function is a CES function $E_s = \phi(E_n, H)$ with an elasticity of substitution of 0.4: i.e. much lower than in ENTICE, where this elasticity is assumed to be 1.6.

The knowledge variable H depends on knowledge creation, which in turn depends on R&D investments and current knowledge, and is modelled as described by (10.3). However, unlike the case with ENTICE, the costs of producing various types of energy cannot be affected through directed R&D in the version of WITCH outlined here.

Energy E_n is a CES function of electric and non-electric energy, with an elasticity of substitution equal to 0.5. Finally, both electric and non-eclectic energy can be made in several different ways, formally modelled as CES production functions with the different fuels and/or technologies as inputs. Elasticities of substitution are larger than 1 for all types of electricity. For non-electric energy the elasticity of substitution between gas, oil and biofuel is assumed to be equal to 0.5. For wind and solar electric energy there

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[22] We actually use growth rates of GDP per capita for the case in which CO_2 concentrations are stabilized at 450 ppm.

[23] The results reported in Chapter 3.5 indicate that WITCH elasticity seems more realistic than ENTICE elasticity.

is endogenous technological development through learning by doing; costs in each region are lower the higher the worldwide capacity.

The model"s solution concept is an open-loop Nash equilibrium: each country chooses its own policy variables, taking policies of other countries as given. Even when the climate externality is ignored, the model gives an outcome that is not Pareto efficient, as there are various imperfections in the market. Among these are differences between countries in marginal productivities of capital and non-internalized technology spillovers.

The model has been used for several exercises related to climate policy. Among these are the consequences of introducing limits on the concentration of CO_2 in the atmosphere and finding the most cost-effective way to achieve this. Such an exercise gives a particular time path for total emissions and allocates these emissions across countries so the price of carbon emissions (carbon tax or quota price) is equalized across countries. Results for this exercise are reported in FEEM WP 95.2007 (Bosetti et al., 2007b). Two stabilization goals are considered, 450 ppm CO_2, corresponding to roughly 550 ppm CO_2-e, and a less ambitious stabilization goal of 550 ppm CO_2, corresponding to roughly 650 ppm CO_2-e. Below we give the results for the most ambitious stabilization goal.

Table 3.4: Results from FEEM WP 95.2007 (Figures 1, 6 and 9 and Tables 1 and 2)

		2012	2032	2052	2102
Industrial CO_2 emissions, BaU, Gt carbon	World	8	12	16	21
Emission reduction as percentage of BaU emissions	World	12	56	72	86
	OECD		52		
	Non-OECD		58		
Reduction in energy/GDP as percentage of BaU	World		34		
	OECD		26		
	Non-OECD		38		
Reduction in CO_2 per unit of energy as percentage of BaU	World		33		
	OECD		34		
	Non-OECD		31		
Energy R&D increase as percentage of BaU (approx.)	World	50	130	175	330
	OECD				
	Non-OECD				
Approx. carbon price, US$ per ton CO_2		20	80	350	

Not surprisingly, emissions must be cut dramatically in order to achieve the stabilization goal of 450 ppm CO_2. Compared with BaU, the cuts are not very different for OECD countries and non-OECD countries. However, since BaU emissions increase more rapidly for non-OECD countries than for other countries, emission reductions compared with 2002 levels are largest for OECD countries: OECD emissions decline by 31% from 2002 to 2032, while non-OECD emissions grow by 5% during the same period.

For both OECD and non-OECD countries, energy saving and increased non-carbon energy give about the same contribution to overall emission reductions (at least till 2032). We also see that energy-related R&D will increase significantly in the stabilization path compared with the BaU path.

The carbon tax necessary to achieve emission reductions starts at a modest level, but becomes very high in 2050. The growth is more than 7% per year, which seems high compared with the assumed interest rates (cf. the discussion in section 3.1). We suspect this has to do with the way the optimization is done, maximizing the sum of the welfare functions of all countries. Since poorer countries have higher marginal utilities of consumption we want to transfer consumption to these countries. This cannot be done directly in the model, but since poorer countries have higher interest rates, we can help them be postponing emission reductions more than we would have done had we had other possibilities of transferring consumption to the poorer countries.

R&D is endogenously determined in the model, with each country choosing R&D expenditure to maximize its own welfare given the restriction the country has on its emissions. From Table 3.4 it might be tempting to conclude that R&D plays an important part in the mitigation effort and that costs of reaching the stabilization target would be much higher had we not had this option. However, according to FEEM WP 14.2009 (Bosetti et al., 2009), this is not the case. In this study the same stabilization target is achieved under the constraints that countries cannot expand their energy R&D investments beyond the BaU levels and that there are no learning by doing effects in the production of wind and solar energy. Compared with the unconstrained case, the world mitigation costs as a percentage of GDP increase only from 3.9% to 4.15% in 2050. The study argues that ‘costs can be reduced to a greater extent by widening the range of technological options available at competitive prices than through improvements in existing technologies”. To illustrate this, the model is run with restrictions on nuclear power (no increase from present capacity), not allowing CCS, and restrictions on the size of solar and wind energy (max. 30% of total electricity). By imposing these restrictions, mitigation costs in 2050 are increased from 3.9% of GDP to more than 7% of GDP.

The study continues with a modification of the model which, if we have understood it correctly, allows for R&D to significantly reduce the costs of non-carbon types of energy (cf. ENTICE). With the modified version of the model, total mitigation costs in 2050 are reduced from 3.9% of GDP to less than 2%.

For further applications of the WITCH model, and also for short policy papers referring to studies using the WITCH model, see http://www.feem-web.it/witch/.

3.5 Production Functions for Climate Policy Modelling

In many economic models treating climate policy issues the production side of the economy (either for the whole economy or for a particular sector) is modelled by a production function with energy (*E*) and other inputs as arguments. Consider first the case with only one other input (*v*), so that output is $F(E,v)$. Typically, it is assumed that when both (or more generally all) inputs increase by1%, output also increases by 1%. An important characteristic of such a production function is the elasticity of substitution. Denote this by *s*: It tells us how the cost-minimizing ratio between *E* and *v* change as the price of *E* increases relative to the price of *v*. More precisely (and in obvious notation): If p_E / p_v increases by 1%, *E/v* will decline by *s*%. A high value of *s* means that it is easy to substitute one input for the other, while the opposite is true is *s* is small.

For a so-called Constant Elasticity of Substitution (CES) production function, the elasticity *s* is constant, i.e. independent of E and v. A special case is $s = 1$, which describes a Cobb Douglas (CD) function: $F(E,v) = E^{\alpha} v^{1-\alpha}$.

Several studies use a production function of the type $F(K,L,E)$ where *K*, *L* and *E* stand for capital, labour and some measure of energy input respectively. In some studies, such as in the ones discussed in sections 3.2 and 3.3, the *F*-function is a Cobb-Douglas function: i.e. the elasticity of substitution is 1 between all three inputs. In other studies, some type of nested CES function is used: e.g. $F(K,L,E) = \Phi(\varphi(K,L),E)$. This is called a (KL)E nesting structure and is the one used in the WITCH models (see section 3.4). For such a structure, there will be one elasticity of substitution between *K* and *L*, and another one between (*KL*) and *E*. In the WITCH models the φ-function is a Cobb-Douglas function: i.e. the elasticity of substitution between *K* and *L* is 1. The elasticity of substitution between (*KL*) and *E* in the WITCH models is assumed to be 0.5: i.e. lower than that assumed in ENTICE and the model used by Grimaud et al. Other nesting structures are also possible: i.e. (KE)L and (LE)K. The combination of the nesting structure and the assumed elasticities of substitution describe how easy it is to reduce the use of fossil energy sources. It is therefore important to study what data can reveal about these issues.

Edwin van der Werf (2007) has undertaken a thorough empirical analysis. Production functions are estimated both for different industries and for different countries. He has tested which types of nesting structure and what magnitudes of elasticity are supported by the data. He has five main conclusions:

- The (KL)E nesting structure seem to fit the data best.
- For several countries and industries, the non-nested structure KLE seems to be as good as the (KL)E nesting structure.
- The size of the elasticities varies considerably over both countries and industries.
- The Cobb-Douglas production function is rejected by the data for all countries and industries.
- For the (KL)E nesting structure, the elasticity of substitution between (*KL*) and *E* ranges from 0.1 to 0.6, while the elasticity of substitution between *K* and *L* ranges from 0.2 to 0.6.

The models we have considered in sections 3.2-3.4 use either a non-nested KLE structure or a (KL)E structure. Those in sections 3.2 and 3.3 use a Cobb-Douglas production function: i.e. assume elasticities of substitution equal to 1. Such high elasticities are, according to van der Werf, rejected by the data. Also the WITCH model (see section 3.4), which has a (KL)E nesting structure, assumes an elasticity of substitution between (*KL*) and *E* that is at the higher end of the range suggested by the data.

Assuming an elasticity of substitution between (*KL*) and *E* higher than it actually is will give an overly optimistic result regarding how easy it is to substitute away from fossil energy. The costs, and the necessary carbon price, associated with a particular emission goal may therefore be biased downwards compared with the true values. Moreover, if it is easy to move away from fossil energy with existing technologies, the importance of developing new technologies will be underestimated.

3.6 Future Climate Change Costs

As shown in section 2.1, the optimal carbon price, and thus the optimal emission path, depends crucially on the size of climate change costs. In the studies we have considered so far, these costs have been treated as a reduction in consumption compared with the consumption level in the absence of climate change. However, by ‘translating” all negative climate effects into reduced consumption, it is easy to underestimate the true future costs. This is because some costs of climate change will come in the form of reductions in non-market goods, such as loss of biodiversity, effects on human well-being (health, amenities), various forms of extreme weather events, risk of conflicts etc. Non-market goods of this type grow only slowly over time, or might even decline. If the number of produced market goods increases rapidly at the same time, we should expect an increased marginal valuation of non-market goods as time passes.

Formally, assume that overall well-being is given by a utility function of the type $u(c, E)$ where c is traditional consumption and E is a non-market environmental good. The willingness to pay for one unit more of the environmental good in terms of the traditional consumption good is given by the ratio of marginal utilities u_E/u_c, which typically will increase if c/E increases. In most studies of climate change effects far into the future, traditional consumption is assumed to grow significantly. For instance, in both the *Stern Review* (see section 4.2) and Nordhaus"s analysis (see section 3.1) per capita consumption is assumed to grow at a rate of 1.3% per year if climate change is ignored. This makes per capita consumption about 12 times higher in 2200 than it is today. Even with the worst climate outcomes considered by Stern (giving an output loss of about 35%) consumption in 2200 will be about eight times higher than today. At the same time, some non-market goods (often defined in terms of quality) will be about as today, or might even decline. With such large changes in c/E, there is good reason to expect willingness to pay for increased E (or to avoid a deterioration of E) to be much higher than today. Exactly how much higher will depend on the elasticity of substitution between the two goods.

Hoel and Sterner (2007) have made a formal analysis of these issues using a CES utility function. This has been followed up by Sterner and Person (2008), who have incorporated them into a model that in other respects is practically identical to Nordhaus"s DICE model. They assume that about half the climate effects are in non-market goods and that the elasticity of substitution between traditional consumption and such non-market goods is equal to 0.5. With this modification of the DICE model, the optimal climate policy is much stricter than what Nordhaus suggests. Even with the high discount rate used by Nordhaus (4.1%) optimal emissions decline sharply in the second half of this century, implying that CO_2-concentrations reach about 450 ppm in 2100 and then decline. This is a very similar result to what we found in the analysis with DICE in section 3.1 when the 2 degree limit was added: see table 3.1.

The exact numbers derived from Sterner and Person should not be taken too literarily, as our knowledge about future preferences over traditional consumption goods and non-market environmental goods is obviously quite limited. But the analysis shows that by introducing some quite small and not implausible changes into the DICE model, major numerical conclusions may change dramatically.

3.7 Handling Uncertainty

There are many uncertainties relating to almost all aspects of climate policy and climate change. In particular:

- The development of future climate policies and climate agreements is uncertain.
- For given policies, their cost and impact on emissions are uncertain.
- For a given emission path, the climate development is uncertain.
- For a given climate development, the impact on nature is uncertain.
- For a given impact on nature, the economic impact (including valuation: see section 3.6) is uncertain.

While these uncertainties are frequently mentioned in the economics literature, very few studies provide an explicit formal treatment of them. Typically, some sensitivity analysis is undertaken, but the main analysis uses point estimates of central variables and parameters as if there were no major uncertainty associated with them.

Perhaps the largest area of uncertainty relates to the impact of emissions on the climate. There are two aspects to the uncertainty: first, the relationship between anthropogenic increases in CO_2 and other greenhouse gases and the ultimate increase in GHG concentrations, including heat-induced feedbacks (such as CH_4 from permafrost) and the weakening of carbon sinks; second, the relationship between GHG concentrations and the climate. The latter relationship is often characterized by the so-called climate sensitivity, which tells us by how much the global average temperature will ultimately increase as a response to a doubling of the atmospheric concentration of CO_2-e.

According to IPCC (2007), climate sensitivity is ‘likely to be in the range 2^{o}C to 4.5^{o}C with a best estimate of 3^{o}C, and is very unlikely to be less than 1.5^{o}C. Values substantially higher than 4.5^{o}C cannot be excluded, but agreement of models with observations is not as good for those values.” In an important recent contribution, Martin Weitzman (2009) focuses on the possibility of ‘values substantially higher than 4.5^{o}C”. Based on the scientific literature on this topic, he argues that there is a 5% probability of climate sensitivity higher than 7 degrees Celsius and a 1% probability of climate sensitivity higher than 10 degrees Celsius. He combines this with a model in which climate costs become very high for large temperature increases. Moreover, the probability distribution of temperature increases is ‘fat-tailed” in the sense that as we move towards higher temperature increases, the probabilities decline less rapidly than the damages increase. As a consequence, he finds that expected climate costs will be ‘infinitely high”. This is of course not meant literally, but it implies that actual expected climate costs will be very sensitive to both details of the probability distribution of the climate sensitivity and the exact costs of very large temperature increases. Weitzman argues that most analyses of optimal climate policy (such as the studies discussed previously in this chapter) ignore this important feature and may therefore give very misleading results. A similar argument has recently also been made by Nævdal and Vislie (2008), based on a formal analysis resembling Weitzman”s. They conclude that ‘if cost-benefit calculations are done within a model that encompasses the type of catastrophic risk that…scientists worry about, the resulting stabilization target will only be slightly influenced by the discount rate”.

3.8 Alternative Policies for Achieving Emission Goals

Policy instruments for achieving emissions goals were discussed theoretically in section 2.4, where an important conclusion was that the correct carbon price is a crucial element in an optimal policy package. However, we also briefly discussed some reasons why it could be desirable to supplement the correct carbon price with other policy instruments. In policy debates the view is sometimes put forward that other policies should be an *alternative* rather than a *supplement* to the correct price: i.e. ‘a carrot is better than a stick”. Economists are reasonably unanimous that the correct price is crucial in order to get an efficient outcome. There is, however, no guarantee that this type of policy recommendation will be followed. It is therefore interesting to see numerical studies indicating how large the efficiency loss may be if we try to achieve an emission goal with policies other than a suitable emission price. One example of such a study is Fischer and Newell (2008).

Fischer and Newell start by presenting a simple two-period model of the electricity sector of the economy. There are three ways to produce electricity: by coal, natural gas and a renewable source. The first two lead to CO_2 emissions. The cost function of renewable energy is assumed to develop endogenously depending on the growth of ‘knowledge capital”. The growth in knowledge depends partly on how much electricity is produced by renewables in the first period – learning by doing (LbD) – and partly by how much is spent on R&D directed at renewable energy in the first period. For both types of knowledge creation, it is assumed that only part of the social value of knowledge creation is appropriated by the agent causing the knowledge increase: i.e. the producer of renewable electricity for LbD and the research sector for knowledge resulting from R&D. This part of the model is therefore quite similar to the model described in section 3.3 (Grimaud et al., 2008). In addition to the supply side of the electricity market, the demand side is modelled in a traditional manner and the market equilibrium can be calculated. The equilibrium will depend on the specification of policies. Six policy instruments are explicitly analysed:

i.) CO_2 emission price;
ii.) tax on fossil-fuelled energy;
iii.) tradable emissions performance standard;
iv.) portfolio standard for renewable energy;
v.) production subsidy for renewable energy;
vi.) subsidies for R&D.

The paper presents a theoretical discussion of the effects of each policy. Note that in order to reach the full social optimum, this model requires the use of three policy instruments: i.e. i), v) and vi). The carbon price is needed to correct for climate externality. The subsidy for renewable energy is needed to compensate for the fact that only part of the benefits of learning from a particular producer of renewable energy goes to this producer. The subsidy for R&D is needed because the research sector is able to appropriate only part of the social value of the innovations it creates.

After the theoretical discussion, the paper gives a numerical analysis of the US electricity sector based on this model. Obviously, such a simple model can only give a very rough description of such a complex sector as the US electricity sector. The numbers derived should therefore be looked upon only as very crude estimates of the true values. The paper first considers the effect of a constant carbon tax of $7 per ton of CO_2. This modest carbon tax reduces CO_2 emissions by 4.8%. The paper then considers each of the alternative policies in turn, used so that they give the same emissions reduction as the carbon tax. As theory would predict, all the alternative policies have higher costs. This is particularly true for the three subsidy policies, iv),[24] v) and vi). Policies iv) and v) give costs between two and three times higher than the costs of a carbon tax, while a pure R&D subsidy has a cost that is more than ten times as high as the cost of using a carbon tax.

As mentioned above, the policy instruments i), v) and vi) must all be used in order to reach the full social optimum. In this model the full optimum is socially beneficial compared with the benchmark case of no policy even if the benefits of emissions reduction are ignored. The reason for this is that even in the absence of a climate externality, there will be some use of renewables and correcting for the market failure in knowledge creation for such production more than outweighs the negative effect (when climate costs are ignored) of the carbon tax.

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[24] A portfolio standard for renewable energy is equivalent to a subsidy for renewable energy financed by a tax on fossil-fuel-based electricity: see, e.g. Amundsen and Mortensen (2001)

3.9 Summary / discussion of articles with a main focus on optimization

The preceding sections have considered the assumptions made and results for several optimization studies. They differ both in methodology (in particular, how technology and technological development are modelled) and in assumptions about exogenous variables. Not all the assumptions are reported, making comparison between the studies quite difficult.

The DICE model (section 3.1) differs from the other studies by having a very simple mitigation cost function, while the other studies (except the one in 3.6, which uses the DICE model) have production functions with fossil and non-fossil energy as inputs along with other inputs. Clearly, the latter type of analysis is ‘better” in the sense that it shows more fundamentally exactly how we can reduce carbon emissions. However, the mitigation cost function used in the DICE model has the advantage of being very transparent, so it is relatively easy to see how the results of the analysis depend on the assumptions made about mitigation costs. As mentioned in section 3.1, it is assumed in this study that the marginal cost of completely eliminating emissions at the end of this century will be approximately US$260 per ton of CO_2. Compared with the results of several other studies in this chapter, that estimate seems to be very low. The estimate is particularly important for determining the appropriate carbon price path to attain ambitious climate targets, such as the 2-degree limit. This price path is lower than carbon price paths for similar climate targets from the other studies: see Table 3.9. With a higher cost of completely eliminating emissions, the whole time path of the carbon price would be moved upwards.

Analyses using a production function with various types of energy as inputs show exactly how carbon emissions can be reduced. However, their reliability depends crucially on parameters such as elasticities of substitution between different inputs and on how technological progress is modelled. Our knowledge of such parameters and function forms is based on historical data, which may give misleading estimates for a low-carbon future. The study in section 3.5 shows that many analyses assume elasticities of substitution between energy and other inputs that are higher than the data suggest. This may give results that are too optimistic, in the sense that reduced emissions with current technologies can seem less costly than they will actually turn out to be. The importance of technological development can therefore also be underestimated. Of the studies reported in this chapter, it is the WITCH model that has a value for this elasticity that seems to be ‘best”, according to the study in section 3.5.

In addition to the elasticity of substitution between energy and other inputs, the studies in this chapter have elasticities between knowledge and energy and between carbon and non-carbon energy. It is difficult to have a firm opinion about the scale of these elasticities, but this is obviously of crucial importance for the results.

The analyses discussed in sections 3.1-3.4 all use a model with a similar structure. However, there are also important differences. In particular, the possibility of CCS (carbon capture and storage) is included in the studies in sections 3.3 and 3.4, but not in those in section 3.2.

In many of the studies an optimal emission path is derived. Most of these suggest that mitigation efforts should be quite moderate, implying optimal temperature increases beyond 3 degrees in the next century. It is important to bear in mind that these results depend crucially on what is assumed about the relationship between emissions and climate change, and how climate change will be valued in the future. Our current knowledge of these factors is fairly limited, but the studies reported in sections 3.6 and 3.7 indicate that by introducing some quite small and not implausible changes into DICE and other optimization models, major numerical conclusions may change dramatically. We should therefore be very cautious about claims that long-term concentration limits of, for example, 450 ppm CO_2 are too ambitious.

Many of the studies also solve constrained optimization problems, where there is a limit on the atmospheric concentration of CO_2 or on temperature increase. These studies thus take a climate goal as given and calculate the optimum given this goal (see section 2.1 for a theoretical discussion of this type of optimization). In Table 3.9 we have summarized the results from the studies for such a constrained optimization. The climate goal is similar across the studies. Nevertheless, there are large differences in the time paths of the carbon price, which is an indicator of how difficult it is to achieve the goal.

One of the most striking features of the table is the very large difference in carbon price, despite the climate goal being roughly the same. One might believe that this is due to large differences in BaU emissions. However, from Table 3.1 it is clear that the study with ENTICE has much lower BaU emissions than the other studies, which should tend to make the carbon price low, while this study actually gives a much higher carbon price than other studies do. It is not obvious to us why the analysis with ENTICE gives such a high carbon price compared to the analyses in the other two studies with similar production functions (Grimaud et al. and WITCH), but we suspect the reason is that CCS is not an option in the study with ENTICE. In any case, the table indicates how the results of the analyses depend heavily on details of the assumptions made.

Table 3.9: Carbon prices for different studies

	Concentration of CO_2 in 2100 (ppm)	Temperature increase in 2100 (degrees Celsius)	Carbon price 2015 (US$ per ton CO_2)	Carbon price 2055 (US$ per ton CO_2)
DICE 2-degree limit	465	2	20	83
ENTICE Constant 1995 emissions		2	182	491
Grimaud et al. 450-ppm limit	450		48	200
WITCH 450-ppm limit	450		20	350

Most of the studies discussed in this chapter say little about policy instruments to achieve emissions goals. Most of them report the carbon price associated with the derived emission path. Without any other market or regulatory failures, this carbon price (as a carbon tax or a quota price) would be sufficient to achieve the desired outcome (see the discussion in section 2.4). The studies in sections 3.3 and 3.8 explicitly address market failures linked to technological development. These studies show how the carbon tax must be supplemented with some subsidies related to technological development in order to achieve the desired outcome. The study in section 3.8 suggests that the welfare loss may be very large if one tries to use subsidies as an alternative rather than a complement to carbon price.

4. Articles with a main focus on simulations

This chapter presents large studies that treat a broad range of issues, and often consider quite complex and disaggregated models of the world economy. These models typically identify a policy that is consistent with a specific emission target and then calculate the costs of such a policy.

4.1 The Fourth IPCC Assessment Report

The IPCC is a scientific intergovernmental body set up by the World Meteorological Organization (WMO) and by the United Nations Environment Programme (UNEP).

The IPCC was established to provide the decision-makers and others interested in climate change with an objective source of information about climate change. The main activity of the IPCC is to provide in regular intervals Assessment Reports of the state of knowledge on climate change. The latest one is "Climate Change 2007", the Fourth IPCC Assessment Report. The Fourth IPCC Assessment Report was prepared by three working groups, each of which produced its own report:

- Working Group I, ‘The Physical Science Bases”,
- Working Group II, ‘Impacts, Adaptation and Vulnerability”, and
- Working Group III, ‘Mitigation”.

In addition, the IPCC published a ‘Synthesis Report” summarizing the work of all three groups.

The IPCC does not try to estimate the economic cost of climate change. Instead, Working Group II”s report includes a descriptive analysis of the likely impact on natural and human systems of an increase in the global temperature and its associated changes.

Working Group III”s report is of most relevance for this study. The summary for policymakers, released on 4 May 2007, is organized into five sections:

i.) Greenhouse gas (GHG) emission trends;
ii.) Mitigation in the short and medium terms across different economic sectors (until 2030);
iii.) Mitigation in the long term (beyond 2030);
iv.) Policies, measures and instruments to mitigate climate change;
v.) Sustainable development and climate change mitigation.

The emission trends are based on a set of scenarios developed by the IPCC in a 'Special Report on Emission Scenarios" (SRES). These assume no explicit climate policy such as, for instance, the Kyoto Protocol, so they should be interpreted as business-as-usual (BaU) scenarios. Basically there are four main families of scenario, A1, A2, B1 and B2, each with a group of sub-scenarios.

The scenarios differ in four parameters:

- the size of economic growth,
- regional difference in economic growth,
- degree of global technology diffusion and
- success of less polluting technology.

Together they cover a range of possible emission time paths which, according to the IPCC, will lead to a concentration of GHG emissions in the atmosphere in the year 2100 of between 855 and 1,130 ppm CO_2-e. Clearly, the chosen BaU scenario is important when considering both the physical need for emission reductions and the cost of emission reductions.

Other key findings of the report are as follows:

- GHG emissions have increased since pre-industrial times, with an increase of 70% between 1970 and 2004. The largest increase in global GHG emissions between 1970 and 2004 came from the energy supply sector (145%). The increase in direct emissions from transport was 120%, from industry 65%, and from land use change and forestry 40%.
- The effect on global emissions of the decrease in global energy intensity (-33%) from 1970 to 2004 was smaller than the combined effect of global income growth (77%) and global population growth (69%), both drivers of increasing energy-related CO_2 emissions. The long-term trend of declining carbon intensity in energy supply reversed after 2000. Differences in terms of per capita income, per capita emissions and energy intensity among countries remain significant.
- With current climate change mitigation policies and related sustainable development practices, global GHG emissions will continue to grow over

the next few decades . The SRES project an increase of baseline global GHG emissions by a range of 9.7 $GtCO_2$-e to 36.7 $GtCO_2$-e (25%–90%) between 2000 and 2030. In these scenarios, fossil fuels are projected to maintain their dominant position in the global energy mix to 2030 and beyond. Hence CO_2 emissions between 2000 and 2030 from energy use are projected to grow between 45% and 110% over that period. Two-thirds to three-quarters of this increase in energy CO_2 emissions is projected to come from non-Annex I countries, with their average per capita energy CO2 emissions being projected to remain substantially lower (2.8–5.1 tCO2/cap) than those in Annex I countries (9.6–15.1 tCO2/cap) by 2030. According to SRES, Annex I countries are projected to have a lower energy use per unit of GDP (6.2–9.9 MJ/US $ GDP) than that of non-Annex I countries (11.0–21.6 MJ/US$ GDP).

- In 2050 global average macroeconomic costs for multi-gas mitigation towards stabilization between 710 and 445 ppm CO_2-e are between a 1% gain and a 5.5% decrease of global GDP. For specific countries and sectors, costs vary considerably from the global average.
- Modelling studies show carbon prices rising to US$20–80/$tCO_2$-e by 2030 and US$30–155/tCO_2-e by 2050 are consistent with stabilization at around 550 ppm CO_2-e by 2100. For the same stabilization level, studies since The Third Assessment Report (TAR, 2001) that take into account induced technological change lower these price ranges to US$5–65/$tCO_2$eq in 2030 and US$15–130/tCO_2-e in 2050.

Most top-down, as well as some 2050 bottom-up assessments, suggest that real or implicit carbon prices of US$20–50/$tCO_2$-e, sustained or increased over decades, could lead to a power generation sector with low-GHG emissions by 2050 and make many mitigation options in the end-use sectors economically attractive. According to IPCC policies that provide a real or implicit price of carbon could create incentives for producers and consumers to significantly invest in low-GHG products, technologies and processes. Such policies could include economic instruments, government funding and regulation.

The cost of mitigation presented in Working Group III"s report is based on many different models and many different model runs. In 2030 macroeconomic costs for multi-gas mitigation, consistent with emissions trajectories towards stabilization between 445 and 710 ppm CO_2-e, are estimated at between a 3% decrease of global GDP and a small increase, compared to the baseline. However, regional costs may differ significantly from global averages. It is pointed out that new energy infrastructure investments in developing countries, upgrades of energy infrastructure in industrialized countries and policies that promote energy security can, in many cases, create opportunities to achieve GHG emission reductions compared to baseline scenarios. Additional co-benefits are country-specific but often include air pollution abatement, balance of trade improvement, provision of modern energy services to rural areas and employment.

Future energy infrastructure investment decisions, expected to total over US$20 trillion between now and 2030, will have long-term impacts on GHG emissions, because of the long lifetime of energy plants and other infrastructure capital stock. The widespread diffusion of low-carbon technologies may take many decades, even if early investments in these technologies are made attractive. Initial estimates show that returning global energy-related CO_2 emissions to 2005 levels by 2030 would require a large shift in the pattern of investment, although the net additional investment required ranges from negligible to 5%–10%.

Baseline emissions scenarios published since SRES are comparable in range to those presented in the IPCC ‘Special Report on Emission Scenarios” (25–135 $GtCO_2$-e/yr in 2100) Studies since SRES used lower values for some drivers for emissions, notably population projections. However, for those studies incorporating these new population projections, changes in other drivers, such as economic growth, resulted in little change in overall emission levels. Economic growth projections for Africa, Latin America and the Middle East to 2030 in post-SRES baseline scenarios are lower than in SRES, but this has only minor effects on global economic growth and overall emissions. Representation of aerosol and aerosol precursor emissions, including sulphur dioxide, black carbon and organic carbon, which have a net cooling effect, has improved. Generally, these are projected to be lower than reported in SRES.

4.2 The Stern Review

The *Stern Review*, which was published in 2007, runs to almost 700 pages and covers a broad range of issues relating to climate change. We will restrict our attention here to the main economic analyses and results, which have been widely discussed in the literature since its publication.

The review looks closely at projections of greenhouse gas emissions under BaU. Based on these, it calculates economic (market and non-market) climate costs associated with a particular projection. The projection used gives a fairly rapid growth in CO_2-e: on average 1.4% per year during the first half of the present decade. Moreover, emissions are assumed to continue to grow at a fairly high rate for the whole period covered in the analysis (which goes to 2200). Behind this projection is an assumption of average population growth until 2200 of 0.6% per year, implying that the world population will be 20 billion in 2200. In addition, world GDP per capita is assumed to have an annual growth rate during the period equal to 1.3% (before subtracting the costs of climate change).

This implies that before correcting for the negative impact of climate change, per capita income will be about 12 times higher than today.

Under the BaU projection, there will be dramatic climate change during the next couple of decades. The costs of such change are considered at length in the *Stern Review*. In economic terms, there is great uncertainty about what these costs will actually be, even if the uncertainty about what the climate will be like is ignored. The Review considers several scenarios, which differ both with respect to what the climate changes will be and what types of costs are included. In all cases costs will rise over time, both in absolute terms and as a percent of GDP.

Monte Carlo simulations are used to illustrate some of the uncertainty, presenting climate change costs at the end of the next century under BaU as a range from about 3% to about 35% of GDP, with a mean of 13.8% (see Table 6.5c in the *Stern Review,* which describes the case with highest costs).

The Review ”translates” these rising costs into “balanced growth equivalents”: These are constant percentage losses of consumption, based on a welfare function of the type (2.5): The reduction in W caused by climate change is translated into a constant percentage reduction in consumption (relative to the case with no climate change) from the present to the infinite future that gives the same reduction in W as the increasing cost. With the costs above this gives an expected consumption loss of 14.4% (with an interval from 2.7% to 32.6%, see Table 6.1 in the Review). It is important to note that it is the consequences in the far future that are most important for the values of the hypothetical constant percentage consumption reduction. While the actual losses described in Figure 6.5 of the Review are independent of the parameters of the function (2.5), the “balanced growth equivalents” depend strongly on the parameters of this function. With parameters implying a higher discount rate, the “balanced growth equivalents” would be lower.

The *Stern Review* does not give a formal optimization in order to find an optimal emission path (as described in section 2.1). However, it discusses the costs of stabilizing greenhouse gases at levels between 500 and 550 ppm CO_2-e: i.e. at the high end about twice the pre-industrial level. Due to very high costs of adopting a target below 500 ppm, the Review recommends a target between 500 and 550 ppm.

Given a climate sensitivity of 3 (the ‘best guess” of the IPCC), this would limit the global mean temperature increase to 3 degrees Celsius (while it would increase to 7–9 degrees by 2200 under the BaU scenario). The review goes into great detail about how such a stabilization might be achieved. Based on several sources, it also gives estimates of the costs involved. In particular, a study by Dennis Anderson (2006) is reported in section 9.8. Here it is argued that mitigation costs might be about 0.3% of GDP in the near future, increasing to about 1% in 2050. However, these numbers are uncertain and the range for 2050 is from -0.6% (i.e. a small gain) to 3.5% of GDP. These costs are compared with the costs of climate change under BaU and it is (informally) argued that the reduction of climate costs resulting from mitigation efforts more than outweigh mitigation costs.

The review is rather vague regarding the marginal costs of mitigation in the near future under the stabilization scenario. This is an important variable, since it tells us what the price of carbon emissions must be in a market economy. Table 9.2 in the Review gives numbers for *average* costs of mitigation, which are reported to be US$61 per ton of CO_2 in 2015, declining to US$22 in 2050. There are two interesting features of this table. First, average costs are assumed to decline over time in spite of strongly increased mitigation. This suggests a very rapid improvement in mitigation technologies. Second, marginal costs are higher than average costs. If the ratio between marginal and average costs is the same in 2050 as in 2015, this table implies that marginal costs will decline over time. As explained in section 2.1, an optimal policy will typically have increasing marginal costs. A declining marginal cost suggests that too much mitigation is assumed in the near future, instead of mitigating more at a later date, when technology is assumed to have improved significantly. Note, however, that if the assumed technological development requires early mitigation as a result of learning by doing (see section 2.4), it may be best to make significant mitigation efforts at an early stage, even if the marginal mitigation costs are higher at this early stage than they will eventually become after the technology has improved.

The social cost of carbon – i.e. the variable given by (2.4) – is discussed in section 13.2 of the *Stern Review* (see in particular boxes 13.1 and 13.3). This variable depends on the time path of carbon in the atmosphere (since D_S in (2.4) depends on S) and thus on the time path of emissions. The review shows that there is a wide range of estimates in the literature under BaU scenarios. This is partly due to different estimates of what emissions will be under BaU, but the uncertainty regarding the size of climate costs is probably a more important reason for the wide range of estimates of the social cost of carbon. For the climate change costs and BaU scenarios used in the review, the estimate of the social cost of carbon is US$85 per ton CO_2. As mentioned above, climate change costs could be more than twice the point estimate; the same is therefore also true for the social cost of carbon. Since marginal climate change costs will be lower under a stabilization scenario, so will the social cost of carbon. In the review the social cost of carbon is estimated to be US$30 per ton CO_2 for an emission path giving stabilization at 550 ppm CO_2-e, while it is estimated to be US$25 per ton CO_2 for an emission path giving stabilization at 450 ppm CO_2-e. Due to the uncertainty regarding climate costs, these estimates are very vague.

Ignoring uncertainty, we have the following numbers in the case of stabilization at 550 ppm CO_2-e: the present (and near-future) social cost of carbon is about US$30 per ton CO_2, while the marginal mitigation cost is more than US$61 per ton (which was the *average* cost in 2015: see above). From chapter 2 we know that in an optimal outcome the marginal mitigation cost should equal the social cost of carbon. The fact that the marginal mitigation cost exceeds the social cost of carbon for an emission path giving stabilization at 550 ppm CO_2-e indicates that such a stabilization target might be too ambitious. However, bearing in mind the uncertainty relating to all these numbers, and also some issues relating to endogenous technological development, we should be cautious before drawing such a conclusion.[25]

Several studies of the *Stern Review* have criticized its estimates of climate change costs (see, e.g., Mendelsohn, 2008) and mitigation costs (see, e.g., Weyant, 2008). However, most of the focus has been on the review"s way of comparing climate change costs and mitigation costs. The major part of climate costs will occur in the next century, with hardly any costs before 2050. Mitigation costs, on the other hand, will be considerable even in the first half of this century. The discount rate used in the comparison of these time-dependent costs is therefore of crucial importance for the result obtained. The *Stern Review* uses a discount rate based on the Ramsey equation (2.6). The annual per capita consumption growth rate is assumed to be 1.3%: i.e. $g(t)$=0.013. The parameters ρ and ω are assumed to be 0.001% and 1 respectively. This gives $r(t)$=0.014: i.e. 1.4%. This is very low compared with what is usually assumed and with a higher discount rate the case for stabilizing greenhouse gas concentrations at 550 ppm CO_2-e compared with a less ambitious goal would be weakened. We will not attempt to summarize the lengthy debate on the discount rate that has followed the *Stern Review*, but a couple of important references are Nordhaus (2008; see section 3.1) and Dasgupta (2008), as well as the references found in these studies.

4.3 Studies by the OECD

The OECD studies we present are based on the OECD"s own Environmental Linkages Model, which is a general equilibrium model of the world economy, with many different sectors and several geographical regions. All the six major GHG gases are included in the model.

The OECD "Environmental Outlook to 2030" (2008) covers a wide range of environmental problems, from climate change to waste and material flows. Many of the results from the chapter on climate change are modified in a later publication, see Burniaux (2008). For instance, the 'Environmental Outlook" includes stabilization at 450 ppm CO_2-e scenario, while the later publication considers only a target of 550 ppm CO_2-e.

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[25] The average mitigation cost is assumed to fall rapidly and be only US$22 dollars in 2050. In this year, therefore, the marginal mitigation cost may be roughly equal to the social cost of carbon.

We will first comment briefly on the ‘OECD Environmental Outlook to 2030”. This analyses a range of climate policy scenarios, among them:

i.) a global CO_2 tax of US$25 from 2008, increasing yearly by 2.4% in real terms;
ii.) an OECD CO_2 tax of US$25 from 2008, followed by BRIC[26] in 2020 and ROW[27] in 2030; and
iii.) the above-mentioned stabilization at 450 ppm CO_2-e, starting in 2008.

Note that already none of these scenarios accord with reality. For instance, at the time of writing there is no economy-wide CO_2 tax of US$25 in the OECD and no global abatement of CO_2 in all sectors. Moreover, the 450 ppm CO_2-e stabilization target is arrived at partly by assuming that halting deforestation and reforestation happen at no cost. Finally, the effect of CCS is not modelled explicitly, but emission reductions from CCS are still factored in, but in a way that, according to the OECD, likely leads to an underestimation of the costs of CCS.

Below we present some of the key results from the phased-in action scenario ii) and the 450 ppm scenario iii):

Table 4.3.1 Selected results from the phased-in action scenario ii) and the 450 ppm scenario. Source: ‘Environmental Outlook to 2030”, OECD (2008)

		2005	2030	2050	2100
	BaU Gt/year (CO_2-e)	46.9	64.1	71.4	
Emission reduction as percentage of BaU emissions (world)	Phased-in action		21%	41%	
	450 ppm CO_2-e		39%	64%	
Carbon price, 2001 US$ per ton CO_2-e	BaU				
	Phased-in action	$25 (OECD only)	$59	$67	
	450 ppm CO_2-e	<$2.4	48	155	
CO_2 in atmosphere, ppm	BaU	380	465	543	1,000
	Phased-in action		455	501	~650
	450 ppm CO_2-e	455	443	463	450
Mean global temperature increase, degrees Celsius, compared to pre-industrial level	BaU		1.2–1.6	1.7–2.4	
	Phased-in action		1.1–1.4	1.5–2.0	
	450 ppm CO_2-e	0.6	1.1–1.4	1.3–1.8	

Note that emission tax in the 450 ppm scenario increases very sharply: It increases from $2.4 in 2010 to $48 in 2030, and from $48 in 2030 to $155

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[26] Brazil, Russia, India and China.

[27] Rest of the world.

in 2050. This corresponds to a growth rate of 16% per year in the first 20 years, and a growth rate of 6% the next 20 years. We do not fully understand the assumptions and/or mechanisms in the OECD study that is driving this steep emission tax path, however, a part of the explanation may be that the initial tax rate is fixed exogenously, and that the study does not allow jumps in the emission tax rate. Hence, the emission tax path has to be steep in order to secure that the concentration target is reached.

Note also that the long-term temperature increases beyond 2050 will be higher than the above reported values as they incorporate only short- and medium-term effects. The expected temperature increase in 2100 is not reported, but according to other reports, such as ‘World Energy Outlook 2008”, temperature increases could be as high as 6 degrees Celsius under BaU. Note also that it is very hard to stabilize GHG concentration levels to below 550 ppm if global action is delayed. We will elaborate on this further in our review of the next report on climate change mitigation by the OECD, see Burniaux et al. (2008).

The OECD measures mitigation costs as reductions in GDP compared to the BaU scenario. The cost of the most ambitious target above is reported by the OECD to be 2.5% lower GDP by 2050 than what it would have been without any measures (BaU). However, as already mentioned, the OECD arrives at another result in their later report, where they do not consider the 450 ppm CO_2-e target (Burniaux et al., 2008)). Burniaux et al. report that the cost of reaching a 550 ppm CO_2-e target to be 4.8% lower world GDP by 2050. Thus, the cost of reaching the 550 ppm target in the OECD's later report, is seemingly nearly twice as high as the cost of reaching the 450 ppm target in the 'Environmental Outlook 2030'. On the other hand, their BaU scenario has also changed, incorporating higher emissions and so making the need for abatement greater. For instance, the assumed growth in GHG emissions in the BaU scenario in the ‘Environmental Outlook” in the period 2005–50 is below 1%, while in the later report it is 1.4% due partly to updated estimates of the emission growth in the BRIC countries.

Moreover, while GHG abatement was taken to begin in 2008 in the ‘Environmental Outlook”, the later report gives 2013 as the starting date. Instead of incorporating halted deforestation and reforestation at no cost, and including CCS in an unsatisfactory way, it has simply disregarded these three options (OECD, 2008b).

The following table shows some of the key numbers.

Table 4.3.2. Key numbers from the OECD 2008 b. Source: Burniaux et al. (2008)

		2005	2025	2050
	BaU Gt/year (CO_2-e)	46.9	73.3	87.7
Emission reduction as percentage of BaU emissions (world)	550 ppm CO_2-e (450 ppm CO_2-e, Env. Outlook to 2030)		19.1% (39%)	62.5% (64%)
Carbon price, 2001 US$ per ton CO_2-e	550 ppm CO_2-e		$75 (2030)	$400

The emission reduction levels from the ‘Environmental Outlook to 2030” are in parentheses in Table 4.3.2. Note that because of the above-mentioned factors (later start, higher BaU emissions etc.), the need for reductions in year 2050 in the 550 ppm scenario is comparable to the need for reductions in the 450 ppm scenario. The emission tax rate in the Burniaux et al. 550 ppm scenario starts low in 2013, reaches US$75 in 2030 and becomes US$400 in 2050. The inclusion of CCS in the model would probably significantly lower this later figure. Moreover, the growth in the tax rate is again very high; from 2030 to 2050 it is about 9% per year. We believe a part of the reason to be an exogenously fixed initial tax rate, and constraint that jumps cannot occur.

There are a number of other interesting results in Burniaux et al. (2008):

- Exempting energy-intensive industries from policy action increases the cost of achieving the 550 ppm all gases concentration target by 50%. Likewise, not including all GHG gases, but only focusing on CO_2, increases the cost of reaching the target by almost 100%. Finally, the cost of incomplete country coverage appears to be high. For example, GHG concentration targets below 750 ppm are out of reach if Annex 1 countries act alone.
- Climate policy is implemented through a tax on emissions. The revenues from the tax amount to 6% of world GDP in 2050. Probably, the cost of achieving the 550 ppm target could be lower if these revenues were used to lower distorting taxes, such as the pay-roll tax. In the current model runs they are recycled back to the consumer as a lump-sum payment. On the other hand, under a cap and trade scheme with grandfathered permits, costs could exceed the above estimates.
- If the European Union acts alone, carbon leakage could be significant. As an illustration, the report considers a 50% reduction in 2050 relative to 2005 levels by the EU. This increases emissions outside the EU such that 20% of the achieved emission reductions are off-set. However, if the EU acts together with the other Annex I countries, the carbon leakage effect is drastically reduced.

4.4 Studies by the IEA

Since 1993 the IEA has presented medium- to long-term energy projections based on the World Energy Model (WEM). This is designed to replicate how energy markets function and is used to generate sector-by-sector and region-by region projections for both the reference scenario and alternative policy scenarios.

The mathematical model is made up of six main modules:

- final energy demand;
- power generation;
- refinery and other transformations;
- fossil-fuel supply;
- CO_2 emissions;
- investment.

The main exogenous assumptions are:

- economic growth;
- demographics;
- international fossil-fuel prices;
- technology.

Electricity consumption and electricity prices link the final energy demand and power generation modules. The refinery model projects throughput and capacity requirements based on global oil demand. Primary demand for fossil fuels serves as input for the supply modules. Complete energy balances are compiled at a regional level and the CO_2 emissions of each region are then calculated using derived carbon factors.

WEM requires access to large quantities of historical data on economic and energy variables, of which most are obtained from the IEA”s own databases of energy and economic statistics.

A number of new features were added to the previous version of WEM for use in ‘World Energy Outlook 2008”:

- The integration of the WEM into a general equilibrium model was further developed, in order to model more precisely the feedback links between energy markets and the macro economy.
- The oil and gas production and trade models were expanded to take better account of economic variables and to reflect the recent surge in cost inflation and the fall in the value of the dollar against most other currencies.

- Oilfield decline rates were analysed in detail on a field-by-field basis in order to assess the prospects for future decline rates.
- Energy-related CO_2 emissions were combined with greenhouse gas (GHG) emissions from all sources to explain the relationship between the level of annual emissions and the long-term concentration of GHG in the atmosphere, which will determine the increase in the future global average temperature.
- A study was undertaken of how overall emissions limitation levels would translate back into an atmospheric concentration of CO_2-e gases and what means might be used to achieve stabilization of that concentration. Energy and emissions are modelled in two scenarios: the 550 policy scenario, in which GHG concentration is stabilized at 550 parts per million of CO_2-e, and a 450 policy scenario, in which concentration is limited to 450 ppm CO_2-e.
- Power-generation capital and operating costs were assessed in detail and the cost assumptions in the WEM were revised to take account of recent cost inflation.

The quantitative implications of these changes, and their influence on direct comparisons between World Energy Outlook 2007 and World Energy Outlook 2008 are not described explicitly. It is important to keep in mind that this affects not only comparisons between the two last World Energy Outlook"s, but also comparisons between World Energy Outlook 2008 and its companion “Energy Technology Perspectives 2008” – which builds on World Energy Outlook 2007. The current WEM is the 12th version of the model. It covers 21 regions (modelled separately) and is designed to analyse:

- Global energy prospects: trends in demand, supply availability and constraints, international trade and energy balances by sector and by fuel to 2030.
- Environmental impact of energy use: CO_2 emissions are derived from the detailed projections of energy consumption.
- Effects of policy actions and technological changes: alternative policy scenarios analyse the impact of policy actions and technological developments on energy demand, supply, trade, investments and emissions (a policies and measures database, with over 3,600 policies in OECD and non-OECD countries, was compiled to support the analysis).
- Investment in the energy sector: the model evaluates investment requirements in the fuel supply chain needed to satisfy projected

energy demand to 2030 and also demand-side investment requirements in the alternative policy scenarios.

Technical aspects and key assumptions in ‘World Energy Outlook 2008”

Demand-side modules

The parameters of the equations of the demand-side modules are estimated econometrically, usually using data for the period 1971–2006.

The reference and alternative policy scenarios

The reference scenario takes account of government policies and measures that have been enacted or adopted by mid-2008. The same macroeconomic and population assumptions are used in the reference and alternative policy scenarios. The projections are based on the average retail prices of each fuel used in final uses, power generation and other transformation sectors. These end-use prices are derived from assumptions about the international prices of fossil fuels. The price assumptions in ‘World Energy Outlook 2008” are significantly higher than assumed in the last edition of the ‘Outlook”.

Population assumptions

Rates of population growth for each region are based on the most recent projections contained in the United Nations” Population Division report, ‘World Population Prospects: The 2006 Revision”. In ‘World Energy Outlook 2008” world population is projected to grow by 1% per year on average, from 6.5 billion in 2006 to over 8.2 billion in 2030. Population growth slows over the projection period, in line with trends of the last three decades: from 1.1% per year in 2006–15 to 0.9% in 2015–30.

Macroeconomic assumptions

Economic growth assumptions for the short to medium term are based largely on those prepared by the OECD, the IMF and the World Bank. Over the long term, growth in each region is assumed to converge to an annual long-term rate. This is dependent on demographic and productivity trends, macroeconomic conditions and the pace of technological change. In ‘World Energy Outlook 2008”, world GDP is expected to grow on average by 3.3% per year over the projection period. Growth is assumed to drop from 4.2% in 2006–15 to 2.8% in 2015–30. India and China are expected to continue to grow faster than all other regions, followed by the Middle East and Africa. The economies of many regions are expected to shift away from energy-intensive heavy manufacturing towards lighter industries and services, though the pace of this process, which is well advanced in the OECD and some emerging economies, varies. Industrial production continues to grow in volume terms.

Technological development

Energy intensity is assumed to decline by 1.7% per year, mainly because of a shift towards service economies in many countries. Technological development in the WEM is mainly based on exogenous assumptions.

Emmisions in the two policy scenarios

World Energy Outlook 2008 considers two climate-policy scenarios corresponding to long-term stabilization of greenhouse-gas concentration at 550 and 450 parts per million of CO_2 equivalent.

In the 550 ppm scenario fossil fuels lose market shares to renewables and nuclear power. Large oil savings occur in the transport sector in OECD countries and other major economies, as a result of sectoral agreements to reduce emissions from light-duty vehicles and aviation.

The 550 ppm scenario involves a plateauing of greenhouse-gas emissions by 2020 and reductions soon after. The emissions in the energy sector are reduced from approximately 41 Gt in the reference scenario, approximately 33 Gt in the 550-scenario. The distribution of the reductions are shown in figure 4.4.1, while further reductions in the 450-scenario are shown in figure 4.4.2.

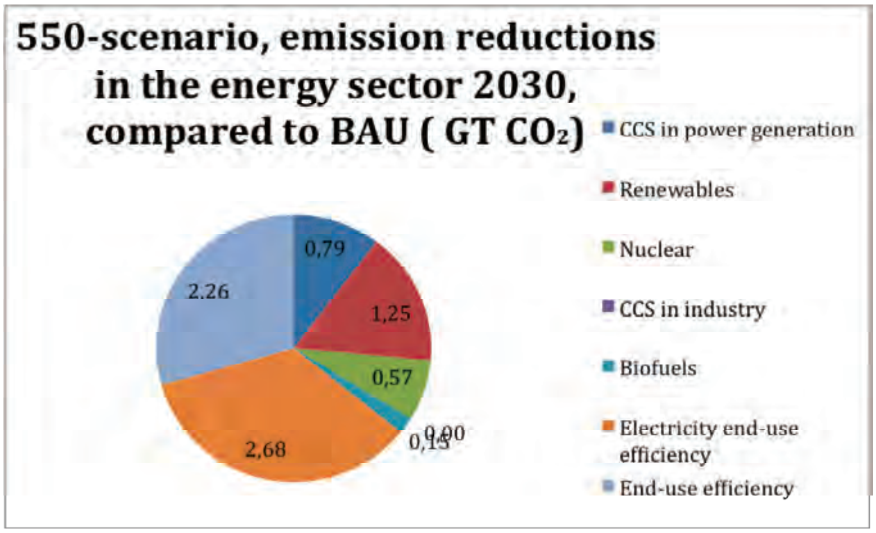

Figure 4.4.1 Distribution of emission reductions in the 550-scenario. Based on figure 18.4 in World Energy Outlook 2008.

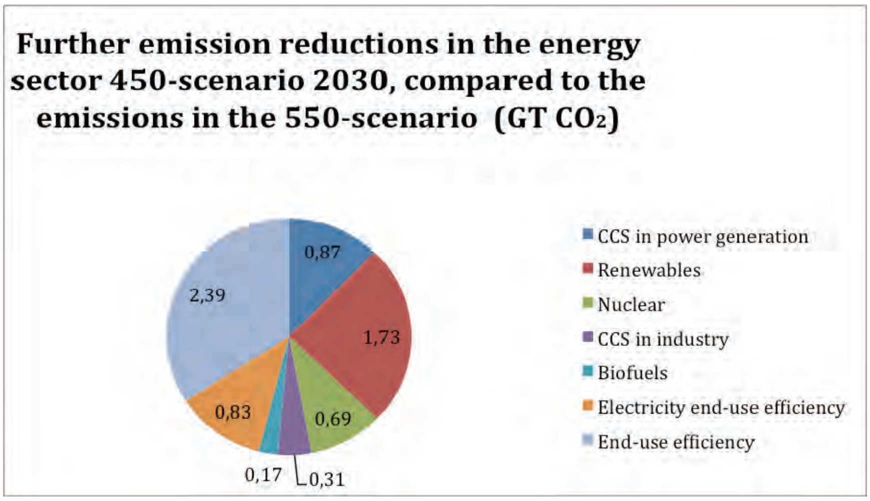

Figure 4.4.2 Distribution of emission reductions in the 450-scenario. Based on figure 18.4 in World Energy Outlook 2008.

The 450 ppm scenario involves stronger and broader policy action from 2020 onwards. Global energy-related CO_2 emissions follow broadly the same trajectory as in the 550 Policy Scenario until 2020, and then fall to 25.7 in 2030. Participation in an international cap-and-trade system is more comprehensive than in the 550 Policy Scenario, comprising all major emitting countries from 2020.

Overall costs have not been calculated, but direct investment costs in the energy sector have been calculated for both policy scenarios – and for the reference scenario.

The consequences of climate change are discussed in the report, but 'World Energy Outlook 2008" contains only indicative calculations of NPV of the additional investments in the energy sector – and no calculations of expected costs of climate change. There are no feedback mechanisms between climate change and population growth/GDP.

About the outcome of the energy demand scenario in 'World Energy Outlook 2008"

Energy demand is an important determinant for emissions – and for investments in the energy sector. The reference scenario suggests an increase in energy consumption of 45% by 2030, a growth extrapolated from present investment trends and governmental policies to the year 2030. This result follows quite directly from:

- energy prices;
- GDP growth;
- energy intensity.

Of these, energy prices are derived from a new iterative model of supply and demand that has been introduced in ‘World Energy Outlook 2008”, calculating the costs of energy based upon interactions between supply and demand.

The others are straightforward exogenous assumptions: GDP is taken from the OECD, the IMF and the World Bank, while energy intensity is assumed to decline by 1.7% per year, meaning primary energy demand per unit of real GDP is expected to decline by 1.7% a year (0.6% faster than the average in the past three decades). Some of the most relevant results with regard to emissions are summarized in table 4.4.1

Table 4.4.1 Selected results from World Energy Outlook 2008.

.		2005	2020	2030	2100
	BaU Gt/year (CO_2-e)	44	55	60	
	550 ppm	0	14,5	20	
Emission reduction as percentage of BaU emissions	450 ppm	0	41	34,5	
Carbon price, 2007 US$ per ton CO_2-e	BaU				
* Price in OECD+.	550 ppm*		40	90	
** Price in OECD+ and other major economies.	450 ppm**			180	
CO_2 (CO_2-e) in atmosphere, ppm	BaU	385 (455)			700 (1,000)
	550 ppm	385 (455)			(550)
	450 ppm	385 (455)			(450)
Mean global temperature increase, degrees Celsius	BaU				6
	550 ppm				3
	450 ppm				2

The 450 ppm CO_2-e scenario involves modest overshooting: i.e. concentrations exceed 450 for some time. Therefore GHG emissions in the second half of the century have to be lower than the natural uptake of GHG gasses.

The Outlook stresses the need for promoting abatement in *all* countries. In particular, large emission reductions must also take place in non-OECD countries, whose emissions in the BaU scenario in 2030 exceed the *global* emissions in the 450 ppm CO_2-e scenario.

‘Energy Technology Perspectives 2008”

‘Energy Technology Perspectives 2008” draws on modeling work within the IEA Secretariat and expertise from the IEA”s international energy technology collaboration network. ‘Energy Technology Perspectives 2008” is a companion to ‘World Energy Outlook 2007 (not the newer version from 2008, presented in 7.1 above), taking the same baseline scenario to 2030 and extending it to 2050. The present study carries forward the analysis contained in ‘Energy Technology Perspectives 2006” in the light of the IPCC 4th Assessment Report, released in November 2007. The IEA Energy Technology Perspectives model (ETP model) have been used to analyse the ACT and BLUE scenarios for the period 2005 to 2050.[28]

The ETP model belongs to the MARKAL family of bottom up modelling tools, and comprises representation of technology options of about 1000 individual technologies. Even though Energy Technology Perspectives 2008 draws on results from the World Energy Model, this is another version than the one used in World Energy Outlook 2008, and many of the assumptions also differ. Therefore, the results cannot easily be compared between the two reports.

Scenarios

Several different scenarios are presented: The set of ACT Scenarios shows how global CO_2 emissions could be brought back to current levels by 2050. The set of BLUE Scenarios targets a 50% reduction (compared to 2008) in CO_2 emissions by 2050. ‘Energy Technology Perspectives 2008” also presents global road maps of 17 prioritized technologies. In the main, what distinguishes this report from the IEA”s ‘World Energy Outlook 2008 is that ‘Energy Technology Perspectives 2008”:

- is less focused on fossil-fuel resources and markets;
- has a stronger focus on technology-specific issues;
- is based on an ‘older” set of assumptions regarding population and GDP-development;
- has a longer time-span (2050 as opposed to 2030).
- An earlier version of the IEA World Energy Model has been used.

The baseline in ‘Energy Technology Perspectives 2008” uses the same population projections as ‘World Energy Outlook 2008”, but the structural composition is slightly different (GDP projections are slightly lower for the OECD countries). The oil price is significantly higher in the ‘World Energy Outlook 2008” baseline, which is probably part of the reason why oil demand in 2030 is 10% lower than in the ‘Energy Technology Perspectives 2008” baseline. Different assumptions, combined with different modes of presentation in figures and tables, partly prevent useful comparisons between ‘World Energy Outlook 2008” and ‘Energy Technology Perspectives 2008”.

The ‘Energy Technology Perspectives 2008” BaU scenario builds on the ‘World Energy Outlook 2007”, which predicts lower world emissions than ‘World Energy Outlook 2008”. While emissions of CO_2-e reaches 62.5 Gt/year in 2050 in the ‘Energy Technology Perspectives 2008” BaU, they reach 59.6 Gt/year already in 2030 in ‘World Energy Outlook 2008”.

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[28] These scenarios are explained in the next section.

The ‘Energy Technology Perspectives 2008” analyses a series of GHG-reduction scenarios, which are divided into two main groups: the ACT Map scenarios and the BLUE Map scenarios. The main differences between the two concern the concentration target and the technology in the transport sector. The ACT Map does not set up a concentration target. Instead emissions are stabilized and brought back to the 2005 level in the year 2050. The BLUE Map scenario aims at a maximum temperature increase of 2–3 degrees Celsius.

Moreover, in the ACT Map scenario neither electric cars nor hydrogen/fuel-cell cars become available. Therefore emission reductions in the transport sector are modest, relying on a limited supply of biofuels. In the BLUE Map scenario either hydrogen/fuel-cell cars or electric cars enter the market. However, the price is fairly high, possibly reaching US$ 500 per ton CO_2 in the more pessimistic scenarios. In table 4.4.2 below, some of the results are shown.

Table 4.4.2 Selected results from IEA Energy Technology Perspectives 2008.

		2005	2030	2050	2100
Emission reduction as percentage of BaU emissions. * Includes only emissions in the energy-sector	BaU* Gt/year	27	44	62.5	
	ACT Map			56.5%	
	BLUE Map (450 ppm)			78.5%	
Carbon price, 2007 US$ per ton CO_2-e	BaU				
	ACT Map			$ 50	
	BLUE Map (450 ppm)			$ 200	
CO_2 (CO_2-e) in atmosphere, ppm	BaU	385 (455)			700 (1,000)
	ACT Map	386 (455)			–
	BLUE Map (450 ppm)	387 (455)			(450)
Mean global temperature increase, degrees Celsius	BaU				6
	ACT Map				–
	BLUE Map (450 ppm)				2

Note the rise in carbon tax from the ‘Energy Technology Perspectives 2008” scenarios to ‘World Energy Outlook 2008”. In the latter carbon tax has already reached $180 in 2030, while in the former it is $200 in 2050. This not only shows the effect of increased BaU emissions but may also indicate that the estimated costs of the different abatement technologies have increased greatly.

4.5 Australia”s Low Pollution Future

The Australian Treasury has conducted a large and complex economic modelling project that investigates the potential economic impact of reducing greenhouse gas (GHG) emissions over the medium and long term.

The assumptions and results of the analysis are published in a comprehensive report of almost 300 pages that contains detailed modelling of the costs and opportunities of acting decisively to meet the challenge of climate change.

The report examines four scenarios in which Australia and the world follow pathways to a low-polluting future. The analysis focuses on the economic impact of policies to reduce GHG emissions. The report positions Australia within the context of global action to reduce GHG emissions and stabilize concentrations at 450–550 ppm CO_2-e around 2100 The modelling framework is based on a suite of economic models: global, national, sectoral and household. The analysis centres on three top-down computable general equilibrium (CGE) models developed in Australia:

- the GTEM (Global Trade and Environment Model; also called GTEM-ABARE),
- G-Cubed and
- MMRF (Monash Multi-Regional Forecasting) models.

Because no single existing model adequately captures the global, national, sectoral and household dimensions or focuses on all relevant aspects of climate change policy in Australia the framework are based on a suite of different models that together span global, national, sectoral and household scales to simultaneously explore these four dimensions. A suite of models approach provides, according to report, a natural hedge against the inherent uncertainty in economic modelling. GTEM is a *backward-looking* model where consumers in the model only learn about the emission price at the start of each year. In contrast, some businesses and consumers in G-Cubed know the future of the emission price with perfect foresight. In G-Cubed, consumers and businesses first learn about the emission trading scheme in 2007. They can then respond immediately, even though the emission price is not introduced until 2010 or 2013. However, not all consumers are forward looking. G-Cubed assumes most consumers are myopic (70 per cent), looking only at their current income.

The models do not capture well the short-term economic adjustment costs; instead, they explore long-term multi-sector impacts. To different degrees, the CGE models approximate short-term adjustment paths. At one end of the spectrum, GTEM assumes that labour and capital are perfectly mobile across industries, at all times and at no cost. Thus, GTEM does not capture any short-term adjustment costs. At the other end of the spectrum, G-Cubed assumes immobility of capital, slow adjustments to wages and liquidity constraints, and includes partial forward-looking behaviour.

MMRF, a model of the Australian economy with rich industry-sector detail, draws on international assumptions from GTEM and is augmented with disaggregated bottom-up modelling for three emission-intensive sectors: electricity, transport and forestry. The results of these three models are drawn together into an integrated set of projections.

We will start by giving a description of the GTEM model and a brief introduction to the other CGE models used in the report. We will then restrict our discussion to the global approach of various analyses and projections from the Australian studies.

GTEM

GTEM is a dynamic general equilibrium model developed at the Australian Bureau of Agricultural and Resource Economics (ABARE). It developed out of the MEGABARE model (ABARE, 1996) and the static Global Trade Analysis Project (GTAP; Hertel, 1997).

GTEM presents a future path for economic growth, population levels, energy consumption and GHG emissions in a world without climate change. The model consists of three modules: economic, population and environment. There is a two-way feedback between the population and economic modules. Economic growth affects fertility and mortality patterns and thus brings changes in population structure and labour supply which affect economic growth. The economic and environment modules have only a one-way relationship. The model does not include risks arising from climate change itself. Even if there is no direct feedback from the environment module to the economic module, emission restriction policies will have an impact on the economic module and so, in this sense, there is a strong link between the economic and environment modules.

For the purposes of GTEM the global economy is represented by 13 regions, 19 industry sectors and a typical household. The model disaggregates three energy-intensive sectors into specific technologies: electricity generation, transport and iron and steel.

GTEM is a Solow-Swan growth model, with exogenus sector-specific technical change. The household demand for private goods responds to changes in income and relative prices and is modelled as a constant difference in elasticity of substitution demand function. The price and income elasticity depends on budget share and is therefore variable over time. The public consumption expenditure shows the optimal allocation of commodities by maximizing a Cobb-Douglas utility function.

On the production side, GTEM specifies four factors of production: land, labour, capital, natural resources and material inputs, of which land and labour are perfectly mobile across sectors. Labour supply is exogenously given and there is an unlimited supply of natural resources at a given real price.

Three key energy-intensive sectors that employ multiple technologies to produce output are identified. These sectors are defined as technology bundle sectors, and include electricity generation, transport, and iron and steel. The sectors use the output of the respective technology bundle, and other commodities, in fixed proportions to distribute to the users. As a default, input substitutions within a technology are not allowed — each technology uses its inputs in fixed proportions — while substitution between technologies is allowed. Outputs from each of the technologies are chosen to minimise the cost of producing a CRESH (constant ratio of elasticities of substitution, homothetic) aggregate of the outputs of all technologies.

Demand and supply of electricity is modelled using 12 established and emerging technologies. Non-technology bundle industries can, through substitution between four energy commodities, produce energy composites. The inter-fuel and inter-factor substitutions, as well as substitution between fuels and primary factors, occur using a nested CES approach (seeSection 3.5).

Given the right market incentives, the model allows for the transport and electricity sectors to be gradually emission-free. This is achieved through endogenous productivity growth via learning by doing, a detailed technology portfolio including a suite of zero or near-zero emission technologies and substitution across technologies. By gaining the right relative prices, households will switch to electricity generated by zero-emission technologies. The model does not allow for substitution between non-energy intermediate inputs in response to relative prices, but allows for energy-efficiency improvements if there is bias in the region-specific exogenous productivity growth. This holds for all inputs and sectors. Markets clear each year, but this is not necessarily an equilibrium condition, as capital and debt accumulation may continue year after year.

The parameters used in the social-accounting matrix are currently based on GTAP”s version 6 database, base year 2001. GTEM specifies the greenhouse gases used. The emission database was developed at ABARE and contains six anthropogenic greenhouse gasses: combustion and non-combustion carbon dioxide, methane, nitrous oxide, HFCs, PFCs and SF, all of them Kyoto gases.

GTEM includes purpose-built carbon capture and storage (CCS) operations and has a single technology for coal and gas. It takes CCS to be available as a generation option from 2020. Nuclear is modelled without specific constraints by assuming that resources and technology will be able to meet demand for nuclear electricity.

G-Cubed, MMRF and bottom-up sector specific models

G-Cubed, a forward-looking global model with macrodynamics, is designed for climate policy mitigation cost analysis (McKibbin and Wilcoxen, 1998). The version used for the report represents the global economy through nine regions and 12 industry sectors (including coal, oil, gas, agriculture and manufacturing). The model has limited technological detail. In order to play a part in linking the models, G-Cubed is broadly calibrated to GTEM BaU and provides comparative cost estimates for policy scenarios.

The MMRF model is a detailed model of the Australian economy (58 industrial sectors and all eight Australian states and territories) developed by the Centre of Policy Studies at Monash University (Adams et al., 2008). The CGE models are complemented by a series of bottom-up sector-specific models for electricity generation, transport, land use change and forestry. Some of the models do make some allowance for learning to reduce the cost of some technologies.

BaU

BaU (the reference scenario) presents a development pathway for Australian and world economics up to 2100. The report contains a wide-ranging discussion of assumptions and projections under BaU. Assumptions used in BaU are, when possible, consistent across the suite of CGE and sectoral models. BaU has no new policy to reduce emissions and no impact on climate change. The pattern and rate of GDP are functions of the assumptions regarding movements in population, change in participation rates and growth in productivity. Productivity growth drives the global economy, with per capita GDP projected to increase by a factor of almost 10 from 2005 to 2100, i.e., an avarage yearly growth rate of 2.4%. Note that this is a much bigger increase than was assumed in, e.g., the *Stern Review* or in the analysis with DICE discussed in section 3.1. Under BaU the global economy (GWP) rises from $54 trillion in 2005 to $268 trillion in 2050. Developed economies accelerate towards, but do not reach, the productivity levels of developed economies. World population is expected to peak at 9.5 billion in 2075, then fall to 9.3 billion in 2100. The annual increases in per capita GDP are higher than in, e.g., the *Stern Review* (before subtracting the costs of climate change).

Despite considerable falls in the emission-intensity of growth, annual GHG emissions increase between 2005 and 2050, from 39 Gt of CO_2-e to just over 102 Gt in 2050. By 2100 annual emissions are projected to be at 161 Gt. The annual rate of growth of emissions is expected to slow from around 2% now to less than 1% by 2100. The concentration of GHG in the atmosphere rises sharply to 1,560 ppm CO_2-e by 2100.

BaU predictions for global emissions are higher than those in other recent studies and similar to the highest-emission scenario in the IPCC"s 'Special Report on Emissions Scenario" (IPCC, 2000). This results from a combination of higher-trend economic growth assumptions, as mentioned above, and slightly higher emission intensity in the area of growth.

In particular, the emission intensity in the area of development in the Asian region has been far above that expected in the IPCC SRES scenarios, due to, among other things, the unexpected growth of brown coal use in China. Over the longer term it is assumed that developing countries will develop towards the productivity frontier of the US (countries do not get anywhere near the frontier in 100 years, but they do move towards it). Economic growth in the OECD BaU is also considerably lower than the BaU in the Australian analysis.

Global emissions price and pathway

A 'Hotelling rule" is used (see section 2.5) to construct a global emissions pathway for each scenario within the global models. The emission price grows from a specified starting level at the real interest rate, assumed to be 4% per year, which represents the rate of increase in comparable financial assets. The ability to bank permits in the early years of the scheme for use later leads to actual global emissions and emission allocations being different. Banking of permits ensures that the global price path satisfies the inter-temporal arbitrage condition.

Initially, actual global emissions are lower than the allocations in all four policy scenarios, resulting in 5%–20% of permits being banked in the first ten years. Banking occurs initially to maintain the Hotelling price path and is accentuated by the step-down in global emissions after emissions pricing is introduced.

To achieve the desired greenhouse gas concentration stabilisation level, the policy scenarios use different starting emission prices, which then grow at around 4 per cent per year The lower the stabilisation level, the higher the starting emission price. The required starting price to achieve a 550 ppm stabilisation level is around US$23 in 2010 and US$27 if the starting year is 2013, in nominal terms. A slightly higher starting price of US$32 in 2010 achieves 510 ppm stabilisation and US$47 in 2013 achieves 450 ppm stabilisation, in nominal terms.

GTEM and the G-Cubed model have different structures and data sets and use a different emissions price path to meet environmental and permit banking constraints. The global emissions price path is considerably lower under the G-Cubed projections than under GTEM. The price of emission (or expectations of the global price path) is an important variable in calculating abatement costs and identifying wherever there would be no need for any policy instruments in addition to a price of emissions. Lower emission prices give higher per dollar mitigation costs.

The discount rate

The analysis focuses on the costs of mitigation, not the benefits, so the debate about discount rate is not important for the results. In the report it is pointed out that if the results were used to judge the importance of future costs from today"s perspective, this would require a consideration of discount rates.

Policy scenarios

The report treats four different scenarios: CPRS-5 and CPRS-15, which differ only with regard to the concentration target, and Garnaut-10 and Garnaut-25, which also differ only with regard to the concentration target. However, while the Garnaut scenarios assumes global action (among other things, global cap and trade) from 2013, the CPRS scenarios assume phased-in action from developing countries with complete coverage from 2025.

Garnaut-10 and Garnaut-25 are consistent with stabilizations of atmospheric concentrations at 550 and 450 ppm CO_2-e by around 2100 respectively. Further, CPRS-5 and CPRS-15 are consistent with stabilizations of atmospheric concentrations at 550 and 510 ppm CO_2-e by around 2100 respectively.

To achieve the desired GHG concentration stabilization level, the policy scenarios use different starting emission prices, which then grow at around 4% per year. The required starting price to achieve a 550 ppm stabilization level is around US$23 in 2010 and US$27 if the starting year is 2013, in nominal terms. A slightly higher starting price of US$32 in 2010 achieves 510 ppm stabilization and US$47 in 2013 achieves 450 ppm stabilization, in nominal terms.

As mentioned, Garnaut-10 and Garnaut-25 assume an 'optimal" international emissions trading scheme, covering all emission sources and all economies, from 2013. These scenarios assume united global action, with all countries taking on emission-reduction obligations from 2013. This represents an optimal post-2012 agreement. National contributions are based on a contraction and convergence approach, whereby the allocation of emission rights among countries converges from current levels to equal per capita rights by 2050.

The other two scenarios, CPRS-10 and CPRS-25, assume that international emissions trading gradually expands, with developed economies participating from 2010, developing economies joining over time and global participation by 2025. Moreover, sectors exposed to trade are exempted until 2020.

The costs of climate change are not included. The global features of scenarios are given in Table 4.5.1.

Table 4.5.1 Globale features of scenarios

	Reference	CPRS-5	CPRS-15	Garnaut-10	Garnaut-25
GHG stabilization goal, ppm CO$_2$-e	1,560	550	510	550	450
Temperature change at stabilization	8ºC or more	3ºC	2.6ºC	3ºC	2ºC
Global emission in 2050 (Gt of CO$_2$-e)	102	35	27	36	22
Global mitigation action	none	Multi-stage from 2010		Unified from 2013	

Source: Australian Government, 'Treasury from MAGICC and GTEM"

The global economy growth in the mitigation scenarios slows slightly relative to BaU. The two global models indicate similar costs of mitigation policy, but the time profiles differ. G-Cubed is a forward-looking model and includes capital adjustment cost. When consumers and businesses plan for higher emission prices, their reactions raise the initial adjustment cost earlier. The GWP changes from BaU are given in Table 4.5.2.

Table 4.5.2 GWP changes from BaU (Source: Australian Government, 'Australia"s Low Pollution Future", Table 5.6)

	2020		2030		2040		2050	
	GTEM	G-Cubed	GTEM	G-Cubed	GTEM	G-Cubed	GTEM	G-Cubed
CPRS-5 (550 ppm)	-0.7	-2.3	-1.4	-3.1	-2.0	-3.2	-2.8	-3.3
CPRS-5 (510 ppm)	-0.9	-2.8	-1.8	-3.6	-2.6	-3.7	-3.5	-3.8
Garnaut-10 (550 ppm)	-0.7	-2.2	-1.3	-2.5	-1.9	-3.0	-2.7	-3.2
Garnaut-25 (450 ppm)	-1.3	-3.3	-2.1	-3.6	-3.2	-4.0	-4.3	-4.2

Mitigation costs vary depending of the global stabilization target. The global environmental objective is the key determinant of emission prices and aggregate global costs. Lower stabilizations generally increase mitigation costs. Restrictions on international permit trade raise the overall economic cost of the CPRS scenarios for some economies. If the limits on international permit trade are lifted, the fall in GWP in 2019 is reduced from 2.9% to 2.5%.

Delaying mitigation action in the global economy is examined. Ignoring climate change risks, locking in more emission-intensive industry and infrastructure, and deferring cost reductions in low-emission technologies will increase the cost of achieving environmental goals. The costs of delaying global mitigation action by seven years but still stabilizing at 550 ppm CO$_2$-e by 2100 is calculated to be about 10% higher in 2050 and to remain high up to 2100. These higher costs come from the need for greater emissions reductions in less time to achieve the same environmental outcome and the high cost of low-emission technology options that have not benefited from reductions in capital costs. The initial benefits of delay come about when emissions are not priced.

Note that in the Australian studies the cost of reaching a 450 ppm CO_2-e target is just about 1% of world GDP in 2050 higher than reaching a 550 ppm target. This is very different from the *Stern Review*, in which costs increase dramatically for a 450 ppm concentration target as compared with a 550 ppm target. Others reports (see, e.g., OECD, 2008) consider the 450 ppm concentration target unreachable.

Careful reading of the Australian report suggests several reasons why the 450 ppm costs are closer to the 550 ppm costs compared to *Stern*:

- CCS technology is included, becoming very important and widespread, and there are developments in other technologies as well. In other words, the possibilities for technological development seem more optimistic in the Australian scenarios.
- The 450 ppm stabilization scenario involves overshooting, so a majority of the costs of reaching the 450 ppm level are pushed into the future, where they are then more heavily discounted.

4.6 Summary / discussion of studies with a main focus on simulations

This chapter has looked at several different studies to do with the economics of climate change. One common denominator has been that they are all based on large and complex computable models of the world economy. Furthermore, none of the studies has conducted a full benefit-cost analysis. The IPCC fourth assessment report is careful not to present figures for the cost of climate change and focuses mainly on describing the physical effects of climate change. The Stern Review bolder in this respect and presents different cost estimates that range from a 2.7% to a 32.7% reduction in consumption now and forever. However, Stern does not calculate the optimal mitigation effort to avoid costs from climate change in which way that, for instance, Nordhaus does in his DICE studies. More recently, the OECD studies, the IEA studies and the Australian studies have all restricted themselves to looking at the cost of reaching different targets for the atmospheric concentration of GHG gases.

All the studies include an analysis of mitigation costs. The IPCC fourth assessment report and the Stern Review assess other studies and present summary figures for them. Neither of them analyses the individual studies in detail, but instead focuses on the mitigation cost estimates and the corresponding carbon price implied by different targets. The

OECD studies, the IEA studies and the Australian studies are all based on runs on specific models and therefore include a much more detailed description of the methodology behind the study. The different approaches taken on the one hand by the IPCC and Stern and on the other by the OECD, the IEA and Australia should be borne in mind when comparing the different results from the studies.

Finally, the IEA studies differ from the OECD and the Australian studies in one important respect. While the OECD and the Australian studies are based on a top-down general equilibrium model of the world economy, the IEA study is based mainly on a bottom-up model of the world energy system. These two methodological approaches differ in a number of ways. In a general equilibrium framework all prices are endogenous and determined by supply and demand, while in a bottom-up model some prices must be determined exogenously: for example, prices for important inputs such as oil prices and wages for skilled and unskilled labour. To the extent that climate policy changes these prices, bottom-up models may yield biased results.

On the other hand, since a general equilibrium model aims to cover all parts of the economy, the degree of detail is much lower. This implies that new technologies such as, for instance, CCS are not modelled explicitly, as they are in the bottom-up models. Instead general equilibrium models rely largely on elasticities of substitution between inputs and/or products with different emission intensity. To the extent that the resulting input and/or product mix induced by the required emission reductions are outside the empirical sample used to estimate the elasticities of substitution, general equilibrium models may also yield biased results. The two modelling approaches must therefore be considered as complementary. The Australian studies have sought to combine the methods.

The choice of a bottom-up model is also the reason why the IEA does not present a mitigation cost figure in the same way as the other reports. The IEA model can measure the social cost of putting emission constraints on the energy system, but not the effect on world GDP. In any case, the IEA has chosen to focus solely on the CO_2 emission price.

In the table below we have summarized the main findings from the studies. First, we note that there are some discrepancies between the BaU emission GHG concentrations, in particular between the Australian study and the other studies. The reasons for the higher Australian figure are both higher trend economic growth assumptions and slightly higher emission intensity of growth. In particular, the emission intensity of development in the Asian region has been far above that expected in the IPCC SRES emission scenarios.

Costs of mitigation are measured as reductions in world GDP by 2050 compared to world GDP in the BaU scenario. Note that the OECD and Australia expect much higher costs of stabilizing GHG concentrations at about 500 ppm in the atmosphere than Stern expects. For Australia the reason seems to be the higher BaU emissions, while for the OECD it seems to be that global policy action is halted until later in the century. The assumptions about the success of new technologies like CCS also differ between the studies.

Halted action plays a role when determining the global CO_2 emission tax path as well. If one constrains the path by saying that the tax cannot exceed a certain level before some years into the future, one will most likely end up with a much steeper path that also has a higher end value.

Table 4.6: Comparison of the studies covered by Chapter 4

Study	GHG target concentration (CO_2-e)	GHG BaU concentration 2100 (CO_2-e)	Initial carbon price	Carbon price 2050	Costs as % of GDP (2050)
Stern Report	550 ppm	> 843 ppm			1% (-0.6-3.5%)
IPCC, 2007	445-535 ppm	855–1130 ppm			< 5.5%
IPCC, 2007	535-590 ppm	855–1130 ppm	US $ 20-80 (in 2030)	US $ 30-150	0.1-4%
OECD, Env. Outlook 2008	450 ppm	>900 ppm	US $ 5 (in 2010)	US $ 177	2.5%
OECD, 2008b	550 ppm	>900 ppm	US $ 5 (in 2013)	US $ 400	4.8%
IEA, World Energy Outlook	550 ppm	1000 ppm	US $ 40 (in 2020)	US $ 90 (in 2030)	
IEA, Energy Technology Perspectives 2008	450 ppm	1000 ppm		US $ 200	
Australia's LPF, Garneau	550 ppm	1560 ppm	US $ 20 (in 2010)	US $ 91	2.7-3.2%
Australia's LPF, Garneau	450 ppm	1560 ppm	US $ 34 (in 2010)	US $ 158	4.2-4.3%

Note that all the figures in the table assume a global CO_2 emission price after some year between 2020 and 2030, and that both the OECD 450 ppm scenario and the Australian 450 ppm scenario assume overshooting. Overshooting occurs when atmospheric concentrations initially exceed and then return to the target level. Overshooting is inherently more risky than approaching stabilization levels from below (Pearman, 2008). If reductions in atmospheric concentrations are not possible, which is debatable, the 550 ppm scenario could turn out to be the only realistic scenario.

This report is being written in 2009. Many people would agree that we are still a long way away from a global price for CO_2 and other GHG emissions, facilitated by an international climate treaty in which all major emitting countries have accepted emission ceilings. Moreover, the current price in the countries that have taken on emission targets – that is, most of the Annex 1 countries, but not the USA – is below the price suggested in some of the other studies discussed in this and the previous chapter. This means that the OECD and the Australian studies could be closer to the actual, unknown future mitigation costs. However, although between 3% and 5% GDP loss is a high figure, it is still small compared to the large increases in world GDP that would result from expected economic growth in this century. For instance, the OECD in their latest study expects world economic growth to be slightly above 3% per year in the period. Taking on the maximum 550 ppm GHG concentration target implies a drop in growth rate of just above -0.1% per year.

Finally, both the OECD studies and the Australian studies stress the need for a global price on CO_2 and other GHG emissions, and an international climate treaty in which all major emitting countries have committed to emission cutbacks. With an incomplete treaty or an incomplete coverage of GHG gases, reaching ambitious targets becomes a lot more costly. Furthermore, if only the Annex 1 countries take action (alone), the 550 ppm target becomes out of reach.

References

Anderson D. (2006), Costs and Finance of Abating Carbon Emissions in the Energy Sector. Imperial College London, October 20, 2006

Amundsen, E. S. and Mortensen, J.B., 2001. "The Danish Green Certificate System: some simple analytical results," Energy Economics 23, 489-509.

Australian Government, 'Australia"s Low Pollution Future: The Economics of Climate Change Mitigation", www. climatechange.gov.au, © Commonwealth of Australia 2008, ISBN 978-0-642-74484-5

Bosetti, V., Massetti, E. and Tavoni, M. (2007a), The WITCH model. Structure, baseline, solutions. FEEM Working Paper 10.2007.

Bosetti, V., Carraro, C., Massetti, E. and Tavoni, M. (2007b), Optimal energy investment and R&D strategies to stabilise greenhouse gas atmospheric concentrations. FEEM Working Paper 95.2007.

Bosetti, V., Carraro, C., Duval, R. and Sgobbi, A. (2009),

The role of R&D and technology diffusion in climate change mitigation: New perspectives using the Witch model. FEEM Working Paper 14.2009.

Burniaux J-M., J. Chateau, R. Duval and S. Jamet (2008), The Economics of Climate Change Mitigation: Policies and Options for the Future, OECD Working Paper No. 658.

Cline W. (1992) The Economics of Global Warming. Institute for International Economics, ISBN 088132132X.

Dasgupta P. (2001) Human Well-being and the Natural Environment, Part III. Oxford University Press.

Dasgupta P. and Heal G. (1979) Economic Theory and Exhaustible Resources, Cambridge Economic Handbooks.

Fischer and Newell (2008), Environmental and technology policies for climate mitigation. Journal of Evnvironmental Economics and Management 55, 142-162.

Garnaut, R. (2008a), Garnaut Climate Change Review Final Report, Cambridge University Press, Port Melbourne.

Garnaut, R. (2008b), Garnaut Climate Change Review Economic Modelling Technical Paper 2: Climate Data Methodology and Assumptions. www.garnautreview.org.au/CA25734E0016A131/ pages/all-reports--resources, accessed 22 October 2008.

Gerlagh, R., Kvedrndokk, S. and Rosendahl, K.E. (2008), "Linking environmental and Innovation policy", FEEM working paper 53.2008.

Gollier, C., P. Koundouri and T. Pantelidis (2008), Declining discount rates: Economic justifications and implications for long-run policy", IDEI Working Paper 525.

Goulder, L.H. and Mathai, K. (2000), "Optimal CO2 abatement in the presence of induced technological change", Journal of Environmental Economics and Management 39, 1-38.

Grimaud, A, Lafforgue, G. and Magne, B. (2008), Climate change mitigation options and direct technical change: A decentralized equilibrium analysis. IDEI Working Paper 510.

Hart, R. (2008), "The timing of taxes on CO2 emissions when tchnological change is endogenous", Journal of Environmental Economics and Management, 55, 194-212.

Hasselmann K. (1999) Intertemporal accounting of climate change—

Harmonising economic efficiency and climate stewardship. Climatic Change 41: 333–350.

Heal G. M. (1997)Discounting and climate change—An editorial comment. Climatic Change 37: 335–343.

HM Treasury (2003), Green Book: Appraisal and evaluation in central government (http://www.hm-reasury.gov.uk/ economic_data_and_tools /greenbook/ data_greenbook_index.cfm)

Horowitz J. K. (1996) Environmental policy under a nonmarket discount rate. Ecological Economics 16: 73–78.

Hoel (2008), ”Bush Meets Hotelling: Effects of Improved Renewable Energy Technology on Greenhouse Gas Emissions”. Memorandum No 29/2008, University of Oslo.

Hoel, M. and Kverndokk, S. (1996), Depletion of Fossil Fuels and the Impacts of Global Warming, Resource and Energy Economics 18, 115-136.

Hoel, M. and Sterner T. (2007), Discounting and Relative Prices, Climatic Change 84, 265-280.

Hotelling, H., 1931. ‘The Economics of Exhaustible Resources”, Journal of Political Economy 39, 137-175.

International Energy Agency: "Energy Technology Perspectives 2008", ISBN: 978-92-64-04142-4

International Energy Agency: ”World Energy Outlook 2008”, ISBN: 978-92-64-04560-6

IPCC (Intergovernmental Panel on Climate Change) (2007a). Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC. [Summary for Policymakers. See also Solomon (2007)].Cambridge: Cambridge University Press. Online at the IPCC site.

IPCC (Intergovernmental Panel on Climate Change) (2007b). Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. B. Metz, et al. (Eds.). Cambridge and New York: Cambridge University Press. Online at the IPCC site

Jaffe, B., G. Newell, R. Stavins (2002), “Environmental policy and technological change,” Environmental and Resource Economics 22 (special issue), 41-69.

Lind R., ed. (1982) Discounting for Time and Risk in Energy Policy., RFF Press, Resources for the Future, Washington, DC.

Long and Sinn (1985), Surprise price shifts, tax changes and teh supply behaviour of resource extracting firms. Australian Economic papars 24, 278-289

Löschel, A. (2002), “Technological change in economic models of environmental policy: A survey,” Ecological Economics 43, 105-126.

Mendelsohn, R. (2008), Is the Stern Review an economic analyses? Review of Environmental Economics and Policy 2, 45-60.

Nordhaus W. D. (1997) Discounting in economics and climate change - An editorial comment. Climatic Change 37: 315–328.

Nævdal and Vislie (2008) Climate change, Catastrophic Risk and the Relative Unimportance of Discounting. Memorandum No 28/2008, University of Oslo.

OECD (2008);Environmental Outlook to 2030,

Parry, I.W.H. (1995), “Optimal pollution taxes and endogenous technological progress”, Resource and Energy Economics 17, 69-85.

Pearman, G., 2008. Climate Change, Risk in Australia under Alternative Emissions Futures, Department of the Treasury, Canberra.

Popp, D. (2004), “ENTICE: Endogenous Technological Change in the DICE Model of Global Warming”, Journal of Environmental Economics and Management 48, 742-768.

Popp, D. (2006), ENTICE-BR: The effects of backstop technology R&B on climate policy models. Energy Economics 28, 188-222.

Portney P. R., and Weyant J. P. eds. (1999) Discounting and Intergenerational Equity. Washington, DC: Resources for the Future.

Requate, T. (2005), Dynamic Incentives by Environmental Policy Instruments - A Survey. Ecological Economics 54, 175-95.

Rosendahl, K.E. (2004), Cost-effective environemntal policy: Implications of induced technological change. Journal of Environmental Economics and <Management 48, 1099-1121.

Schelling, T.C. (1995), “Intergenerational discounting”, Energy Policy 23, 395–401.

Shogren J. F. (2000) Speaking for citizens from the far distant future. Climatic Change 45: 489–491.

Sinn, H.W. (2008), “Public Policies against Global Warming: a supply side approach",International Tax and Public Finance 15, 360-394.

Sterner, T. and Persson, M. (2008), An even Sterner Review: Introducing relative prices into the discounting debate. Review of Environmental Economics and Policy 2, 61-76.

Strand, J. (2007), Technology Treaties and Fossil Fuels Extraction, The Energy Journal 28, 129-142.

Tahvonen, O. (1997): Fossil Fuels, Stock Externalitites, and Backstop Technology, Canadian Journal of Economics 30, 855-874.

Ulph, A. and Ulph, D. (1994): The optimal time path of a carbon tax, Oxford Economic Papers 46, 857-868.

Weitzman M. L. (1994) On the ‘environmental” discount rate. Journal of Environmental Economics and Management 26: 200–209.

Weitzman M. L. (1998) Why the far-distant future should be discounted at its lowest possible rate. Journal of Environmental Economics and Management 36: 201–208.

Weizman M.L.(2001) Gamma discounting. American Economic Review 91,, 260-271.

Weitzman, M.L. (2009), On modeling and interpreting the economics of catastrophic climate change. The Review of Economics and Statistics 91, 1-19.

van der Werf, E. (2007), Production Functions for Climate Policy Modeling: An Empirical Analysis. FEEM working paper 47.2007

Weyant, J.P. (2008), A critique of the Stern Review”s mitigation cost analysis and integrated assessment. Review of Environmental Economics and Policy 2, 77-93.

Withagen, C. (1994): Pollution and exhaustibility of fossil fuels, Resource and Energy Economics 16: 235 - 242.

Zerbe R.O. Jr. (2004) Should moral sentiments be incorporated into benefit-cost analysis? An example of long-term discounting. Policy Sciences 37, 305-318.

Norsk sammendrag: Klimapolitikk: Kostnader og utforming

Det finnes en stor og voksende litteratur om økonomiske problemstillinger knyttet til klimaendringer, klimatiltak og klimapolitikk. I denne rapporten presenteres og vurderes noen av de nyere studiene på området. Oppmerksomheten er hovedsakelig rettet mot numeriske analyser, ikke mot de rent teoretiske studiene.[29]

Blant de viktige temaene som behandles, er følgende:

a) Hvordan forventes utslippene av klimagasser å utvikle seg, og hvilke klimaendringer vil dette resultere i dersom ikke ny politikk settes ut i livet?
b) Hva kan økonomiske analyser fortelle om klimapolitiske mål?
c) Hva koster det å redusere utslippene?
d) Hvilke tiltak og politiske virkemidler bør benyttes?
e) Hva blir merkostnaden for å nå klimapolitiske mål dersom en benytter sub-optimale virkemidler?

I hver enkelt av studiene i rapporten, blir ett eller flere av disse temaene behandlet.

a) Utslipp for "Business as usual" (BaU)

Fremskrivninger av klimagass-utslippene og klimaendringene dersom ingen nye tiltak setes ut i livet kalles ofte 'business as usual" (BaU) fremskrivninger. De vil være sterkt påvirket av forutsetninger om befolkningsvekst og økonomisk utvikling (BNP per capita). Ettersom disse forutsetningene er svært usikre for de lange tidsperspektivene som er aktuelle for studier av klimaendringer (100 år +), benyttes ofte flere alternative sett av forutsetninger.

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[29] Vi ser altså på analyser som beregner tallanslag for viktige økonomiske størrelser.

Utslipp av klimagasser kan fordeles på tre hovedkategorier; energirelaterte CO_2-utslipp (fra forbrenning av olje, kull og gass til energiformål), andre CO_2-utslipp (f eks fra avskoging) og øvrige klimagasser. Ved tallfesting av samlede utslipp oppgis ofte mengdene som CO_2-ekvivalenter (CO_2-e). Den viktigste hovedkategorien (ca 60 %) er energirelaterte CO_2-utslipp, som inkluderer all forbrenning av fossile energibærere samt prosessutslipp fra industrien. Disse utslippene blir ofte modellert som endogene størrelser, mens de andre to utslippskategoriene (andre CO_2-utslipp og øvrige klimagasser) vanligvis blir angitt som eksogene størrelser.[30]

Ulike fremskrivninger av CO_2-utslipp gir tilsvarende forskjeller for fremtidige konsentrasjonsnivåer av klimagasser i atmosfæren - og for tilhørende temperaturendringer. I de siste IPCC-rapportene er utslippstrendene basert på et sett av scenarier som er presentert i IPCC"s rapport 'Special Report on Emission Scenarios". Disse scenariene bør forstås som BaU scenarier, og gir resultater som peker mot en konsentrasjon av drivhusgasser i atmosfæren mellom 855 ppm og 1.130 ppm CO_2-e i år 2100. De fleste av studiene som er behandlet her gir konsentrasjonsnivåer innenfor det samme området.

Forventede klimaendringer i BaU avhenger selvsagt av de fremskrivningene en benytter for konsentrasjonene av klimagasser i atmosfæren. Forholdet mellom konsentrasjon og klimaendring beskrives gjerne som "klimasensitivitet", og angir hvor mye den globale gjennomsnittstemperaturen vil øke på lang sikt (i forhold til før-industrielt nivå) ved en dobling av atmosfærisk konsentrasjon av CO_2-e. I henhold til IPCC (2007) vil denne koeffisienten ligge innenfor området 2^oC til 4.5^oC, med 3^oC som den mest sannsynlige verdien, og med svært liten sannsynlighet for verdier under 1.5^oC. Verdier høyere enn 4.5^oC kan ikke utelukkes, men i dette området er det mindre samsvar mellom observasjoner og modellresultater.

b) Optimale utslippsforløp

Dersom vi unnlater å forebygge klimaendringer kan de fremtidige kostnadene bli store, særlig i neste århundre. Utslippsreduksjoner nå gir umiddelbare kostnader, og en fornuftig klimapolitikk bør ha en god balanse mellom tiltakskostnader og kostnadene forbundet med de fremtidige klimaendringene. Ideelt sett er det ønskelig å minimere nåverdien av fremtidige kostnader[31] – summen av tiltakskostnader og kostnader vi påføres av klimaendringene. I tillegg til å gi et optimalt utslippsforløp vil en slik tilnærming gi marginale tiltakskostnader over tid, dvs. karbonprisen. Dette prisnivået vil til enhver tid gi en øvre grense for tiltakskostna-

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[30] Eksogene størrelser er gitt utenfra modellen (fra andre kilder) mens endogense størrelser er beregnet i modellen.

[31] Nåverdien av fremtidige kostnader er en veiet sum av alle fremtidige kostnader, hvor kostnadene får lavere vekt jo lengre frem i tid de kommer. Fremdtidige kostnader blir lavere jo høyere diskonteringsrenten er.

der; ethvert tiltak som koster mindre, bør gjennomføres. Karbonprisen vil typisk vokse over tid, med en vekstrate som er mindre enn diskonteringsrenten.[32]

Utslippsforløpene og karbonprisene slike analyser gir vil være avhengige av tre faktorer: (i) tiltakskostnader, (ii) klimaendringenes kostnader og (iii) diskonteringsrenten (for å kunne sammenligne kostnader og inntekter på ulike tidspunkter). Resultatene fra mange av de studier vi har gjennomgått indikerer at det er optimalt å ha et moderat ambisjonsnivå. Optimalisering med Nordhaus"s modell DICE tilsier f eks at det er optimalt å la CO_2-konsentrasjonen øke til 659 ppm i slutten av neste århundre, hvilket tilsier en temperaturøkning på 3.5^{o}C. Disse studiene benytter, grovt sett, de samme kostnadene for klimaendringer i fremtiden: For DICE er kostnadene for 3, 4 og 6^{o}C henholdsvis 2.5%, 4.5% og 10% av verdens samlede BNP. Det er vanskelig å vurdere om disse estimatene er ”høye” eller ”lave”, men antatt kostnad for en økning på 4^{o}C er godt innenfor det kostnadsområdet som er anslått av IPCC.

Antatt diskonteringsrente er viktig for utfallet av en optimalisering av typen over, ettersom de største klimaendringene vil komme i fjern fremtid. Mange optimaliseringsstudier benytter diskonteringsrenter i området 4 – 5%. I Stern Review argumenteres det for en mye lavere diskonteringsrente, og 1,4% er benyttet i rapportens egne beregninger. Med utgangspunkt i tentative, mindre formaliserte optimaliseringsberegninger, anbefaler Stern Review et konsentrasjonsmål mellom 500 og 550 ppm CO_2-e. Med en klimasensitivitet på 3 (IPCC"s beste anslag) vil dette begrense global temperaturøkning til 3^{o}C (mens den ville øke 7–9^{o}C i 2200 i det BaU-scenariet som benyttes i Stern Review).

Mye av debatten om optimale klimamål i litteraturen er rettet mot diskonteringsrenten. Hva som er ”korrekt” diskonteringsrente i dynamiske optimaliseringsanalyser har vært drøftet i stort omfang i mange år i økonomisk litteratur, bl.a. spørsmål knyttet til verdien av observerte markedsdata. Det er relativt stor enighet om at observerte markedsrenter kan benyttes i tidsperspektiver inntil ca 20 år, men det er ikke åpenbart at samme type data kan benyttes for analyser av lengre tidsperspektiver.

Diskonteringsrenten er ikke den eneste viktige faktoren i optimaliseringsanalyser. Noen av klimaendringenes kostnader vil komme i form av redusert biologisk mangfold, redusert helse, ekstremvær, økt konfliktnivå og lignende. Slike goder, som ikke omsettes på noen markeder, vil typisk vokse sakte over tid eller til og med avta. Hvis mengden av produserte markedsgoder samtidig øker sterkt, vil vi vente en økt verdsetting av godene som vokser langsomt eller avtar. Dette trekker i retning av at klimaendringene kan bli mye mer kostbare enn hva som er forutsatt i de fleste analyser. En av studiene vi behandler tar opp denne problemstil-

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[32] Strengt tatt skal denne vekstraten være mindre enn summen av diskonteringsrenten og den raten karbon fjernes fra atmosfæren med. Sistnevnte rate er imidlertid lav - mindre enn 1% av karbonet i atmosfæren fjernes hvert år.

lingen og behandler den i en modell som for øvrig er nesten identisk med Nordhaus"s DICE-modell. Denne endringen gir et optimalt utslippsforløp som er betydelig mer restriktivt enn det som beskrives av Nordhaus.

Som nevnt over er det knyttet betydelig usikkerhet til beregningene av klimasensitivitet. Et ferskt bidrag i denne sammenheng kommer fra Martin Weitzman (2009), som fokuserer på mulighetene for at klimasensitiviteten er ”betydelig høyere enn 4,5^{o}C”. Med utgangspunkt i tilgjengelig vitenskapelig litteratur på området mener han det er 5% sannsynlighet for en klimasensitivitet høyere enn 7^{o}C og en sannsynlighet på 1% for en sensitivitet høyere enn 10^{o}C. Han benytter disse forutsetningene i en modell der kostnadene for klimaendringer forutsettes å være høye for store temperaturendringer. Han viser at forventede klimakostnader vil være svært følsomme overfor både sannsynlighetsfordelingen for klimasensitivitet og sammenhengen mellom kostnader og store temperaturøkninger. Weitzman påpeker at de fleste analyser av optimal klimapolitikk ikke tar hensyn til disse forholdene, og at de derfor kan gi misvisende resultater.

Mange studier ser også på optimalisering under beskrankninger, der beskrankningen består av en øvre grense for atmosfærisk konsentrasjon av klimagasser eller temperaturøkning. På denne måten tar studiene klimamålene for gitt, og beregner optimal utvikling med disse betingelsene som utgangspunkt. I mange av studiene som er oppsummert i tabellen nedenfor, er utslippsforløp og karbonpriser beregnet med slike forutsetninger.

c) Kostnadene for utslippsreduksjoner

Kostnadene for utslippsreduksjoner vil være høyere desto:

- mer ambisiøst klimamål;
- høyere BaU-utslipp;
- høyere tiltakskostnader.

Mange av studiene vi ser på rapporterer kostnader av å stabilisere atmosfærisk CO_2 –nivå på ca 450 ppm CO_2, tilsvarende 500-550 ppm CO_2-e. Den langsiktige temperaturendringen for dette konsentrasjonsmålet antas å være ca 2.5 - 3^{o}C. Det er to relevante former for kostnader, nemlig *total*kostnader og *marginal*kostnader.

Tabellen nedenfor inneholder slike kostnadstall for noen av studiene, og vi ser at estimatene varierer betydelig. For omtrent like klimamål har Stern Review og DICE-analysene sammenlignbare anslag for totale kostnader, tilnærmet 1-1.5% av BNP. Andre studier, særlig en av OECD-studiene, anslår at kostnadene kan bli betydelig høyere. Det er grunn til å tro at årsaken til at OECD-studien har betydelig høyere kostnadene i 2050 enn andre studier skyldes en utslippsbane med små tiltak i nær fremtid – og tilhørende behov for omfattende tiltak senere (i 2050).

Den marginale tiltakskostnaden, karbonprisen, er et uttrykk for hvor streng klimapolitikken må være for å nå et gitt mål. Nivået på karbonprisen vil til enhver tid gi en øvre grense for tiltakskostnader: Ethvert tiltak som koster mindre enn karbonprisen, bør gjennomføres. Karbonprisen er derfor et godt mål på ambisjonsnivået i klimapolitikken. For et gitt klimamål vil en minimering av tiltakskostnadene gi en karbonpris som vokser med en rate som tilsvarer diskonteringsrenten + den raten som CO_2 fjernes fra atmosfæren med (se fotnote 4). Hvis vi også legger vekt på når en øvre konsentrasjonsgrense nås (desto senere, jo bedre), vil karbonprisen vokse med en lavere rate. For de to studiene fra OECD og en av IEA-studiene vokser den beregnede karbonprisen raskere enn diskonteringsrenten. Dette indikerer at den utslippsbanen som er lagt til grunn i disse rapportene ikke gir minimale neddiskonterte kostnader for å nå de konsentrasjonsgrenser som er benyttet. Det faktum at karbonprisen er for lav i en tidlig fase betyr at utslippene er for høye i denne fasen. For å holde CO_2–konsentrasjonen under de angitte grenser, må derfor utslippene kuttes dramatisk i 2050. Dette vil medføre høye karbonpriser og høye tiltakskostnader i 2050.

I tabellen nedenfor ser vi at det er store forskjeller i den langsiktige (2050) karbonprisen, også for sammenlignbare klimamål. Tabellen viser at analyseresultatene er sterkt avhengige av de forutsetninger og antagelser som er lagt til grunn.

d) Hvilke virkemidler bør bli brukt for å redusere utslippene?

Uansett om en ønsket utslippsbane er resultatet av en optimalisering eller en tilpasning til klimamål som er gitt utenfra, må det tas i bruk virkemidler for å oppnå de ønskede utslippsreduksjoner. Et sentralt virkemiddel vil være korrekt prising av utslipp, enten i form av karbonavgifter eller kvotepriser. Et viktig spørsmål er hvorvidt det er nødvendig med andre virkemidler. Hvis markedene fungerte perfekt og klimaendringene var den eneste eksternaliteten som skulle håndteres, ville det ikke være nødvendig med andre virkemidler enn en korrekt prising av utslippene. Imidlertid finnes det en rekke imperfeksjoner i økonomien, inkludert områder som er særlig relevante for klimapolitikken, f eks energisektoren og teknologiutviklingen. Reguleringssvikt kan også forekomme, og det er f eks umulig for myndighetene å forplikte seg til en bestemt karbonpris i fjern fremtid. Mange beslutninger i nåtid vil ha konsekvenser for utslippene på lang sikt, samtidig som nåtidens utslipp vil være påvirket av forventningene til fremtidige karbonpriser. Hvis markedsaktørene forventer mindre vekst i karbonprisene enn myndighetene har tilsiktet, vil dette lede til beslutninger som gir høyere fremtidige tiltakskostnader enn det som ville vært optimalt.

I tillegg til en korrekt karbonprising bør politikken og virkemiddelbruken utformes slik at den korrigerer for andre typer imperfeksjoner av relevans for klimautviklingen. Ulike typer subsidier og reguleringer kan inngå i en slik pakke, men der et viktig at virkemiddelbruken er gjennomtenkt og målrettet, slik at det er klart hvilke imperfeksjoner de ulike virkemidlene er ment å korrigere for.

Fremtidig teknologiutvikling vil være viktig for kostnadsutviklingen uansett hvilke utslippsmål som settes. En korrekt karbonpris vil gi markedsaktørene sterke insentiver til å utvikle klimavennlige teknologier. Det er likevel liten tvil om at uregulerte markeder vil gi utilstrekkelige insentiver for slik teknologiutvikling. En viktig årsak til dette er at gevinstene ved ny kunnskap i stor grad vil tilflyte andre enn dem som utvikler den nye kunnskapen. Dette er hovedårsaken til at offentlig sektor delta i kunnskapsutvikling (typisk gjennom offentlig finansiert grunnforskning) og for å gi ulike typer offentlig støtte til kunnskapsutvikling i privat sektor.

e) For et gitt klimamål – hva blir tilleggskostnadene for å benytte sub-optimale virkemidler?

Uansett hvordan tiltakskostnader (eller fordelene ved utslippsreduksjoner) modelleres, vil de totale kostnadene være påvirket av hvordan tiltakene (og utslippene) fordeles på sektorer og utslippskilder. En kostnadsminimerende allokering betegnes ofte som kostnadseffektiv. Mange analyser sammenligner ofte kostnadene for et sett av virkemidler med et annet sett av virkemidler som er designet for å gi de samme samlede utslippene. Avvik fra de mest kostnadseffektive virkemidlene gir typisk store kostnadsøkninger.

Dette illustreres blant annet gjennom analyser med DICE-modellen, der en har antatt at det etableres en avtale mellom USA, EU og åtte andre, store land. Til sammen representerte avtalepartene 75% av de globale utslippene i 2004. For en gitt, samlet utslippsreduksjon i disse landene ville kostnadene være 68% høyere enn ved å fordele de samme reduksjonene på *alle* land på en kostnadseffektiv måte.

OECD- og IEA-studiene behandler flere scenarier for internasjonalt samarbeid om klimapolitikken. Resultatene peker i samme retning som de analyser som er utført ved hjelp av DICE-modellen: kostnaden er vesentlig høyere ved begrenset deltagelse enn ved full deltagelse. En av OECD-studiene viser for eksempel at et mål om 750 ppm CO_2-e er uoppnåelig hvis Annex 1 landene alene skal sørge for utslippsreduksjonene. Den samme studien viser at omfattende unntak for energiintensiv industri vil øke kostnadene for å nå et 550 ppm mål med 50%. Tilsvarende vil en få betydelig høyere kostnader (100%) for et gitt mål, dersom bare CO_2 tas med i en avtale, mens andre drivhusgasser holdes utenfor.

Lignende illustrasjoner fremkommer i analyser med WITCH-modellen når den kjøres med restriksjoner for bruk av kjernekraft, CCS, solenergi og vindkraft. Disse restriksjonene gir kostnader som er 7% av BNP i 2050 – sammenlignet med 3,9% uten restriksjoner.

Vi har allerede behandlet årsaken til at det kan være ønskelig å *supplere* en karbonpris med andre virkemidler og tiltak. I debatter om dette temaet fremkommer det regelmessig påstander om at det vil være gunstig å *erstatte* karbonpriser med andre virkemidler – snarere enn å supplere dem; ”*det må være bedre med gulrot enn pisk*”. Økonomer er samstemte om at en prising av utslipp er helt nødvendig dersom en skal unngå vesentlig høyere kostnader enn nødvendig. Det foreligger imidlertid ingen garantier for at disse synspunktene får gjennomslag. Det er derfor interessant å se på numeriske studier som beregner kostnadsøkningen av å velge andre virkemidler enn en riktig karbonpris for å nå et bestemt klimamål. En av studiene viser at for et gitt utslippsmål vil det oppstå et moderat effektivitetstap om en *utelukkende* benytter karbonprising som virkemiddel, mens tapet blir betraktelig større dersom en *unnlater* å benytte karbonprising – og kun tar i bruk subsidiering av fornybare energikilder og/eller FoU.

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Tabellen nedenfor oppsummerer noen av resultatene i studiene vi har sett på. Selv om stabiliseringsmålene varierer, er de relativt like i forhold til forventet temperaturendring: 2.5 - 3^{o}C. Som nevnt tidligere er det store forskjeller i nødvendig karbonpris for å nå dette målet. De fleste av studiene anslår en karbonpris på 100-400 US $ per tonn CO_2 i 2050.

Utslipp og karbonpriser (US $ per tonn CO_2)

Studie	**Stabiliseringsmål**	**Karbonpris**[33] **2010-2015**	**Karbonpris**[34] **2050-2055**	**Kostnader som % av BNP (2050)**
Nordhaus, Dice	Mål om max 2°C temperaturøkning	US $ 20	US $ 83	0.6%[35]
Nordhaus, Dice	420 ppm CO_2	US $ 67	US $ 189	1.4%
ENTICE	Konstante 1995 utslipp	US $ 182	US $ 491	1.6%
Grimaud et al.	450 ppm CO_2	US $ 48	US $ 200	
WITCH	450 ppm CO_2	US $ 20	US $ 350	3.9%
Stern Report	550 ppm CO_2-e	US $ 40 (i 2005)	US $ 98	1%
IPCC, 2007	445-535 ppm CO_2-e			< 5.5%
IPCC, 2007	535-590 ppm CO_2-e	US $ 20-80 (i 2030)	US $ 30-150	0.1-4%
OECD, Env. Outlook 2008	450 ppm CO_2-e	US $ 5	US $ 177	2.5%
OECD, 2008b	550 ppm CO_2-e	US $ 5	US $ 400	4.8%
IEA, World Energy Outlook	550 ppm CO_2-e	US $ 40 (i 2020)	US $ 90 (i 2030)	
IEA, Energy Technology Perspectives 2008	450 ppm CO_2-e		US $ 200	
Australia's LPF, Garneau	550 ppm CO_2-e	US $ 20	US $ 91	2.7-3.2%
Australia's LPF, Garneau	450 ppm CO_2-e	US $ 34	US $ 158	4.2-4.3%

Appendices

Appendix to Section 2.1

The problem of maximizing (2.1) subject to (2.2) with a constraint $S(t) \le S^*$ is solved using optimal control theory. The present-value Hamiltonian is (written so all shadow prices are non-negative)

$$H = B(e(t) - D(S(t),t) - q(t)\left[e(t) - \delta S(t)\right] - \mu(t)S(t)$$

The optimal solution satisfies the following equations (for an interior solution: i.e. for *e*(*t*)>0 for all *t*):

(2A.1) $$\frac{\partial H}{\partial e} = 0$$

(2A.2) $$\dot{q}(t) - rq(t) = \frac{\partial H}{\partial S}$$

(2A.3) $\mu(t) \ge 0$ and $\mu(t)(S^* - S(t)) = 0$

(2A.4) $\lim_{t \to \infty} e^{-rt} q(t) = 0$

Equation (2A.1) gives us (2.3) – i.e. $B'(e(t)) = q(t)$ – while (2A.2) implies

(2A.5) $$\dot{q}(t) = (r + \delta)q(t) - D_S(S(t),t) - \mu(t)$$

Solving this differential equation and using (2A.4) gives us

(2A.6) $$q(t) = \int_t^\infty e^{-(r+\delta)(\tau - t)}\left[D_S(S(\tau),\tau) + \mu(t)\right]d\tau$$

Consider first the case in which the constraint $S(t) \le S^*$ is never binding so that $\mu(t) = 0$ for all *t*. If $D(S,t) = mS(t)$, where *m* is a constant parameter, it immediately follows from (2A.6) that

(2A.7) $$q(t) = \frac{m}{r + \delta}$$

More generally, it follows from (2A.6) that $q(t)$ will be rising at a time t if D_S is rising for all $\tau > t$.

When $\mu(t) = 0$ it follows from (2A.5) that

$$\frac{\dot{q}(t)}{q(t)} = (r+\delta) - \frac{D_S(S(t),t)}{q(t)} \tag{2A.8}$$

We see from (2A.8) that as long as $D_S > 0$, the growth rate of q is less than $r+\delta$. For the special case of $D_S = 0$ (which could be the case for low values of S), the growth rate of q will be equal to $r+\delta$.

Consider the special case in which $D(S,t)=m(t)S$. Here (2A.6) can be written as

$$q(t) = \int_t^\infty e^{-(r+\delta)(\tau-t)} m(\tau)d\tau + \int_t^\infty e^{-(r+\delta)(\tau-t)} \mu(\tau)d\tau \tag{2A.9}$$

If the constraint $S(t) \le S^*$ is binding for some t, $\mu(t)$ will be positive for these values of t. Assume that this is the case and that the optimal $S(t)$ reaches S^* at some date T. In this case $\mu(t)$ is positive immediately after T. This implies that the second integral in (2A.9) is positive, so the path of $q(t)$ must be higher than the price path when the constraint $S(t) \le S^*$ is never binding: i.e. the price path given by the first term in (2A.9). It is useful to first consider the situation during which $S(t) = S^*$. When this holds it follows from (2.2) that $e(t) = \delta S^*$ is constant, so that our assumption $B_{et} = 0$ implies that $q(t)$ is constant. This constant value, denoted q^*, follows from (2.3) with $e(t) = \delta S^*$ inserted. The value of $\mu(t)$ is determined by (2A.9) and $q(t) = q^*$ for all t when $S(t) = S^*$ holds. If $m(t)$ eventually becomes sufficiently large, the first term in (2A.9) will eventually reach q^*. From this time onwards $\mu(t) = 0$ and $e(t) < \delta S(t)$, so that $S(t)$ will decline and the constraint $S(t) \le S^*$ will no longer be binding.