7. STABILIZING GREENHOUSE GAS CONCENTRATIONS AT LOW LEVELS: AN ASSESSMENT OF REDUCTION STRATEGIES AND COSTS

Abstract. On the basis of the IPCC B2, A1b and B1 baseline scenarios, mitigation scenarios were developed that stabilize the greenhouse gas concentrations in the long-term at 650, 550 and 450 and – subject to specific assumptions – 400 ppm CO_2-eq. The analysis takes into account a large number of reduction options, such as reduction of non-CO_2 greenhouse gases, carbon plantations and measures in the energy system. The study shows stabilization as low as 450 ppm CO_2-eq. to be technically feasible, even given relatively high baseline scenarios. To achieve these lower concentration levels, global emissions need to peak within the first two decades. The present net present value of abatement costs for the B2 baseline scenario (a medium scenario) increases from 0.2% of cumulative GDP to 1.1% as the shift is made from 650 to 450 ppm. On the other hand, the probability of meeting a two-degree target increases from 0-10% to 20-70%. The mitigation scenarios lead to lower emissions of regional air pollutants (co-benefit) but also to increased land use. The uncertainty in the calculated costs is at least in the order of 50%, with the most important uncertainties including land-use emissions, the potential for bio-energy and the contribution of energy efficiency. Furthermore, creating the right socio-economic and political conditions for mitigation is more important than any of the technical constraints.

This chapter was published earlier as van Vuuren, D.P., den Elzen, M.G.J., Lucas, P.L., Eickhout, B., Strengers, B., van Ruijven, B., Wonink, S. and van Houdt, R. (2007). Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. *Climatic Change*. 81: 2, March 2007, Pages 119-159.

7.1 Introduction

Climate change appears to be among the most prominent sustainability problems of this century. IPCC's Third Assessment Report concludes that the earth's climate system has demonstrably changed since the pre-industrial era and that – without climate policy responses – changes in the global climate are likely to become much greater, with expected increases in global temperature in the 2000-2100 period ranging from 1.4 to 5.8 °C (IPCC, 2001). Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC) states as its ultimate objective: “Stabilization of greenhouse gas (GHG) concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system”. However, what constitutes a non-dangerous level is an open question, as this depends on all kinds of uncertainties in the cause–effect chain of climate change and on political decisions about the risks to be avoided. Some of the recent literature suggests that climate risks could already be substantial for an increase of 1–3°C compared to pre-industrial levels (see O'Neill and Oppenheimer, 2002; ECF and PIK, 2004; Leemans and Eickhout, 2004; Mastandrea and Schneider, 2004; Corfee Morlot et al., 2005; MNP, 2005a). As one of the political actors, the EU has adopted the climate policy goal of limiting the temperature increase to a maximum of 2°C compared to pre-industrial levels (EU, 1996; EU, 2005). However, uncertainties still allow for other interpretations of what constitutes dangerous climate change in the context of Article 2. Actors can, in their interpretation, weigh such factors as the risks of climate change as function of temperature increase, but also factors such as the potential and costs of adaptation, and the costs and effectiveness of mitigation action.

Apart from the temperature target, the required level of emission reduction also depends on the uncertain relationship between atmospheric GHG concentrations and temperature increase, in other words "climate sensitivity". Several probability-distribution functions (PDF) for climate sensitivity have been published in recent years, each indicating a broad range of probable values for climate sensitivity (Wigley and Raper, 2001; Murphy, 2004). Several authors have indicated that these PDFs can be translated into a risk approach toward climate change (Azar and Rodhe, 1997; Hare and Meinshausen, 2004; Richels et al., 2004; Yohe et al., 2004; den Elzen and Meinshausen, 2005; Meinshausen, 2006). These studies show that a high degree of certainty in terms of achieving a 2°C temperature target is likely to require stabilization at low GHG concentration (for instance, a probability greater than 50% will require stabilization below 450 ppm CO_2-eq[i]). The stabilization of GHG concentrations at such a low level will require drastic emission reductions compared to the likely course of emissions in the absence of climate policies. Even for more modest concentration targets such as 650 ppm CO_2-eq., emissions in 2100 will generally need to be reduced by about 50% compared to probable levels in the absence of a climate policy (IPCC, 2001).

A large number of scenario studies have been published that aim to identify mitigation strategies for achieving different levels of GHG emission reductions (see among others Hourcade and Shukla, 2001; Morita and Robinson, 2001). However, most of these studies have focused on reducing only the energy-related CO_2 emissions, and have disregarded abatement options that reduce non-CO_2 gases and the use of carbon plantations. Furthermore, the number of studies looking at stabilization levels below 550 ppm CO_2-eq. is very limited. There are a few studies that explore the feasibility to stabilize CO_2 only at 350-450 ppm CO_2; the lowest multi-gas stabilization studies in the literature focus on 550 ppm CO_2-eq. (see Section 7.2). This implies that very little information exists on mitigation strategies that could stabilize GHG concentrations at the low levels required to achieve a 2-3°C temperature target with a high degree of certainty. As a matter of fact, even the number of studies looking at stabilizing at 550 ppm CO_2-eq. is far lower than for higher stabilization targets (Morita et al., 2000; see Swart et al., 2002). Finally, most earlier studies have not considered the more recent mitigation options currently being discussed in the context of ambitious emission re-

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[i] "CO_2 equivalence" expresses the radiative forcing of other anthropogenic radiative forcing agents in terms of the equivalent CO_2 concentration that would result at the same level of forcing. Here, the definition of CO_2-eq. concentrations includes the Kyoto gases, tropospheric ozone and sulfur aerosols.

duction, such as carbon capture and storage (CCS); the importance of this option is highlighted in Edmonds et al. (2004), IEA (2004a) and IPCC (2005). Given current insights into climate risks and the state of the mitigation literature, then, there is a very clear and explicit need for comprehensive scenarios that explore different long-term strategies to stabilize GHG emissions at low levels (Morita and Robinson, 2001; Metz and Van Vuuren, 2006).

This chapter explores different multi-gas stabilization scenarios for concentration levels for which no scenarios are currently available (below 550 ppm CO_2-eq). In order to study the impact of different stabilization levels, we have chosen to explore scenarios for a range of concentrations levels (i.e. 650, 550 and 450 ppm CO_2-eq. and, under specific assumptions, 400 ppm CO_2-eq)[ii]. As such, the study also goes beyond our own research that did not cover stabilization scenarios below 550 ppm CO_2-eq. (van Vuuren et al., 2006b)[iii]. The chapter makes an important contribution to the existing literature by exploring pathways to those GHG stabilization levels required for achieving global mean temperature change targets of 2-3°C with a high degree of certainty. We focus specifically on the following questions:

- What portfolios of measures could constitute promising strategies for stabilizing GHG concentrations at 650, 550 and 450 ppm CO_2-eq. and below?
- What are the cost levels involved in such strategies and what are the implications for the energy sector, investment strategies and fuel trade?
- How do uncertainties in the potentials and costs of various options play a role in terms of the costs and selection of a portfolio of measures?

The focus here will be on mitigation strategies, abatement costs and climate consequences from a global perspective. In a related article, we focused on the regional costs and abatement strategies[iv] (den Elzen et al., 2007). For costs, we focus on direct abatement costs from climate policy and do not capture macro-economic costs; for benefits, we focus on the impact on global mean temperature and co-benefits for air pollutants. Furthermore, for instance, we do not consider the avoided damages caused by climate change). In our analysis, we deliberately use an integrated approach, dealing with a wide range of issues that are relevant in the context of stabilization scenarios; these include land-use consequences and changes in the energy system. Although several of these issues were studied earlier for single stabilization scenarios, here we wanted to see how they are related to the GHG stabilization level.

The analysis was conducted using the IMAGE 2.3 model framework, including the energy model, TIMER 2.0, coupled to the climate policy model, FAIR–SiMCaP (for model

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[ii] The term “specific assumptions” here emphasizes the fact that we need to include additional reduction measures to reach this target as explained in Section 7.6.3).

[iii] Earlier we published emission profiles that would lead to stabilization at low GHG concentration levels, but that study did not look into the question how these emission profiles could be reached (den Elzen and Meinshausen, 2005).

[iv] Regional costs also depend on possible agreements on regional reduction targets and therefore constitute a separate topic that cannot be dealt with in the context of this article. It should, however, be noted that the analysis has been done using models that include regional detail.

description, see Section 7.3 and Chapter 2 of this thesis). A similar framework (using FAIR instead of FAIR–SiMCaP) was used earlier to study mitigation strategies, for example, in the context of EU climate policy targets (Criqui et al., 2003; van Vuuren et al., 2003c). This model framework was designed to provide a broad description of the issues involved in the chain of events causing climate change. It covers a broad range of emission sources (and therefore abatement options), dealing not only with the energy sector but also with land use, forestry and industry. It is therefore suitable for studying the type of mitigation strategies required to stabilize radiative forcing from GHG and the possible environmental and economic consequences of such strategies. We used this framework to explore stabilization strategies based on three different baseline scenarios, i.e. updated implementations of the IPCC SRES B2, B1 and A1b scenarios. We performed an extensive sensitivity analysis for the different options to map out some of the main uncertainties.

The chapter starts with a brief overview of earlier work on stabilization scenarios and is followed by an explanation of the methods used to develop the new scenarios. Then there is a discussion on the initial results from the stabilization scenarios and the associated benefits and co-benefits. We then present the results of our uncertainty analysis and also address the question of whether it is possible to reduce emissions to levels even lower than 450 ppm CO_2-eq. Subsequently, we compare our results to earlier studies and examine the implications of the uncertainties that have been identified. The chapter ends with a presentation of our overall findings.

7.2 Earlier work on stabilization scenarios

A large number of the scenario studies published have explored global mitigation strategies for stabilizing GHG concentrations. A recent inventory estimated the number of published GHG emission scenarios at a few hundred, although a large majority of these are baseline scenarios (scenarios that do not take the effect of climate policy into account) (NIES, 2005).[v] In the literature on mitigation scenarios, there are a number of recurring themes. These include:

- the issue of stabilization targets and overshoot;
- the identification of overall cost levels of stabilization;
- the issue of timing (early action or delayed response), partly in relation to technology development, and
- the role of individual technologies and mitigation measures.

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[v] It is possible to distinguish between *scenarios* and emission *pathways*. Emission pathways focus solely on emissions, whereas *scenarios* represent a more complete description of possible future states of the world. The literature distinguishes between baseline, and mitigation or stabilization scenarios. The first category includes scenarios without explicit new climate policies. These scenarios do, however, need to assume policies in other fields than climate policy, and may still unintentionally have a significant impact on GHG emissions (e.g. other environmental policies and trade policies). Mitigation scenarios (or climate policy scenarios) purposely assume climate policies to explore the impact of these policies. Stabilization scenarios are a group of scenarios that include mitigation measures intended to stabilize atmospheric GHG concentrations.

Here, we will briefly discuss the available literature and indicate how these themes have been dealt with. The IPCC Third Assessment Report (TAR) (Hourcade and Shukla, 2001; Morita and Robinson, 2001) and Fourth Assessment Report (AR4) (Fisher et al., 2007) provide an overview of the stabilization scenarios in a larger context.

On the issue of *stabilization targets*, many studies in the past have focused on stabilizing CO_2 concentration levels. Consistent with this, new multi-gas studies focus mostly on the comparable measure for the stabilization of radiative forcing (expressed in W/m^2 or CO_2-eq.) (van Vuuren et al., 2006d). Alternatively, some studies look at temperature increase targets (as they are more directly related to impacts). One implication of using a temperature target, however, is the higher level of uncertainty relating to mitigation action (Matthews and van Ypersele, 2003; Richels et al., 2004). Another issue is that staying below a certain temperature level with a specific likelihood can either be achieved by: (a) stabilizing at a certain radiative forcing level or by (b) peaking at somewhat higher levels, immediately followed by a reduction of the forcing level ("overshoot scenarios"). The second strategy prevents some of the temperature increase that will occur in the longer term (Wigley, 2003; den Elzen and Meinshausen, 2005; Meinshausen, 2006).

In general, these overshoot scenarios show lower costs than the corresponding stabilization scenarios for a given radiative forcing target. For the lower stabilization levels, overshoot scenarios are, in fact, the only feasible scenarios since current concentrations have either already passed these levels, or will do so in the very near future. In broad terms, the current scenario literature covers stabilization levels from 750 to 450 ppm CO_2 for "CO_2-only" studies. There are only a few studies that have looked into stabilizing concentrations at low concentration levels. Exceptions include the work of Nakicenovic and Riahi (2003), Azar et al. (2006) and Hijoka et al.(2005). These studies show that low stabilization levels (below 450 ppm CO_2) can, in principle, be achieved at mitigation costs in the order of 1-2% of GDP. However, both studies started from relatively low-emission baseline scenarios.

In multi-gas studies, the range of stabilization targets considered in analysis is actually much more limited, with studies typically only looking at 650 ppm CO_2-eq. (van Vuuren et al., 2006d; Weyant et al., 2006). The lowest scenarios currently found in the literature aim at 550 ppm CO_2-eq. (Criqui et al., 2003; van Vuuren et al., 2006b), a concentration level that leads to only a probability of limiting temperature increase to less than 2°C. For a range of probability-distribution functions (PDF), Hare and Meinshausen (2004) estimated the probability to be about 0-30%. The probability of staying within 2.5°C is 10-50%. A 50% probability (on average) of staying within 2°C is obtained for 450 ppm CO_2-eq. The only multi-gas studies in the literature that are currently exploring the consequences of aiming to achieve such low stabilization levels are emission pathway studies that do not specify the type of mitigation measures leading to the required emission reductions (den Elzen and Meinshausen, 2005; Meinshausen, 2006; Meinshausen et al., in press).

Different measures are used for the costs of mitigation. Energy system models (that do not describe the whole economy, but only the energy sector) generally report costs as increased energy system costs or abatement costs. These are annual costs that can be expressed as percentages of GDP. General equilibrium models describe the total macro-economy including the energy system, and can thus estimate the feedbacks on increased investments in the energy system. As a more integrated costs measure, these models generally report costs in terms of reductions of GDP or private consumption relative to the baseline scenario. For the 30-40 stabilization scenarios analyzed in TAR, the assessment found very small costs for stabilizing at 750 ppm and GDP losses in the order of 1-4% for 450 ppm (Hourcade and Shukla, 2001). Costs were found to be a function of the GHG stabilization level and the baseline emission scenario. This implies that socio-economic conditions, including policies outside the field of climate policy, are just as important for stabilization costs as climate policies.

The issue of the *timing* of the abatement effort was initiated by Hamitt et al. (1992) and later by Wigley et al. (1996). Wigley et al. (1996) argued that their scenarios, that postponed abatement action in comparison to earlier pathways developed by IPCC, were more cost-effective because of the benefits of technology development, more CO_2 absorption by the biosphere and ocean and discounting of future costs. Their arguments were confirmed in the analysis of the EMF-14 (Energy Modeling Forum) study (as reported by (Hourcade and Shukla, 2001). Other authors, however, responded that this conclusion depended on the assumptions on discounting, technological change, inertia and uncertainty (Ha-Duong et al., 1997; Azar, 1998; Azar and Dowlatabadi, 1999; van Vuuren and de Vries, 2001). For low-range concentration targets, Den Elzen and Meinshausen (2005) reported that delaying the peak in global emissions beyond 2020 would lead to very high reduction rates later in the century and therefore to probable high costs. Assumption of induced technology change (instead of exogenous technological progress simply as function of time) and explicit capital turnover rates could lead to a preference for early action, or at least a spread of the reduction effort over the century as a whole (see also van Vuuren et al., 2004). The debate about optimal timing is still ongoing. Yohe et al. (2004) recently showed that hedging strategies (i.e. cost-optimal reduction pathways incorporating the risk of more, or less, stringent action later in the century if new evidence comes in) to deal with uncertainties may lead to relatively early reduction pathways, leaving as many options open as possible (Berk et al., 2002).

Recently, considerable attention has been paid to extending the number of reduction options considered in scenario analysis. One possibility is the inclusion of *non-*CO_2 *GHGs*. The Energy Modeling Forum (EMF-21) performed a model comparison study, showing that extending the reduction options from CO_2 only to include other GHGs can reduce costs by about a third (van Vuuren et al., 2006d; Weyant et al., 2006). Recent publications also put forward several "*new technologies*" that could be pivotal in mitigation strategies. First of all, CCS could play an important role in reducing GHG emissions in the power sector. This technology could become cost-effective at emission permit prices of around 100-200 US$/tC (IPCC, 2005) and therefore considerably reduce mitigation costs (Edmonds et al., 2004; IEA, 2004a). Recent work on hydrogen as an energy carrier has shown that although hydrogen may also reduce mitigation costs, this conclusion will depend very much on the assumption of technology development (e.g. Edmonds et al., 2004). Bio-energy in combination with CCS could be an attractive technology if very ambitious stabilization targets were adopted (Azar et al., 2006). Finally, the debate is still ongoing about whether accounting for technology change (induced learning vs. exogenous assumptions) in itself results in different conclusions about optimal climate policies. Some studies claim that induced technological change will lead to very significant cost reductions, justifying a preference for early action (Azar and Dowlatabadi, 1999; van Vuuren and de Vries, 2001; Barker et al., 2005). Others report fewer benefits and/or no impact on timing (Manne and Richels, 2004).

What are the implications of the current state of knowledge for this study? The most important aim here is to determine whether low concentration levels are achievable. In terms of the objective of climate policy, we focus on the stabilization of concentration (and thus not temperature) to increase the comparability with other studies. Den Elzen et al. (2005) indicated how the results of the emission pathways compared to alternative peaking scenarios. With reference to the debate on new mitigation options, the model framework used in this study covers a large range of mitigation options and several technologies are described in terms of induced technological change. Given the major uncertainties involved in each of the mitigation options, we will analyze how some of these uncertainties impact the overall results.

7.3 Methodology

7.3.1 Overall methodology

For the construction of the stabilization scenarios, we used an interlinked model framework consisting of the IMAGE 2.3 Integrated Assessment model (IMAGE-team, 2001), which included the TIMER 2.0 energy model (Chapter 2) coupled to the climate policy model FAIR-SiMCaP (den Elzen and Lucas, 2005; den Elzen and Meinshausen, 2005).[vi] These models have been linked for the purpose of this analysis in a way similar to that described earlier by Van Vuuren et al. (2003c), as shown in Figure 7.1. Chapter 2 (TIMER and IMAGE) and Appendix 7.A (FAIR) provides additional information on the different models used.

The IMAGE 2.3 model is an integrated assessment model consisting of a set of linked and integrated models that together describe important elements of the long-term

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[vi] IMAGE 2.3 is an updated version of IMAGE 2.2, the difference being the option of exploring impacts of bio-energy and carbon plantations. TIMER 2.0 is an updated version of TIMER 1.0. The main differences are additions with respect to hydrogen, bio-energy and modeling of the electric power sector. The FAIR model used in this study is actually a version coupled to SiMCaP. Here, FAIR is a policy-support tool focusing on the costs of climate change and the influence of burden-sharing agreements. The SiMCaP model is able to develop emission pathways that lead to certain climate targets. The FAIR-SiMCaP model is further abbreviated to FAIR.

dynamics of global environmental change, such as air pollution, climate change and land-use change. IMAGE 2.3 uses a simple climate model and a pattern-scaling method to project climate change at grid level. At grid level, agriculture is described by a rule-based system driven by regional production levels. Finally, natural ecosystems are described by an adapted version of the BIOME model. The global energy model, TIMER 2.0, a component of the IMAGE model, describes primary and secondary demand for, and production of, energy and the related emissions of GHG and regional air pollutants. The FAIR model is a combination of the multi-gas abatement-cost model and module relating emission pathways to long-term targets (SiMCaP). The FAIR cost model distributes the difference between baseline and global emission pathways using a least-cost approach involving regional Marginal Abatement Cost (MAC) curves for the different emission sources (den Elzen and Lucas, 2005) (den Elzen and Meinshausen, 2005).[vii] Calculations in all three main models are carried out for 17 regions[viii] of the world.

The overall analysis consists of three major steps (Figure 7.1):

1. Both the IMAGE and the TIMER model are used to construct a *baseline emission scenario*. Furthermore, the TIMER model yields the *potentials and abatement costs* of reducing emissions from energy-related sources, while the IMAGE model provides the potentials and abatement costs associated with carbon plantations (7.3.2/7.3.3).
2. The FAIR/SIMCAP model is used to develop *global emission pathways* that lead to a stabilization of the atmospheric GHG concentration. The concentration calculations are done using the MAGICC 4.1 model (Wigley and Raper, 2001) that is included in FAIR/SIMCAP. The FAIR model distributes the global emission reduction from the baseline across the different regions, gases and sources in a cost-optimal way using the marginal abatement costs. It is assumed that these gases are substituted on the basis of GWPs. Furthermore, the model calculates the international permit price[ix], the regional emission reductions, and the global and regional costs of emission reductions (7.3.4).
3. The IMAGE/TIMER model implements the changes in emission levels resulting from the abatement action (emission reductions) and the permit price, as determined in the previous step, to develop the final *mitigation scenario* (emissions, land use, energy system). Furthermore, the environmental impacts are assessed using the climate model of IMAGE.

In our analysis, we assume that reductions could be cost-optimally distributed across all 17 regions from 2013 onwards. This implies the presence of some form of international mechanism that justifies this least-cost assumption, such as emission trading.

[vii] Marginal Abatement Cost (MAC) curves reflect the additional costs of reducing the last unit of CO_2-eq. emissions.

[viii] Canada, USA, OECD-Europe, Eastern Europe, the Former Soviet Union, Oceania and Japan, Central America, South America, Northern Africa, Western Africa, Eastern Africa, Southern Africa, Middle East and Turkey, South Asia (incl. India), South-East Asia and East Asia (incl. China) (IMAGE-team, 2001).

[ix] This “permit price” is equal to the marginal costs of reducing greenhouse gas emissions to the required level of reduction. In the energy model the permit price is equal to carbon tax.

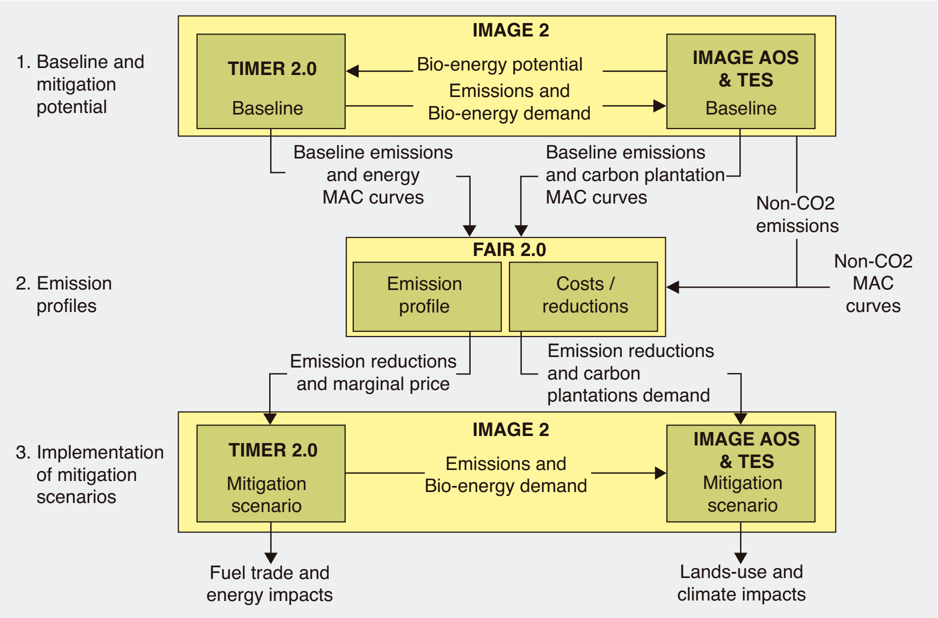

Figure 7.1 Linkage and information flows of the applied modeling framework. The 3 numbers in the figure are explained in the text. AOS = Atmosphere/Ocean System; TES = Terrestrial environment system.

7.3.2 Baseline emissions

The baseline scenarios used in this study are based on IPCC-SRES scenarios (Nakicenovic and Swart, 2000). This set of baseline scenarios explores different possible pathways for GHG emissions and can roughly be categorized along two dimensions: the degree of globalization vs. regionalization, and the degree of orientation towards economic objectives as opposed to an orientation towards social and environmental objectives. In 2001, the IMAGE team published detailed elaborations of these scenarios (IMAGE-team, 2001). Chapters 4 and 5 provide more information on the assumptions and storylines underlying the SRES scenarios. Although the scenarios are still broadly consistent with the literature, new insights have emerged for some parameters. For instance, current projections for population and economic growth for low-income regions are generally lower than assumed in SRES (Chapter 3). Against this background, a set of updated IMAGE scenarios was developed recently (see Figure 7.2). Here, we use the B2 scenario as the main baseline scenario, with the A1b and B1 scenarios being used to show the impacts of different baseline assumptions.

The new implementation of B2 focuses explicitly on exploring the possible trajectory of greenhouse gas emissions on the basis of medium assumptions for the most important drivers (population, economy, technology development and lifestyle). In terms of its quantification, the B2 scenario follows roughly the reference scenario of the World Energy Outlook 2004 for the first 30 years (IEA, 2004b). After 2030, economic growth

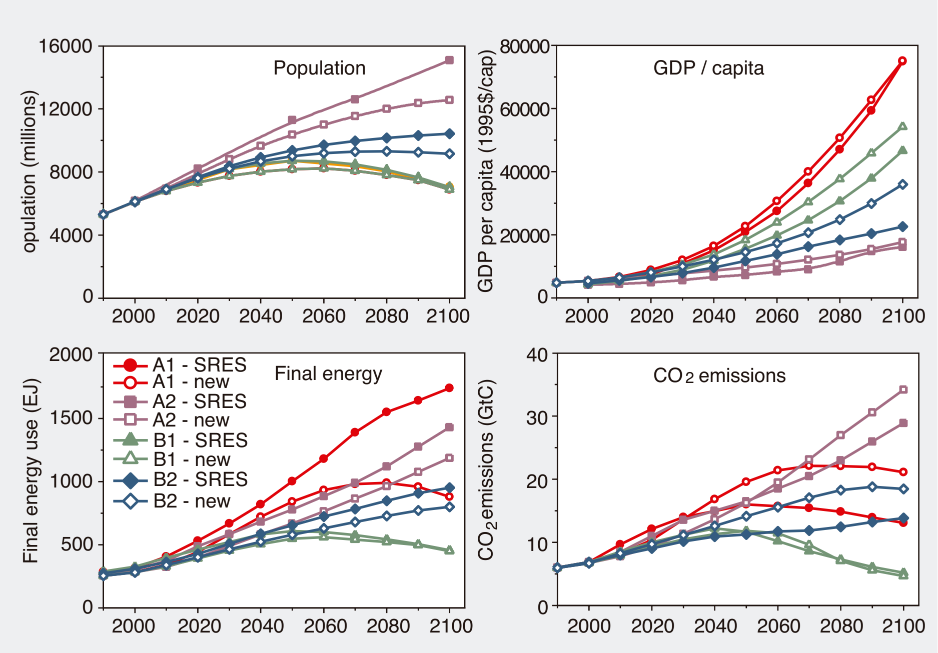

Figure 7.2 Driving forces and fossil fuel CO_2 emissions in the IMAGE 2.3 SRES scenarios in comparison to the IPCC SRES Marker scenarios (Nakicenovic and Swart, 2000).

converges to the B2 trajectory of the previous IMAGE scenarios (IMAGE-team, 2001). The long-term UN medium population projection is used for population (UN, 2004).

The A1b scenario, by contrast, represents a world with fast economic growth driven by further globalization and rapid technology development. As the scenario also assumes material-intensive lifestyle, energy consumption grows rapidly. The B1 scenario describes a world characterized by strong globalization in combination with environmental protection and a reduction of global inequality. It assumes the use of very efficient technologies, resulting in relatively low energy use. The assumptions for population and economic growth in the A1 and B1 scenarios have been taken from, the Global Orchestration and Technogarden scenarios of the Millennium Ecosystem Assessment, respectively (Carpenter and Pingali, 2006). In all three scenarios, trends in agricultural production (production levels and yields) are also based on the Millennium Ecosystem Scenarios, which were elaborated for these parameters by the IMPACT model (Rosegrant et al., 2002). All other assumptions conform to earlier implementation of the SRES scenarios.

As shown in Figure 7.2, the resulting emissions are still broadly consistent with the IPCC Marker scenarios. The A1 scenario shows higher emissions than the corresponding marker, given slightly different assumptions on technology change and fuel choices – but is easily within the range of other elaborations of this storyline. The B2 scenario also has higher emissions than the corresponding marker, partly reflecting the shift in storyline from an environmental-focus scenario to a medium emission scenario as described above.

7.3.3 Assumptions in the different subsystems and marginal abatement costs

We adopted a hybrid approach to determine the abatement efforts among the different categories of abatement options. First, the possible abatement in different parts of the system (energy, carbon plantations and non-CO_2) is translated into aggregated baseline- and time-dependent MAC curves. These curves are then used in the FAIR model to distribute the mitigation effort among these different categories and to determine the international permit price. Finally, the corresponding reduction measures at the more detailed level are determined by implementing the permit price in the different "expert" models for energy (TIMER) and carbon plantations (IMAGE). For instance, in the case of energy, the TIMER model results in a consistent description of the energy system under the global emission constraint set by FAIR.

The TIMER, IMAGE and FAIR models have been linked so that output of one model is the input of the second model (see Figure 7.1). In addition, also the model-specific assumptions in the different models have been harmonized. In most cases, this was done on the basis of the storyline of the different scenarios being implemented. For example, technology development is set low for all parameters in the different models in the A2 scenario. The same holds for other driving forces. In terms of land use, both carbon plantations and bio-energy calculations start with the same land-use scenario (implementation factors prevent them using the same land) and the same land price equations. A 5% per year social discount rate is used to calculate the Net Present Value for the mitigation scenarios (this discount rate is chosen for comparison with other studies (Hourcade and Shukla, 2001); the level is relatively high, but as costs in this study are mostly used in comparison to income levels or relative to other levels, it does not really impact the results of the study. In the energy system, investment decisions are compared using a 10% per year discount rate, which provides a better reflection of the medium-term investment criteria used in making such investments. Table 7.1 summarizes some of the assumptions made. All costs are expressed in 1995 US$.

Energy

The TIMER MAC curves (used by the FAIR model) are constructed by imposing an emission permit price (carbon tax) and recording the induced reduction of CO_2 emissions[x]. There are several responses in TIMER to posing an emission permit price. In energy supply, options with high carbon emissions (such as conventional use of coal and oil) become more expensive compared to options with low or zero emissions (such as natu-

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[x] The carbon tax is intended to induce a cost-effective set of measures and is, in the model, equivalent to an emission permit price. In the rest of the article, we will use the term (emission) permit price. It should be noted that in reality, the same set of measures as induced by the permit price can also be implemented through other types of policies.

ral gas, fossil fuels with CCS, bio-energy, nuclear power, solar and wind power). The latter options therefore gain market shares. In energy demand, investments in efficiency become more attractive.

To construct the MAC curves, the induced reduction of CO_2 emissions is recorded for sight years from 2010 to 2100 (in ten-year steps). In the energy model TIMER, the response to a carbon tax does depend on the pathway of introduction (e.g. early introduction leads to induced technology change); see also Chapter 8. To capture (as a first-order approximation) the time pathway, two very different permit price profiles were used to explore responses: one that assumes a linear increase from 2010 to the permit price value in the sight year (“linear price MAC”) and one that reaches the maximum value 30 years earlier (“block price MAC”). The second profile results in more CO_2 reductions because the energy system has more time to respond (corresponding to “early-action”). Depending on the pathway of the actual permit price in the stabilization scenario, FAIR combines the linear price MAC curves and the block price MAC curves, so that some of the dynamics can be captured.[xi]

In the baseline, stricter investment criteria are used for investments in energy efficiency than for investments in energy supply. Investments in energy efficiency are made only if the apparent average pay-back time is less than three years (for industry) or two years (other sectors) (see de Beer, 1998)[xii]. In low-income countries, we assume that lower efficiency in industry and other sectors are caused by even lower apparent average pay-back-time criteria (de Vries et al., 2001). The criteria used in energy supply (based on a 10% discount rate and the economic life time depending on the type of technology applied) corresponds more-or-less to a pay-back time of 6-7 years. The difference between demand and supply investment criteria is based on historical evidence (barriers to demand-side investments that include lack of information, more diffuse investors, higher risks and lack of capital). Under climate policies, investments into energy efficiency could therefore form a very cost-effective measure if these barriers can be overcome. In our calculations, we assume that this is the case as a result of: 1) an increase in attention for ways to reduce carbon emissions (leading to more information) and 2) the availability of capital flows, including flows to developing countries, which could result from carbon trading (or other flexible mechanisms). Based on this, we assume a convergence of the pay-back-time criterion to six years as a function of the existing emission permit price – with full convergence at the highest price considered, i.e. 1000 US$/tCeq.

[xi] The actual tax profile chosen in FAIR is compared to the underlying the two TIMER “MACs”. On this basis, FAIR constructs a linear combination for the next time step of the two types of response curves. A rapidly increasing tax in FAIR implies that the profile resembles more the profile underlying the linear tax, while a more constant tax level in FAIR implies that the profile shows more resemblance to the block tax. In the former situation more emphasis is given to the MAC of the linear tax profile, while in the latter the block tax MAC is given more weight.

[xii] A pay-back-time is a simple investment criterion that indicates the time-period required to earn back the original investment. Research indicates that many actors are not aware of the energy efficiency improvement measures or face all kinds of implementation barriers. As a result, the average apparent pay-back-time of a sector is considerably lower than the investment criteria that are stated to be used by these actors (de Beer, 1998).

Carbon plantations

The MAC curves for carbon plantations have been derived using the IMAGE model (for methodology, see Graveland et al., 2002; Strengers et al., 2007). In IMAGE, the potential carbon uptake of plantation tree species is estimated for land that is abandoned by agriculture (using a 0.5 x 0.5 grid), and compared to carbon uptake by natural vegetation. Only those grid cells are considered in which sequestration by plantations is greater than sequestration by natural vegetation. In the calculations, we assumed that carbon plantations are harvested at regular time intervals, and that the wood is used to meet existing (commercial) wood demand. Regional carbon sequestration supply curves are constructed on the basis of grid cells that are potentially attractive for carbon plantations. These are converted into MAC curves by adding two kinds of costs: land costs and establishment costs. We found the cumulative abandoned agricultural area under the SRES scenarios to range from 725 and 940 Mha in 2100, potentially sequestering 116 to 146 GtC over the century (the term agricultural land in this chapter covers both cropland and pasture land). The costs of the reductions vary over a wide range.

Non-CO_2 gases

For non-CO_2 gases the starting point of our analysis consists of the MAC curves provided by EMF-21 (van Vuuren et al., 2006d; Weyant et al., 2006). This set is based on detailed abatement options, and includes curves for CH_4 and N_2O emissions from energy- and industry-related emissions, and from agricultural sources, as well as abatement options for the halocarbons. This set includes MAC curves over a limited cost range of 0 to 200 US$/tC-eq., and does not include technological improvements over time. Lucas et al. (2007) have extended this set on the basis of a literature survey and expert judgement on long-term abatement potential and costs. They assume that the long-term potential is significantly higher than current potential as a result of technology development and the removal of implementation barriers. The overall potential amounts to about 3 GtC-eq. annually (with the lion's share available below 200 US$/tC-eq.).

7.3.4 Emission pathways

This study uses the global multi-gas emission pathways that meet the GHG concentration stabilization targets 450, 550 and 650 ppm CO_2-eq. (den Elzen et al., 2006). As explained by Den Elzen et al., these emission pathways are different from hypothetical emission pathways constructed in some other studies, given the fact that at each point of time they are constrained by reduction potential of the MAC curves discussed above. As these curves aim to reflect technically feasible reductions, also the pathways can be considered as such. In that context, three additional criteria were used in developing the pathways:

- First, a maximum reduction rate was assumed, reflecting the technical (and political) inertia that limits emission reductions. Fast reduction rates would require early replacement of existing fossil-fuel-based capital stock, and this may involve high costs. The selected values (maximum 2-3% per year) are based on the reduction rates

Table 7.1 Default assumptions for various reduction options and the alternative assumptions used in the sensitivity analysis

Mitigation option	Pessimistic assumption	Base case	Optimistic assumption
Carbon plantations	Carbon uptake reduced by 25% + implementation factor reduced to 30%	Implementation factor is 40% (i.e. 40% of maximum potential is used).	Carbon uptake increased by 25% + implementation factor increased to 50%
Non-CO_2	20% increase in costs; 20% decrease in potential	Expert judgment as described in Lucas et al. (2007). Total reduction potential of non-CO_2 gases slightly above 50%.	20% decrease in costs; 20% increase in potential
Hydrogen	No hydrogen penetration	Default assumptions lead to hydrogen penetration by the end of the century in the baseline scenario.	Optimistic assumptions for fuels cells and H_2 production costs (10% reduction of investment costs) lead to penetration around 2050 (baseline scenario).
Efficiency improvement	Climate policies do not lead to removal of implementation barriers for efficiency.	Climate policies lead to some removal of implementation barriers for efficiency.	Climate policies lead to full removal of implementation barriers for efficiency.
Bio-energy	Less available land for bio-energy (50% less)		Bio-energy can also be used in combination with CCS technology.
Technology development	No climate policy-induced learning	Climate policy-induced learning	
Carbon capture and storage	No carbon capture and storage	Medium estimates for CCS storage potential (see Table A1)	
Nuclear	Nuclear not available as mitigation option	Nuclear available as mitigation option	
Emission trading	Emission trading restricted due to transaction costs of 15$/tC.	Full emission trading	
Land use	Agricultural yields do not improve as fast (following MA's Order from Strength Scenario).	Medium yield increases (following MA's Adaptive Mosaic Scenario).	Agricultural yields improve fast (following MA's Global Orchestration scenario).
Baseline	IMAGE 2.3 A1b	IMAGE 2.3 B2	IMAGE 2.3 B1
All	All above, excluding land use and baseline	All above, excluding land use and baseline	All above, excluding land use and baseline

Note: Not for all the options were more optimistic assumptions tested. The variation of baseline in this sensitivity analysis changes also storyline-related assumptions for other parameters.

of the post-SRES mitigation scenarios (e.g., Swart et al., 2002) and the lower range of published mitigation scenarios (Nakicenovic and Riahi, 2003; Azar et al., 2006).
- Secondly, the reduction rates compared to baseline were spread as far as possible over time –avoiding rapid early reduction rates.
- Thirdly, the reduction rates were only allowed to change slowly over time.

In the case of the 650 and 550 ppm CO_2-eq. goals, the resulting pathway leads to stabilization between 2100 and 2200 below the target level and without overshoot. For the 450 ppm CO_2-eq. concentration target, however, a certain overshoot (or peaking) is assumed. In other words, concentrations may first increase to 510 ppm before stabilizing at 450 ppm CO_2-eq. before 2200. This overshoot is justified by reference to present concentration levels, which are already substantial (430 ppm CO_2-eq, not accounting for sulfur aerosols and slightly below 400 ppm if sulfur is included). Overshoot is also justified by the attempt to avoid drastic sudden reductions in the emission pathways presented.

The FAIR model distributes the global emission across the different regions, gases and sources in a cost-optimal way, using the marginal abatement costs. Different gases are assumed to be substituted on the basis of Global Warming Potentials, an approach consistent with climate policies under the Kyoto Protocol and the US domestic climate policy (White-House, 2002). Chapter 6 of this thesis discusses the consequences of using a GWP-based approach.

7.4 Stabilizing GHG concentration at 650, 550, 450 ppm: central scenarios

7.4.1 Emission pathways and reductions

Under the central baseline, B2, worldwide primary energy use nearly doubles between 2000 and 2050 and increases by another 35% between 2050 and 2100. Most of this growth occurs in non-Annex I regions (about 80%). Oil continues to be the most important energy carrier in the first half of the century, with demand being mainly driven by the transport sector. Natural gas dominates new capacity in electric power in the first decades, but starts to be replaced by coal from 2030 onwards due to increasing gas prices. As a result, coal becomes the dominant energy carrier in the second half of the 21st century. Energy-sector CO_2 emissions continue to rise for most of the century, peaking at 18 GtC in 2080. Total GHG emissions[xiii] also increase, i.e. from about 10 GtC-eq. today to 23 GtC-eq. in 2100 (Figure 7.3). Figure 7.3 also shows that compared to the existing scenario literature; this baseline is a medium-high emission baseline. As a result of decreasing deforestation rates, CO_2 emissions from land use decrease. At the same time, CH_4 emissions, mostly from agriculture, increase. The GHG concentration

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[xiii] The term total GHG emissions in this report refers to all GHG covered by the Kyoto Protocol: i.e.CO_2, CH_4, N_2O, HFCs, PFCs and SF_6.

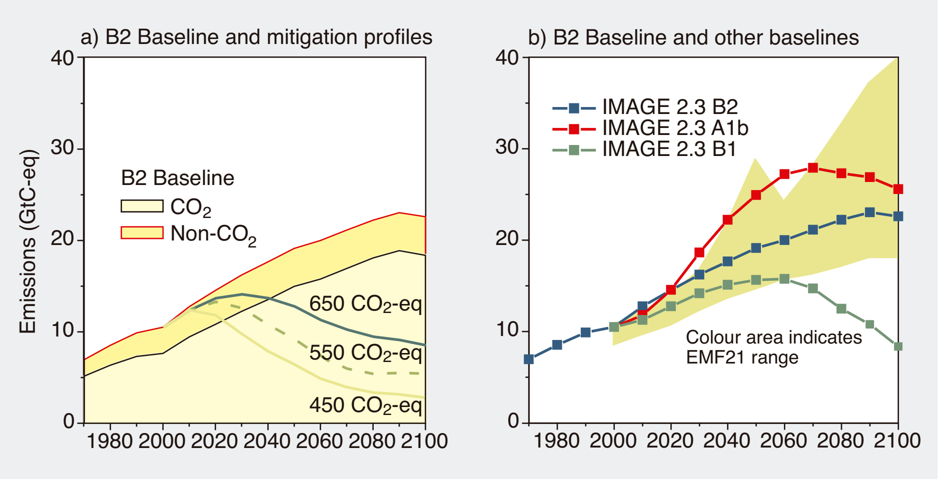

Figure 7.3 Global CO_2-eq. emissions (all sources$_2$) for the B2 baseline emission and pathways to stabilization at a concentration of 650, 550 and 450 ppm CO_2-eq. (panel a; left) and the B2 baseline emissions compared to alternative baselines (panel b; right). Sources:(van Vuuren et al., 2006d; Weyant et al., 2006), for EMF-21 scenarios.

reaches a level of 925 ppm CO_2-eq., leading to an increase in the global mean temperature of 3°C in 2100 (for a climate sensitivity of 2.5 °C, i.e. the equilibrium temperature increase for a doubling of GHG concentrations).

Figure 7.3a shows that in order to reach the selected emission pathway that leads to stabilization of GHG radiative forcing at 650, 550 and 450 ppm CO_2-eq., GHG emissions need to be reduced in 2100 by 65%, 80% and 90%, respectively, compared to the B2 baseline. The short-term differences are even more significant. In the case of the 650 ppm CO_2-eq. pathway, emissions can still increase slightly and stabilize at a level that is 40% above current emissions in the next 3 to 4 decades, followed by a slow decrease. In the case of the 550 ppm CO_2-eq. pathway, however, global emissions need to peak around 2020, directly followed by steep reductions in order to avoid overshooting the 550 ppm CO_2-eq. concentration level. For stabilization at 450 ppm CO_2-eq., short-term reductions become even more stringent, with global emissions peaking around 2015/2020 at a level of 20% above 2000 levels.

7.4.2 Abatement action in the stabilization scenarios

7.4.2.1 Abatement across different gases

Figure 7.4 shows the (cost-optimal) reduction in the mitigation scenarios in terms of different gases (upper panel). Table 7.2, in addition, indicates the emission levels. In all stabilization scenarios, a substantial share of the reduction is achieved in the short term by reducing non-CO_2 gases while only 10% of the reductions come from reducing energy-related CO_2 emissions (see also Lucas et al., 2005). The disproportionate contribution of non-CO_2 abatement is caused mainly by relatively low-cost abatement options that have been identified for non-CO_2 gases (e.g. reducing CH_4 emissions from

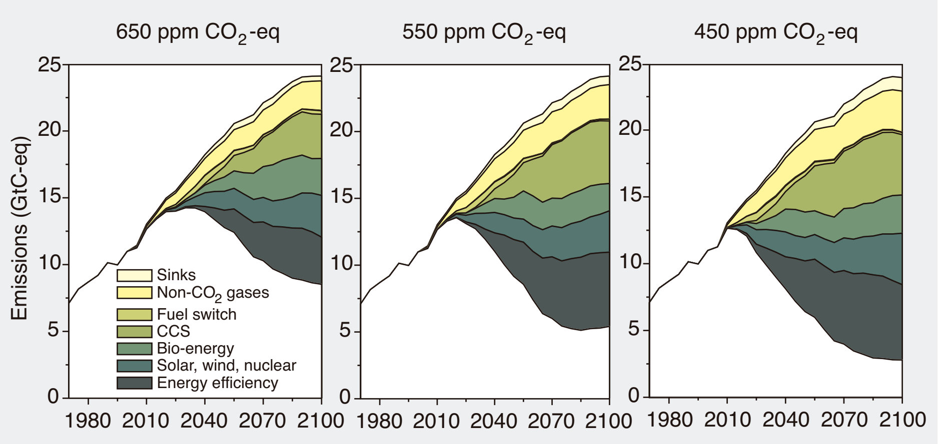

Figure 7.4 Emission reductions for total GHG emissions contributed by gas (upper panel; a) and for energy CO_2 emissions contribute by reduction measure category (lower panel; b) applied to stabilization scenarios at 650, 550 and 450 ppm CO_2-eq.

energy production and N_2O emissions from adipic and acidic acid industries). It should be noted that this is related to the fact that we use GWPs to determine the cost-effective mix of reductions among the different GHGs (see method section and Chapter 6 of this thesis). Alternative approaches, e.g. long-term costs optimization under a radiative forcing target, may result in a different mix (van Vuuren et al., 2006d). After 2015, more and more reductions will need to come from CO_2 in the energy system, increasing to 85% by 2100. This shift simply reflects that non-CO_2 represents about 20% of total GHG emissions and the limited reduction potential for some of the non-CO_2 gases. In addition, some non-CO_2 GHGs cannot be reduced fully due to limited reduction potential (this is the case for some sources of land-use-related CH_4 but is particularly true for some of the N_2O emission sources, see below). The proportion of non-CO_2 abatement does decline somewhat further in the 450 ppm CO_2-eq. scenario than in the 650 ppm CO_2-eq. scenario (with the proportion being limited by the absolute non-CO_2 reduction potential).

More detailed analysis across the different sources shows that for CH_4 relatively large reductions are achieved in for the sources landfills and the production of coal, oil and gas. In total, under the 450 ppm CO_2-eq. stabilization scenario, emissions are reduced by 70% compared to the baseline. In the less stringent 650 ppm stabilization case, CH_4 emissions are halved (returning roughly to today's levels). In the case of N_2O, substantial reductions are achieved for acidic and adipic acid production (up to 70% reduction). However, in comparison to land-use related N_2O emissions, this only represents a small source. For the land-use-related N_2O sources, emission reduction rates are smaller. As a result, total N_2O emission reductions in the strictest scenario amount to about 35% compared to baseline. In the most stringent case, emissions of halocarbons are reduced to almost zero for the group as a whole. In the other two scenarios, considerable reduction rates are still achieved.

Table 7.2 Emissions in 2000 and in 2100 for the B2 baseline and the stabilization scenarios

	2000	2100			
		Baseline	Stabilization scenarios (ppm CO2-eq.)		
			650	550	450
			GtC-eq.		
CO_2 energy/industry					
Electricity sector	2.38	7.96	1.04	0.23	0.09
Industry	0.62	1.54	0.38	0.18	0.03
Buildings	0.50	0.80	0.32	0.23	0.06
Transport	0.79	2.48	0.69	0.32	0.03
Other	0.79	2.11	0.82	0.40	0.15
Total	**6.96**	**18.40**	**5.20**	**2.50**	**0.94**
CO_2 land use	0.90	0.10	0.75	0.67	0.77
CH_4	1.88	3.02	1.33	1.11	0.91
N_2O	0.68	1.03	0.81	0.78	0.69
F-gases	0.14	0.87	0.35	0.27	0.04
Total	**10.56**	**23.42**	**8.44**	**5.33**	**3.35**

The use of carbon plantations contributes about 0.9 GtC annually to the overall mitigation objective in 2100 in the 450 ppm CO_2-eq. scenario, but less in the other two scenarios (0.5 and 0.25 GtC annually). All three scenarios, East Asia, South America and the Former Soviet Union, together account for more than 50% of the carbon plantation mitigation effort (regional detail not shown in figures – but can be found in Strengers et al. (2007)). The trees used vary according to the location and include *Populus nigra* (East Asia and Europe), *Picea abies* (Canada, USA and former USSR) and *E. grandis* (South America, Central Africa and Indonesia). In all three scenarios, high sequestration rates (more than 0.1 GtC annually) are achieved only after 2030-2035 due to the fact that we only allow sinks on abandoned agricultural land, a possibility not available early on. Some of the mitigation by carbon plantations can be achieved at relatively low costs, forming a substantial part of the potential used in the 650 ppm CO_2-eq. stabilization scenario. As a result, the use of carbon plantations depends more on external assumptions (demand for land for food production, yield increases) than on the stabilization target.

7.4.2.2 Abatement action in the energy system

Figure 7.5 shows that the climate policies required to reach the stabilization pathways lead to substantial changes in the energy system compared to the baseline scenario (shown for 450 ppm CO_2-eq.). These changes are more profound when going from 650 to 450 ppm CO_2-eq. In the most stringent scenario, global primary energy use is reduced by around 20%. Most of this reduction occurs in the 2015-2040 period as a result of a rapidly increasing carbon tax. Clearly, the reductions are not similar for the different energy carriers. The largest reductions occur for coal, with the remaining coal consumption being primarily used in electric power stations using CCS. There is also a substantial reduction for oil. Reductions for natural gas are less substantial, while other

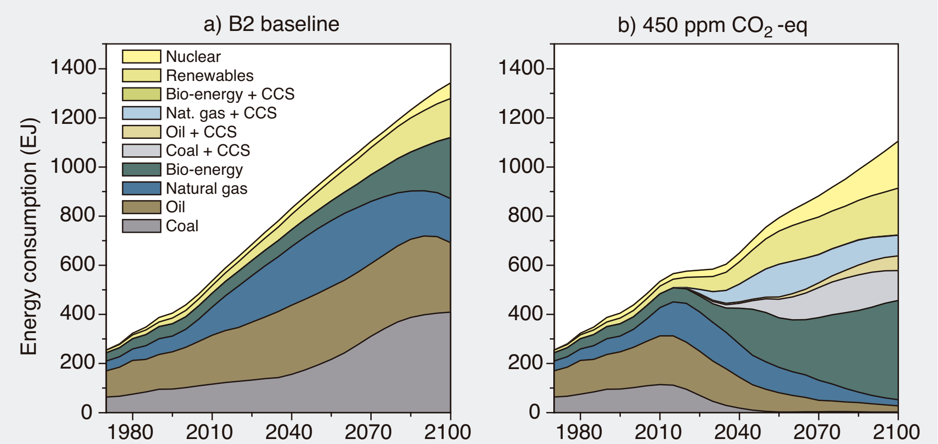

Figure 7.5 Primary energy use in the B2 baseline (left; panel a) and the 450 ppm CO_2-eq. stabilization scenario (right; panel b). Note: Nuclear, solar, wind and hydro power have been reported at a virtual efficiency of 40%; "bio-energy" includes traditional bio-energy; renewables include hydro, solar and wind power.

energy carriers – in particular, solar, wind and nuclear-based electricity and modern biomass – gain market shares.[xiv]

The largest reduction in the energy sector results from changes in the energy supply (Figure 7.4; lower panel). Some changes stand out. First of all, under our default assumptions, CCS – mainly in the power sector – accounts for a major proportion of the emission reductions (up to a third of the reductions in energy-related CO_2 emissions). As a result, large amounts of CO_2 are stored. In the 650 ppm case, 160 GtC, or about 2 GtC annually on average, needs to be stored, mainly in empty gas and oil fields. In the 550 and 450 cases, these numbers are 250 GtC and 300 GtC, or about 3 GtC annually. Here, we use medium estimates of storage capacity (around 1000 GtC) but estimates in the low range are in the order of 100 GtC (Hendriks et al., 2002a). In the more densely populated regions, we find that under our medium assumptions reservoirs from depleted fossil fuel resources will be filled near the end of the century so that these regions will also use aquifers as a storage option[xv]. The decreasing reservoir capacity will lead to slightly higher costs. It should be noted that CCS technology still has to be proven in large-scale application – and safe aquifer capacity (with sufficiently low leakage risks) is uncertain.

[xiv] Modern biomass includes gaseous or liquid fuels produced from plants or trees. It differs from traditional biomass, which refers to gathered wood, straw, dung, charcoal, etc.

[xv] In our analysis we have used the reservoir estimates of Hendriks et al. 2002, including their estimates for aquifers. Hendriks et al. (2002) restricted the potentially available storage capacity in aquifers strictly based on safety requirements for storage. Still, one might argue that the reservoir estimates for aquifers are more uncertain than those for (empty) fossil fuel reservoirs.

Bio-energy use also accounts for a large proportion of the emission reductions. In the baseline scenario of this study about 200 EJ of bio-energy are used. In the most stringent stabilization scenario, bio-energy use increases to 350 EJ. In terms of crops, the bio-energy is produced from a mixture of sources (sugar cane, maize, woody bio-energy and residues, depending on the region). The use of bio-energy in most cases requires land where, in the baseline, there would be natural vegetation sequestering carbon (see Section 7.5.2). The decrease in carbon sequestration by bio-energy production compared to natural vegetation re-growth amounts to about 1–5 kg C per GJ of bio-energy produced, depending on the region and biome (this number represents the annual average across the whole scenario period, by taking the cumulative bio-energy production and the cumulative difference in carbon uptake between the land used for bio-energy production and the original vegetation). This compares to standard emission factors of 25 kg C per GJ for coal, 20 kg C per GJ for oil and 15 kg C per GJ for natural gas. The contribution indicated in Figure 7.4 is the net contribution.

Solar, wind and nuclear power also account for a considerable proportion of the required reductions (it should be noted that we assume that solar, wind, nuclear and hydro power do not lead to GHG emissions; an assumption that is not always correct). In our baseline scenario, the application of renewables (i.e. hydro, wind and solar power) is considerably larger than that of nuclear power (based on current policies and costs). In the mitigation scenarios, both categories increase their market share. For hydro power, we assumed no response to climate policy, given the fact that in the baseline most regions are already approaching their maximum potential levels and that investments into hydropower are often related to other objectives than energy alone. As a result of their intermittent character, the contribution of solar and wind power is somewhat limited by a declining ability to contribute to a sufficiently reliable electric power system at high penetration rates. As a result, the increase in nuclear power shown in the model compared to the baseline is larger than that of renewables. The finding that under climate policy, nuclear power could become a competitive option to produce electric power is consistent with several other studies (MIT, 2003; Sims et al., 2003). However, more flexible power systems, different assumptions on the consequences of intermittency for renewables, the development of storage systems, technological breakthroughs or taking account of public acceptance of nuclear power could easily lead to a different mix of nuclear power, solar and wind power and CCS technologies (and still lead to a similar reduction rate).

Energy efficiency represents a relatively important part of the portfolio early on in the century – but a much smaller share compared to baseline later on. The main reason for the decreasing impact is that the (assumed) cost reductions with zero carbon energy supply options reduce the effectiveness of energy efficiency measures. In addition, the fact that energy efficiency will be closer to the technology frontier in many parts of world will slow down further improvement. Globally, energy use is reduced in 2100 by about 10% in the 650 ppm case and about 20% in the 450 ppm case (see Figure 7.4). The contribution of efficiency differs strongly by region and over time. In Western Europe, for instance, the annual rate of real efficiency improvement in the model in the baseline is about 1.1% per year in the first half of the century, and 0.8% per year over the century as a whole. These numbers refer to the underlying efficiency indicators in the model (see Chapter 2), not the energy intensity (energy over GDP) that improves even somewhat faster due to structural change. The increased energy prices under climate policies in combination with the reduction of investment barriers could raise the numbers to 1.5% and 1.0% per year, respectively, in the 450 ppm CO_2-eq. scenario. In India, climate policy could have a much larger impact. Here, baseline efficiency improvement is assessed at 2.2% per year in the first 40 years and 1.8% per year over the century. Climate policies could push up these numbers to 2.9% per year and 2.1% per year respectively.

An alternative way to look at these data is to use the Kaya indicators of energy intensity (GJ/$) and the carbon factor (kg C/GJ) (Kaya, 1989). Under the baseline scenario, energy intensity improves significantly by about 70% worldwide between 2000 and 2100. The carbon factor remains virtually constant (in line with historic trends). It is only in the last few decades that some decarbonization occurs as high oil prices induce a transition to bio-energy. This implies that in the baseline scenario energy intensity improvement is the main contributor to decreasing the ratio between CO_2 emissions and GDP growth. In the mitigation scenarios, the rates increase for both energy intensity and carbon factor improvement. While the contribution of the two factors to emission reductions compared to baseline levels is about the same in 2020, changes in the carbon factor compared to baseline (in other words: changes in energy supply) in 2050 and 2100 contribute much more to lower emission levels than energy intensity. This can be seen in Figure 7.6 by the fact that in 2020 the mitigation scenario points are moved parallel to the diagonal compared to the baseline scenario points, while in 2050 and 2100 they move strongly in the direction of carbon factor increases. Under the 450 ppm scenario, the carbon factor decreases by about 85% compared to baseline by the end of the century.

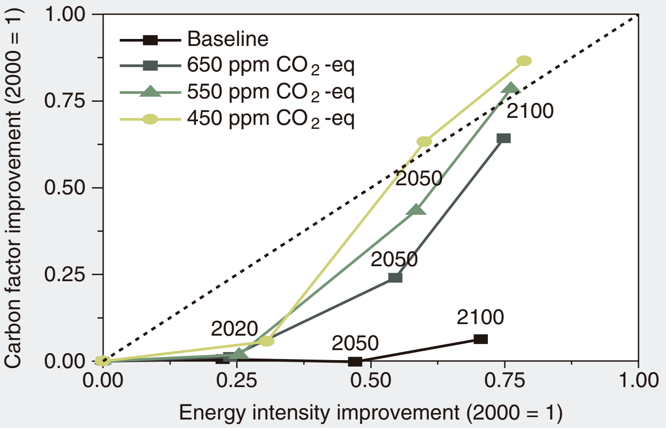

Figure 7.6 Relative changes in global energy intensity (energy/GDP) and the carbon factor (CO_2/energy) in the B2 baseline and the three mitigation cases compared to 2000 values. Note: The diagonal line indicates equal reduction in the energy intensity and carbon factor compared to 2000. Values are indicated for all the scenarios: 2020, 2050 and 2100.

7.4.3 Costs

7.4.3.1 Abatement costs

As cost measures, we will focus on permit prices and abatement costs. The latter are calculated on the basis of the surface under marginal abatement cost curves and represent the direct additional costs due to climate policy, but do not capture macro-economic costs or feedbacks (nor the avoided damages of climate change). Figure 7.7 shows that the scenarios involving stabilization at 650 and 550 ppm CO_2-eq. ppm are characterized by a rather smooth increase in the permit price, followed by a drop by the end of the century. This drop is caused by a fall in emissions in the baseline and further cost reductions in mitigation technologies (in particular, hydrogen fuel cells start entering the market by this time, allowing for reductions in the transport sector at much lower costs). For the 450 ppm stabilization scenario, the price rises steeply during the first part of the century – reaching over 600 US$/tC-eq. by 2050 – and finally stabilizes at 800 US$/tC-eq. by the end of the century. The high price is particularly necessary to reduce emissions from the more non-responsive sources such as CO_2 emissions from transport or some of the non-CO_2 emissions from agricultural sources, while other sources, such as electric power, already reduce their emissions to virtually zero at a permit prices of “only” 200-300 US$/tC-eq.

Costs can also be expressed as abatement costs as a percentage of GDP. This indicator is shown over time (Figure 7.7; right panel), and accumulated across the century (net present value; discounted at 5%) (Figure 7.8). In the 650 ppm CO_2-eq. stabilization scenario, costs first increase to about 0.5% of GDP, after which they decline slightly to about 0.3% of GDP. This reduction is caused by an increase in global GDP and a stabilization of climate costs due to a somewhat lower permit price and a stabilizing emission gap between baseline and the mitigation scenario. The same trend is observed for the

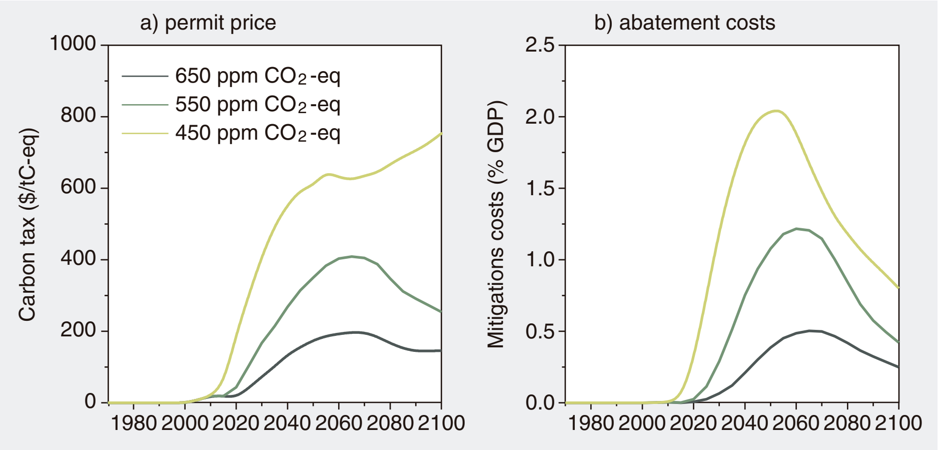

Figure 7.7 Marginal carbon-equivalent price for stabilizing greenhouse gas concentration at 650, 550 and 450 ppm CO_2-eq. from the B2 baseline (left; panel a) and abatement costs as a percentage of GDP for these scenarios (right; panel b).

other stabilization scenarios, although at higher costs. The abatement costs of the 550 ppm CO_2-eq. stabilization scenario increase to 1.2% of GDP, while the abatement costs of the 450 ppm CO_2-eq. stabilization scenario increase to 2.0% of global GDP. The direct abatement costs of about 0–2.5% of GDP can be compared to the total expenditures of the energy sector (which, worldwide, are about 7.5% of GDP today and expected to remain nearly constant under our baseline) or to the expenditures on environmental policy (in the EU around 2.0–2.8%, mostly for waste and wastewater management).

The net present value of the abatement costs follow a similar trend (across the different stabilization levels), as described above for the costs over time (Figure 7.8). For default baseline (B2), the costs vary from 0.2% of GDP for stabilization at 650 ppm to 1.1% of GDP in the 450 case.

7.4.3.2 Changes in fuel trade patterns

Figure 7.9 shows the imports and exports of different fuels in 2050. The clearest differences are found in the oil and coal trades, which are greatly reduced as a result of lower consumption levels. So, on the one hand, oil-exporting regions will see their exports reduced by a factor of about 2–3. On the other hand, the oil imports of importing countries are significantly reduced. Interestingly, natural gas trade is hardly affected because natural gas will be used in combination with CCS. An interesting aspect is the role played by the bio-energy trade. This trade increases substantially, a factor that major exporting regions (including, for instance, South America and the Former Soviet Union) could benefit from. Currently, oil-importing regions (such as the USA, Western Europe and Asia) could become major bio-energy importing regions. Obviously, the changes in fuel trade depicted here also lead to substantial changes in the financial transfers related to fuel trade (significantly impacting regional costs and benefits of climate policy).

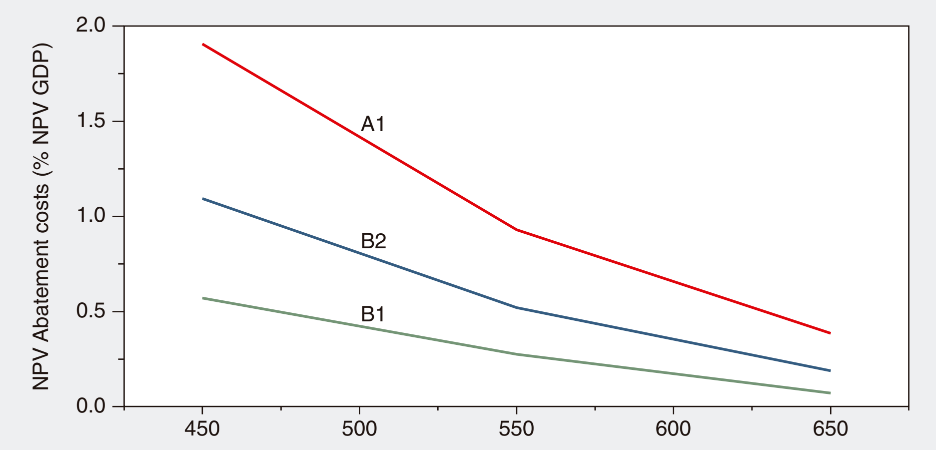

Figure 7.8 Net Present Value (NPV) of abatement costs for different stabilization levels as percentage of the NPV of GDP, starting from different baseline scenarios (discount rate 5%).

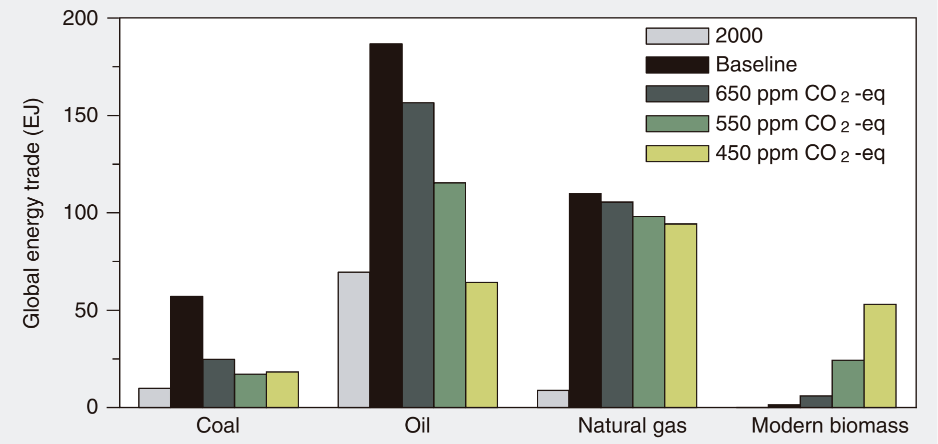

Figure 7.9 World volume of fuel trade between the 17 world regions (EJ) in 2000 and 2050. Baseline (B2) and stabilization scenarios (650, 550 and 450 ppm CO_2-eq)

7.5 Benefits and co-benefits

7.5.1 Climate benefits of stabilization

The three multi-gas stabilization scenarios analyzed here lead to clearly different temperature increases, both during this century and in the long term. Table 7.3 shows some of the parameters, describing the different scenarios in more detail and using a single value for climate sensitivity (2.5°C). The table shows that, in 2100, the 650 and 550 ppm CO_2-eq. stabilization scenarios are still approaching the stabilization levels, while the 450 ppm CO_2-eq. scenario has, in fact, overshot its target (as designed) and is approaching its target from a higher concentration level (the 2100 CO_2-eq. concentration is 479 ppm). For CO_2 only, our three scenarios generate CO_2 concentrations of 524, 463 and 424 ppm for 2100 and this is indeed on the lower side of existing CO_2-only stabilization scenarios in the literature.

It should be noted, however, that the temperature results of the different stabilization scenarios do depend to a considerable extent on the uncertain relationship between the GHG concentration and temperature increase. This implies that impacts on tem-

Table 7.3 Overview of several key parameters for the stabilization scenarios explored

	Concentration in 2100 (in ppm)		*Reduction of cumulative emissions in 2000-2100 period*	*Temperature change (in °C)*	
	CO_2-eq.	*CO_2*	*%*	*2100*	*Equilibrium*
B2	*947*	*708*	*0*	*3.0*	*-*
B2 650 ppm CO_2-eq.	*625*	*524*	*36*	*2.3*	*2.9*
B2 550 ppm CO_2-eq.	*538*	*463*	*50*	*2.0*	*2.5*
B2 450 ppm CO_2-eq.	479	424	61	1.7	2.0

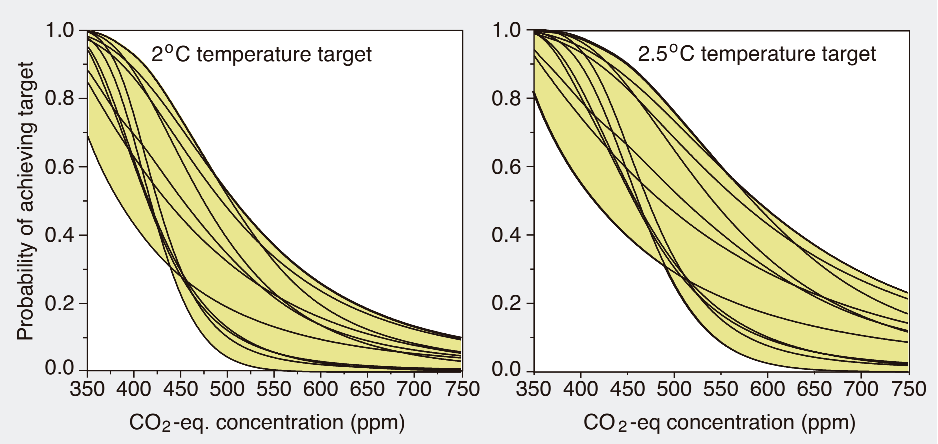

Figure 7.10 Probability of equilibrium temperature change staying within the 2°C or 2.5°C limit compared to pre-industrial for different CO_2-eq. concentration levels compared to pre-industrial (following calculations of (Meinshausen, 2006). Note: The lines indicate the probability function as shown in the individual studies quoted by (Meinshausen, 2006); the grey area indicates the total range from the highest and lowest studies.

perature can better be expressed in probabilistic terms. Figure 7.10 shows, on the basis of the work of Meinshausen (2006), the probabilities of overshooting a 2°C and a 2.5°C target in the light of the different stabilization levels explored in this chapter (the corridor shown is a result of Meinshausen's consideration of several PDFs published in the literature). In the case of a 2°C target, stabilizing at 650 ppm gives a probability of meeting this target between 0 and18%, depending on the PDF used. By contrast, stabilizing at 450 ppm results in a probability range of 22-73%. Similar numbers apply to a 2.5°C target. Here, 650 ppm provides a probability range of 0-37%, and 450 ppm, a range of 40-90%.

Although we have not specifically targeted any rate of temperature change, a rate can be a useful proxy for the risk of adverse impacts from climate change (in particular, ecosystems) (see Figure 7.11). In the baseline scenario, the rate of temperature change is around 0.25°C per decade. In the mitigation scenarios, the rate of temperature increase drops significantly, particularly in the second half of the century. In the 650 ppm stabilization scenario, the rate drops below 0.2°C per decade around 2050 and below 0.1°C in 2080. In the 550 and 650 stabilization scenarios, the rate of change drops even further while, for 450 ppm CO_2-eq., the rate actually falls below zero in 2100.

In the early decades (up to 2030), the mitigation scenarios hardly perform any better than the baseline. The reason is that, in the mitigation scenarios, changes in the energy system to reduce CO_2 emissions also lead to a reduction in sulfur cooling (as already emphasized by Wigley, (1991)[xvi]. In our earlier calculations, in fact, this could even lead to an temporarily higher rate of temperature increase for some of our mitigation scenarios compared to baseline (van Vuuren et al., 2006b). The somewhat smaller impact

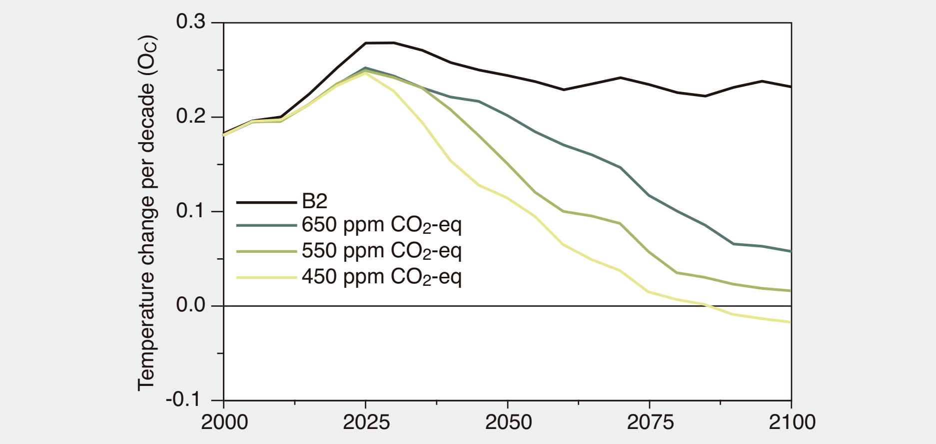

Figure 7.11 Rate of temperature change for 2000-2100 assuming a 2.5°C climate sensitivity.

here is mostly due to the increased potential for reducing non-CO_2 GHGs in combination with the higher overall rates of GHG emission reduction. By using GWPs as the basis of substitution between the different greenhouse gases, our method evaluates CH_4 emission reduction as relatively cheap compared to reducing CO_2 (see also (van Vuuren et al., 2006d). As reducing CH_4 is much less coupled to reducing sulfur and the impact of reducing CH_4 on radiative forcing is much more direct, the high degree of CH_4 reduction in our scenarios mitigates the impact of reduced sulfur cooling. This is somewhat comparable to the "alternative" mitigation scenario suggested by Hansen et al. (2000).

7.5.2 Co-benefits and additional costs

7.5.2.1 Impacts on regional air pollutants

Many air pollutants and GHGs have common sources. Their emissions interact in the atmosphere and, separately or jointly, cause a variety of environmental effects on local, regional and global scales. Emission control strategies that simultaneously address air pollutants and GHGs may therefore lead to a more efficient use of resources on all scales (so-called co-benefits). Current studies indicate that, when climate policies are in place, potential co-benefits could be substantial in the short-term (in particular the Kyoto period), with financial savings in the order of 20–50% of the abatement costs of the climate policy (see Chapter 9 of this thesis). In this study, we have focused our analysis on the consequences of climate policies for SO_2 and NO_x emissions by using the same emission coefficients for SO_2 and NO_x as those assumed under the baseline (reflecting similar policies for emissions of these substances). We also aimed at simply quantifying the impact of changes in the energy system on emissions.

[xvi] The impact of sulfur emissions on temperature increase is calculated in IMAGE on the basis of a pattern-scaling methodology that was developed by (Schlesinger et al., 2000).

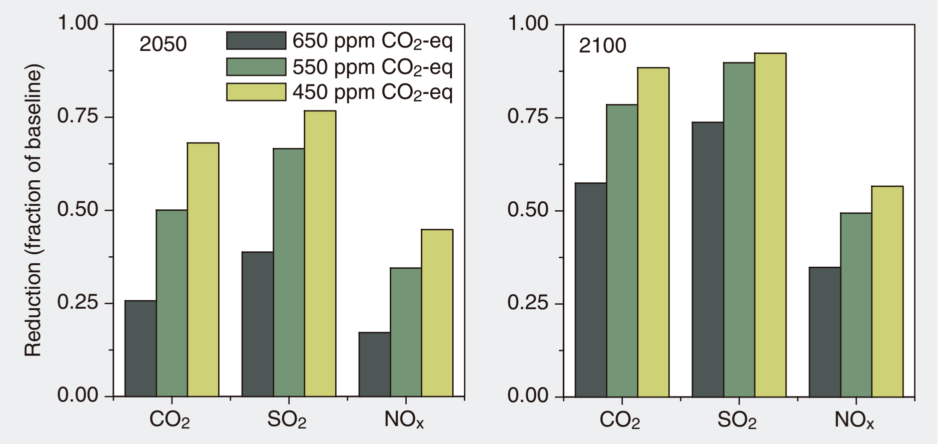

Figure 7.12 Reduction of CO_2, SO_2 and NO_x emission compared to baseline (0% is no reduction; 100% is full reduction) in the 3 B2 stabilization scenarios (2050 on left; 2100 on right).

Figure 7.12 shows that the changes induced by climate policy in the energy system to reduce CO_2 emissions also reduce SO_2 emissions, in particular at lower reduction levels. This can be explained by the fact that coal, in particular, is used in conventional power plants, contributing to an even larger proportion of SO_2 emissions than of CO_2 emissions. Phasing out conventional fossil-fired power plants and reducing oil inputs into transport, and replacing them by either fossil plants with CCS or renewables, does significantly reduce SO_2 emissions. In the case of NO_x, there is a similar relationship between CO_2 emission reductions and NO_x emission reductions – although here NO_x emissions reductions are smaller than those of CO_2. The figures show that there are clear co-benefits for regional air pollution resulting from climate policy. In low-income countries, a focus on the potential synergies of climate change policies and air pollution policies could be even more important than in high-income countries. Synergy effects of climate policies on regional and urban air pollution may, in fact, be a reason for non-OECD countries to contribute to early emission reductions.

7.5.2.2 Impacts on Land Use

Several of the mitigation options considered have an impact on land use. Table 7.4 describes land use under the three main mitigation scenarios. As explained in the methods section, for bio-energy crops the modeling system may use 60% of the abandoned agricultural land and 25% of natural grassland or similar biomes. Carbon plantations may use 40% of abandoned agricultural land. The potential thus does not include the land currently used for food production nor does it include forests. It should be noted that land impacts of other energy options (e.g. wind power, solar power, hydro power, fossil fuel production) have not been accounted for, but these are small compared to those of bio-energy and carbon plantations.

In our scenarios significant amounts of agricultural land (for food production) are abandoned through the simulation period. In the first half of the century, this occurs in OECD regions and the Former Soviet Union – mostly as result of a stabilizing food demand (due to a stabilizing population) and continuing yield increases (see (IMAGE-team, 2001; Rosegrant et al., 2002; Strengers et al., 2004). In some developing regions (e.g. East Asia) similar dynamics may result in the availability of abandoned agricultural land in the second half of the century (Strengers et al., 2004). This result obviously depends on the yield improvements that are assumed in the scenarios.

In the mitigation scenarios, the most significant change compared to the baseline is the increased demand for land for bio-energy: from 3.9 million km^2 in the baseline scenario to 9.3 million km^2 in the 450 ppm CO_2-eq. stabilization scenario. This means that the bio-energy crop area is equal to about 50% of the total food and feed crop area in 2100. Most of this land is located in the former Soviet Union, South America, and the USA and, in the second part of the century, East Asia (see also Hoogwijk et al., 2004). In 2100, carbon plantations occupy about 2.6 million km^2 (about 5% of all forest at that time). Here, most of the land is in the former Soviet Union, South America and again East Asia (Strengers et al., 2007). It should be noted that the agricultural land area for food and feed crops increases slightly. Although we have not included agricultural land in our bio-energy and carbon plantation potential, in the actual scenario implementation some conflicts may still occur (the model chooses at any point in time the most attractive area for each option that requires land).

Moreover, reducing the CO_2 concentration also reduces the carbon fertilization effect. The total “domesticated” area increases by nearly 20% while, in the baseline, land use in 2100 is virtually equal to land use in 2000. Land use does not differ much for the different stabilization scenarios as most of the bio-energy and carbon plantation potential is also used as part of the portfolio for stabilization at less ambitious levels.

The question of whether the land-use consequences shown here lead to a similar loss of biodiversity is a more difficult one. The area used for bio-energy production and carbon plantations is mostly abandoned agricultural land, including both crop and pasture land, with a considerable area coming from natural grass land. In the former case, secondary forest would, at best, have grown in these locations. Although others have pointed out that, in many cases, land is not likely to recover automatically, in which case it will be transformed into degraded land. Moreover, it is to some degree possible to combine biodiversity targets and carbon plantations. The impact on biodi-

Table 7.4 Land use under the baseline (IMAGE 2.3 SRES B2 scenario) and mitigation scenarios in 2100 (million km^2)

	Baseline	650 ppm CO2-eq.	550 ppm CO2-eq.	450 ppm CO2-eq.
Agricultural land	43.5	44.7	45.3	45.6
Land for bio-energy	3.9	9.3	9.3	10.2
Land for carbon plantations	0.0	1.6	2.2	2.6
Total	47.4	55.5	56.7	58.3

versity, therefore, is likely to be much smaller than the reduction suggested by looking at the land-use impacts alone.

7.6 Uncertainties in stabilizing emissions

In the discussion of the existing literature in Section 7.2, it was concluded that there are several categories of uncertainties that can substantially influence the results of stabilization scenarios. Here, we will discuss two of these: the baseline scenario and specific assumptions for individual technologies.

7.6.1 Reducing emissions from different baselines

Four scenario families were developed in the SRES report. Of these, the B2 scenario represented the most average development. The A1b and B1 families lead to higher and lower emissions respectively. Hourcade and Shukla (2001) showed the baseline to be just as important for mitigation costs as stabilization levels. We have therefore explored the influence of costs here on the basis of the implementation of these scenarios in the IMAGE 2.3 model. It should be noted that we have not included the A2 scenario. The reason is that the storyline of this scenario, i.e. little international cooperation and little focus on environmental issues, provides a very unfavorable situation for climate policy to be developed.

The A1b scenario leads to far higher per capita energy use than B2, although it has a lower population level and a lower share of coal in total energy use. Total GHG emissions are substantially higher than the B2 level, at around 26 GtC-eq. in 2050 and 25 GtC-eq. in 2100. The B1 scenario, by contrast, results in much lower energy use as a result of greater efficiency and lower population levels. Here, total GHG emissions peak at around 2050 at 15 GtC-eq. and decline thereafter to 8 GtC-eq. in 2100. As a result, the emission reduction objectives for the different stabilization levels are higher for the A1b scenario and lower for the B1 scenario (see also Figure 7.3).

The costs of stabilization from these baselines for the low-range stabilization targets explored in this study are shown in Figure 7.8. As expected on the basis of higher baseline emissions, abatement costs for the A1b scenario are higher than those for the B2 scenario. In fact, the NPVs of abatement costs for each of the A1b stabilization cases are about double the costs of the corresponding B2 cases. By contrast, the costs of stabilization for B1 are substantially lower. In addition, across the range considered here, costs rise more slowly for B1 than for A1b and B2 as a result of the smaller absolute gap between baseline emissions and the emissions under the stabilization case, the high technology development rate and the resulting lower prices.

7.6.2 Sensitivity to key assumptions for abatement options

Our analysis takes a wide range of abatement options into account. In all cases, the reduction potential and costs are subject to considerable uncertainties. The long time scale used (100 years) implies that assumptions need to be made about technology development, implementation barriers and fundamental changes in the system as a whole; these may either assist or hinder certain reduction measures. As the uncertainties with regard to the individual options accumulate in our combined assessment, we have therefore performed a sensitivity analysis for the 550 ppm CO_2-eq. stabilizing scenario, as indicated in Table 7.1. The results are shown in Figure 7.13.

In the case of emissions from the *energy sector*, one set of critical uncertainties include factors such as the rate of technology change, lifestyle, economic growth and population dynamics. The impacts of these "storyline-related" uncertainties have been explored earlier as part of the influence of the baseline scenario (A1b and B1) and taken together could impact costs by at least a factor of 2. However, several other important uncertainties exist. As pointed out by Edmonds et al. (2004), the development of hydrogen technology itself is not strongly influenced by climate policy. However, once hydrogen is part of the system, stronger reductions are feasible than without hydrogen, given the fact that hydrogen can – at relatively low additional cost – be produced without GHG emissions (Edmonds et al., 2004; Van Ruijven et al., in press). In the analy-

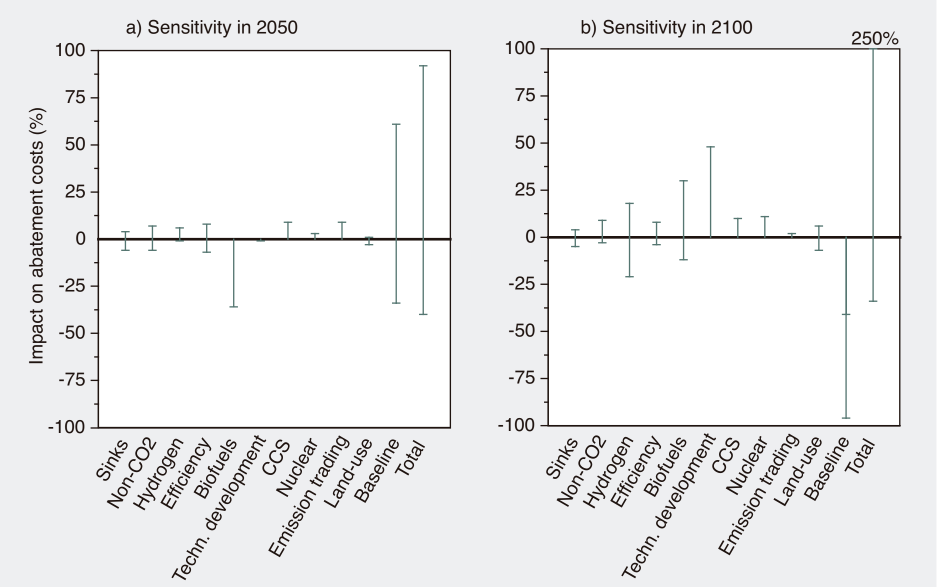

Figure 7.13 Impacts of different uncertainties on global abatement costs (compare to Figure 7.8) for stabilization at 550 ppm CO_2-eq., 2050 (left) and 2100 (right). The column total is restricted to the assumptions that only impact the stabilization scenario, and therefore does not include the impacts of baseline and land-use.

sis, therefore, we explored the impact of a scenario with no hydrogen (a pessimistic assumption) and a scenario with large-scale penetration of hydrogen. The sensitivity to these assumptions was found to be small in 2050 (as the system hardly contains hydrogen) but substantial in 2100 (20% difference in abatement costs either way).

Another important uncertainty concerns the potential of, and technology used for, bio-energy. As shown by Hoogwijk (2004), the uncertainty relating to bio-energy supply results in figures for potential use of between 100 and 800 EJ. In our central assumptions, the bio-energy use is about 400 EJ. We have lowered supply in our sensitivity runs for the pessimistic case. Azar et al. (2006) have shown that including the option of Bio-Energy and Carbon Storage (BECS) can reduce costs at low concentration levels by at least 50%. We will therefore use BECS for the high end of our range. Figure 7.13 shows that this is, in fact, a very important uncertainty, influencing costs by about 40% downward (in the case of BECS) or 30% upwards (in the case of restricted bio-energy supply). The influence of BECS is relatively low in the long term as the analysis is done for the 550 ppm stabilization scenario – for which the reduction requirement in the long term is still relatively low compared to the number of reduction options.

Another uncertainty relates to the contribution of energy efficiency. In the default run, we assumed that the permit price and international emissions trading would lead to a convergence of investment criteria in energy efficiency worldwide towards levels that currently also apply to energy supply. In our sensitivity analysis, these assumptions ranged from full convergence towards supply-side criteria to no convergence. The influence of this factor is shown to be relatively modest – and to influence costs in 2100 by about 10% either way.

The results show that the cost-optimal implementation of the stabilization scenarios includes the large-scale use of CCS and nuclear power. For both options, not only do technological uncertainties play an important role, but also social acceptability; for instance, at the moment several countries have indicated that they will not build new nuclear power plants. In this context and as a form of sensitivity analysis, we excluded both options (one by one). In each case, costs for 2100 are about 10% higher. In 2050, the influence on costs is smaller. The reason for the relatively small impact is that by excluding only one option, the electric power sector still has enough reduction potential left to effectively respond to climate policy.

Another uncertain factor is induced technology change (in terms of investment costs) in response to climate policy. This factor is described by learning curves in the default run for solar, wind and nuclear power, bio-energy conversion, hydrogen production technologies, production of oil, natural gas and coal, and costs of energy efficiency. In Chapter 8, we will show that most of the “learning” already occurs under the baseline scenario; the additional learning that results from the investments induced by climate policy is (in most cases) smaller than the baseline improvements (see also (van Vuuren et al., 2004)). In the sensitivity run, we set this second factor, induced technology change, at zero, implying that technology change in the mitigation scenario is equal to baseline development. While this factor is not important in 2050, it still represents a major uncertainty in the long term (around 50% increase in cost), as shown in Figure 7.13.

The effect of several crucial parameters that work directly on the supply and cost of *carbon sequestration through plantations* was examined in Strengers et al. (2007). These parameters are the CO_2 fertilization factor, the harvest regime, land costs, land use, the establishment costs, the discount rate and the increased growth rates of managed trees over natural trees (additional growth factor). Of these, the last factor proved to have the most impact on outcomes. If the additional growth factor is reduced by 20%, potential sequestration by carbon plantations is found to fall by about 37% and average cost of sinks to increase sharply. On the other hand, an increase of 20% results in 33% more sequestration potential and a cost decrease of 35%. Another important factor is the degree to which areas suitable for carbon plantation can actually be used for that purpose. A shortage of planting material, lack of knowledge and experience, other priorities for the land (e.g. bio-energy), etc. may reduce the abandoned agricultural area that can actually be planted. Waterloo et al. (2001) estimated that, in the case of CDM under the Kyoto Protocol, only 8% of the potential area would actually be available. This number could increase in time and with increasing permit prices. As a result, in our standard runs, we defined an exogenous implementation factor equal to 40% of the total potential. In the sensitivity runs, this factor varied between 20% and 50%, respectively. However, the impact of these assumptions on overall global costs is relatively minor given the small contribution of carbon plantations to the total portfolio of reduction measures (about 5% of cost increase or decrease, both in 2050 and 2100).

The *non-CO_2 emission reduction potential* is based on the EMF-21 database and extrapolated for the period up to 2100 on the basis of assumptions on technological developments, and maximum reduction potentials and accompanying costs. The assumptions about the maximum reduction potentials have the most impact on the final outcomes. To assess this impact from a pessimistic perspective, we reduced the reduction potential by 20% - and increased costs by 20%. In the optimistic case, we assumed the opposite. We found that sensitivity of overall costs to the non-CO_2 assumptions are about 5-10%, comparable to the sensitivity to the carbon plantation assumptions.

Land use represents another major uncertainty. It impacts our results in several ways: 1) by influencing directly CO_2 emissions from land use change, 2) by determining land available for carbon plantations and 3) by determining land available for bio-energy. With respect to CO_2-emission-related changes in land use, it should be noted that even current base-year emission levels are highly uncertain. Houghton (2003) estimated carbon emissions at 2.2 GtC/yr, with an uncertainty range varying from 1.4 to 3.0 GtC per year. Future projections for the carbon budget vary even more given uncertainties on the effect of CO_2 fertilization, the response of soil respiration due to changes in climate and the uncertainties in future land-use patterns (Leemans et al., 2002; Gitz and Ciais, 2004; Strengers et al., 2004). If we focus solely on the latter factor, future land-use change depends on both socio-economic developments and technological improvements in the agricultural system (Rosegrant et al., 2002; Bruinsma, 2003). In the literature, there are different views about the possibilities of technological improvement (Carpenter and Pingali, 2006).

To take these uncertainties into account, we assessed the implications of uncertainties in technological improvement by varying the achieved agricultural yields – and recalculating CO_2 emissions from land-use change and the Marginal Abatement Curves for carbon plantations and energy (bio-energy). We took the yield increase of the least positive scenario in the Millennium Ecosystem Assessment (the Order from Strength scenario) as a basis for the pessimistic run, and the yield increase of the most optimistic scenario (the Global Orchestration scenario) as the optimistic run. This variation provides an understanding of the importance of uncertainties in technological improvement for land-use emissions and potentials for bio-energy and carbon plantations. The impact of these assumptions on global costs is in the order of 5-10% (in both directions).

We have not varied the other factors mentioned above for land-use related emissions such as CO_2 fertilization and other parameters that influence the carbon cycle. The carbon cycle feedbacks are assumed at their IPCC TAR default values. It should be noted, however, that the latest insights seem to suggest that carbon fertilization might be substantially weaker than assumed earlier. If this is the case, all greenhouse gas concentrations – in particular those for the higher concentration levels – will shift upward. Or, by the same token, more abatement action (and higher costs) will be needed to achieve the same stabilization level.

As discussed earlier in Section 7.6.1, Figure 7.13 confirms the baseline development to be one of the most crucial uncertainties determining overall costs. The overall sensitivity here is in the order of 50–100% (on the basis of the alternative B1 and A1b scenarios). It should be noted that in 2100, both the A1b and B1 scenario have lower cost compared to GDP than the central B2 scenario. Therefore, the annual costs in 2100 are (as a result of our sensitivity analysis set-up) only influenced downward. It should be noted, however, that other baselines could have an upward influence on 2100 abatement costs – and also that despite lower costs in 2100, the A1b scenario still results in higher 2000-2100 cumulative costs as shown in Figure 7.8. The major role played by the baseline assumptions is to be expected since it changes the overall reduction objective, as well as technology assumptions, preferences for reduction options and GDP levels (used here as the nominator of the cost indicator).

In the last sensitivity runs, we combined all high-cost and low-cost assumptions (except for baseline and land use). Variation was far higher than suggested by the individual options, especially on the high-cost side. The reason is that without CCS and nuclear power as zero-carbon options in the electric power sector and with low bio-energy supply, this system is much less amenable to substantial emission reductions. While undergoing a one-by-one sensitivity analysis, the system has enough flexibility to substitute, but when all uncertainties work in a negative way, this flexibility disappears.

So in summary, the most important parameters in terms of sensitivity of stabilization costs include baseline, bio-energy, assumptions on hydrogen penetration, and the rate of technology development. Other important uncertainties are future land use (agricultural yields), bio-energy (the use of BECS), assumptions about efficiency improvement and, to some degree, the availability of CCS and nuclear power. The combined effect of all parameters can be far larger than the effect of individual options, so that abatement costs estimates range from 1 to 4% of GDP by 2050.

7.6.3 Possibility of stabilizing at even lower levels

In our analysis, we explored a set of scenarios that would lead to stabilization at levels as low as 450 ppm CO_2-eq. In the previous section, we showed that there are important uncertainties in our analysis, some of which might lead to lower costs (and/or more reduction potential). With the more optimistic assumptions, it would also be possible to stabilize at lower levels than those explored in our central scenarios. Such scenarios will first overshoot the target concentration (given all delays in the system) and only start to approach this target by the end of the century. Of the uncertainties explored earlier, in particular more optimistic assumptions for land use, efficiency and bio-energy (both the available potential and the combination of bio-energy and CCS, BECS) could significantly increase reduction potential and thus allow lower stabilization levels to be reached. Here, we specifically explored whether changing our assumptions for bio-energy alone –from the default assumption to the optimistic assumptions that allow for the combination of BECS– would be enough to reach the emission levels of a 400 ppm CO_2-eq.

The results, as indicated in Figure 7.14, show that this change alone is sufficient to reach the emission pathway. An important element here is that adding BECS allows for a net carbon uptake during the growth of bio-energy which is then stored under-

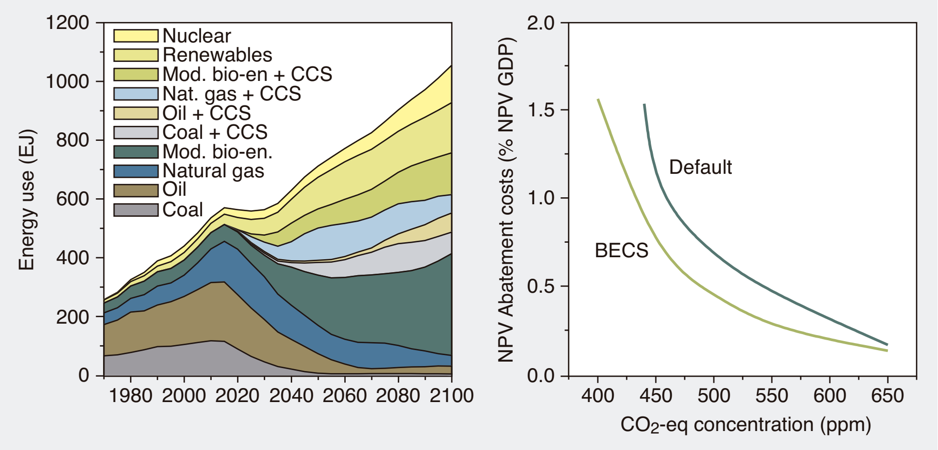

Figure 7.14 Alternative scenario for stabilizing GHG concentration at 400 ppm CO_2-eq. (left panel) and the associated costs (right panel).

ground. These net “negative emissions” are, in particular, important for low emission scenarios (Azar et al., 2006). The costs of BECS are a combination of the bio-energy costs and CCS costs, which certainly makes this technology attractive at the permit price levels explored earlier for the 450 ppm CO_2-eq. scenario. Thus, as a result of the more optimistic assumptions, our overall costs are comparable to our default case, but this obviously requires conditions that allow for the achievement of this more optimistic view of technology development. This is illustrated by Figure 7.14b, where abatement costs are plotted for several stabilization levels, both including and excluding BECS as abatement option.

7.7 Discussion

7.7.1 Important limitations of the current study

In this study, we used a linked set of integrated assessment models (TIMER, FAIR and IMAGE) to explore scenarios that lead to low GHG concentration levels using a multi-gas approach. There are a few important limitations to the study that are essential to interpreting the results:

- The cost concept used in this study refers to direct abatement cost only on the basis of marginal abatement curves derived from underlying expert models – and does not capture the macro-economic impacts of climate policy. Macro-economic cost measures (such as consumption or GDP losses, but also sectoral impacts) might in some cases be larger as they also include effects of transaction costs, combined effects of climate policy and existing taxes etc. On the other hand, they can also be smaller, since there be will sectors and industries that profit from climate policy and since there might be benefits from recycling the revenues of carbon taxes (see (Weyant, 2000)).
- The IMAGE 2.3 model does not explicitly model land-use competition. For this reason, we have restricted the potential land use for climate policy (bio-energy, carbon plantations) to those areas that do not impact food production (i.e. abandoned agricultural land and natural grasslands). It might be interesting to explore how climate policy may impact food production in models that endogenously model competition for land.
- Not all reduction options are included. For instance, in the electric power system, emissions can also be reduced by geothermal power or concentrating solar power plants. However, as such technologies will compete mainly with other zero-carbon emission options; we do not think that including the new options will lead to significantly different results.
- The emission pathways are created by employing the FAIR–SiMCaP model, which uses a different climate model (MAGICC) than IMAGE 2.3. Considerable attention, however, was given to making sure that the results of the two models were consistent. The remaining differences (for example, up to about 10 ppm for CO_2 concentration) are certainly within the uncertainty ranges.

- In view of this being a long-term study, many assumptions are beset with uncertainty. This, for instance, is the case for assumptions on technological progress, and reduction potential. Some of these uncertainties have been taken care of by an extensive sensitivity analysis (Section 7.6.2).
- Finally, the most important limitation is that we do not deal with all kinds of societal barriers that exist in formulating ambitious climate policies. Such barriers may include the specific interests of different actors, inertia in international negotiations, other societal priorities etc. Instead, we assumed that from 2013 onwards all regions participate in climate policy (without necessarily paying for it). . This allowed us to explore, first, how ambitious climate stabilization strategies may look. In future research, it will be important to explore further what barriers exist – and how these may impact the results shown.

7.7.2 Comparing the results to other studies

As indicated in the introduction, there are hardly any other studies that describe mitigation strategies for all GHGs at relatively low concentration levels. Comparison therefore has to be made mostly on the basis of the CO_2 concentration that is achieved in our scenarios (instead of total GHG forcing).

In terms of mapping mitigation costs as a function of stabilization levels, the main comparisons that can be made are with the studies summarized in the IPCC Third Assessment Report (TAR) (these studies focus on CO_2 only). Figure 7.15 shows the stabilization costs in terms of the discounted net present value as a function of CO_2 concentration levels on the basis of this study, the TAR ranges and two more recent studies.

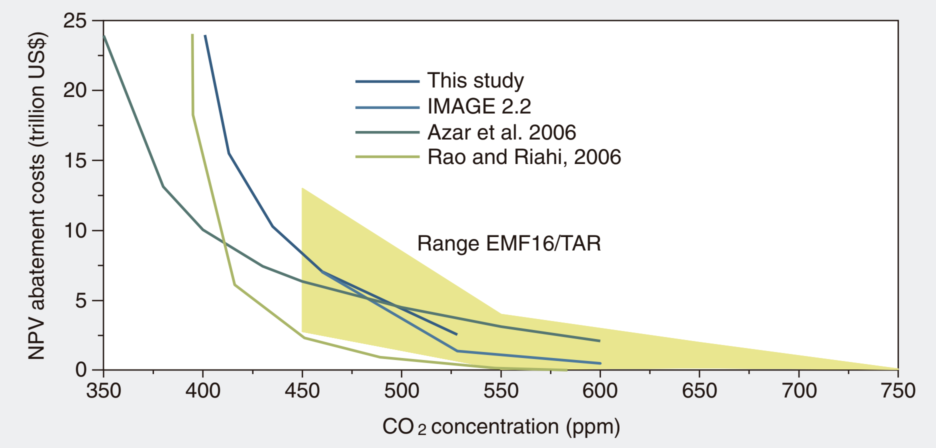

Figure 7.15 Cost levels in this chapter compared to alternative studies. All studies report the Net Present Value of mitigation costs (discount rate of 5%). The sources of the data shown are: EMF-16 results [(Hourcade and Shukla, 2001).Note that the EMF-16 results have been summarized here in terms of the highest and lowest values for different concentration levels across a range of models]; IMAGE 2.2 (van Vuuren et al., 2006b); Azar et al. (2006) and (Rao and Riahi, 2006).

Average cost values reported in IPCC TAR are around 0.8, 1.3 and 6.4 trillion US$ for stabilizing at 650, 550 and 450 ppm $CO_{2,}$ respectively (the lowest and highest values are typically 75% lower and 2-3 times higher, respectively). The corresponding values found in this study are 0.5, 1.7 and 8 trillion (interpolating our results to the rounded-off concentration levels on the basis of the CO_2 concentration in 2100). Our cost numbers, however, also include the mitigation costs for reducing non-CO_2 gases (about 20-30%). Given our baseline emissions (following the updated B2 scenario), and correcting for these non-CO_2 costs, we can conclude that values found (including the trend) are generally consistent with those reported for CO_2 stabilization studies. Azar et al. (2006) and Rao and Riahi (2006) also discuss similar cost levels as a function of concentration targets (again only for CO_2) for considerably lower levels (here, we report the results of their study for model runs that include fossil fuel CCS). Across the whole range of concentration levels, the function of costs as a function of lower concentration level are comparable – although for individual concentration levels, costs may differ over a factor of 5. Reasons that can lead to different cost levels (between all studies cited here) include differences in baseline, the number of options included, and the technology assumptions for these options and the type of models.

For multi-gas stabilization strategies, a comparison can be made with the results of EMF-21 (van Vuuren et al., 2006d; Weyant et al., 2006). With a few exceptions, the results of the models participating in EMF-21 are only available for stabilization at 650 ppm CO_2-eq. In general terms, the findings described in this study seem to be consistent with those found in the EMF-21 study, where the contribution of non-CO_2 gases and overall cost levels is concerned; however, they extend them to lower levels. Given the wider range of abatement options considered, the marginal costs are lower than those presented by Van Vuuren et al. (2006b). Included in the options are a larger potential to reduce non-CO_2 gases, a larger potential for carbon plantations and more possibilities to apply CCS).

7.7.3 Dealing with uncertainties

Uncertainty plays a dominant role in determining relevant targets for climate policy. Climate impacts are uncertain and – probably most important – climate sensitivity is very uncertain, creating a range of possible temperature outcomes for different stabilization levels, as indicated in Figure 7.10. This chapter has also shown that the potential and costs of several mitigation options are subject to uncertainties.

Designing climate strategies that can manage uncertainty will therefore be important. In this light, it is crucial to note that not all uncertainties are similar. An important difference is the lag time between impact, the time when the impact becomes noticeable and the reversibility of the impact. It can still take decades before the uncertainty related to climate impacts and climate sensitivity is significantly reduced. Moreover, once the uncertainties are resolved (in whole or in part), the climate system may already be irreversibly on a path of “dangerous anthropogenic interference” because of all the delays. Most of the uncertainties relating to mitigation options, however, are much more directly noticeable. For instance, if costs develop less favorably for major mitigation options, mid-course corrections can be made in either the portfolio of mitigation options used, the stabilization target or the financial budget (policies will not, after all, be cast in stone for the next 50 or 100 years). Similarly, if certain options prove less effective, they can be removed from the total package. There are some exceptions to this, however. One is that if a mitigation option leads to lock-in effects, a change of course might be less easy to accomplish. Secondly, in theory, CCS and nuclear power could lead to a situation of irreversible damage if the storage of CO_2 or nuclear waste is not as safe as expected. In this light one may ask what elements can be used to establish strategies that can cope with uncertainties?

First of all, such a strategy will include elements of hedging against climate risk. As described by Yohe at al. (2004), hedging implies aiming in the short term for emission pathways that do not exclude the possibility of reaching low stabilization levels. This is obviously important if the climate system proves to be near the upper ranges of current estimates. Secondly, monitoring of the most crucial uncertain elements will be important. Obviously, this in particular relates to parameters associated with temperature increase and climate impact, but also to the costs and potential of mitigation options. Thirdly, it will be necessary, as far as possible, to select a portfolio of mitigation options instead of only a few options. As shown in this chapter, a portfolio is in fact already the result of the modeling that has taken place, but risk reduction is an additional argument not included in the modeling itself. A fourth element is flexibility in targets. Here, there is obviously a trade-off between providing enough long-term certainty to actors involved in climate mitigation to make long-term investments attractive, while being flexible enough to deal with resolving uncertainty.

7.8 Conclusions

The main issue addressed in this chapter was to indicate what portfolio of measures could constitute promising strategies for stabilizing GHG concentrations at low levels. The lowest multi-gas scenarios up to recent discussions in the literature examine stabilization at 550 ppm CO_2-eq. and higher. These scenarios only have a small chance of limiting global mean temperature change to 2°C or 2.5 °C. The main purpose of this chapter therefore has been to try to identify whether stabilization at lower concentration levels is feasible. Against this background, we developed a set of mitigation scenarios for stabilizing atmospheric GHG concentrations at 650, 550 and 450 ppm CO_2-eq., and – subject to specific assumptions – 400 ppm. The scenarios focus on a larger set of mitigation options than most other studies, and extend the lower range of multi-gas scenarios currently discussed in the literature. The analysis has led to the following conclusions.

- **Technically, stabilizing greenhouse concentrations at 650, 550, 450 ppm and, under specific assumptions, 400 ppm CO_2-eq. is feasible from median baseline scenarios on the basis of known technologies.**

In order to prevent "dangerous anthropogenic interference with the climate system", the stabilization of GHGs at low levels (e.g. 450 ppm CO_2 eq. or below) might be needed. Currently, there are only a limited number of studies that identify mitigation strategies that could lead to such low stabilization levels – and none of these are based on a multi-gas approach. Here, we show that there are sufficient technical options to reduce emissions to the level required, and that these options can be combined into effective stabilization strategies. In fact, under favorable conditions, stabilization at 400 ppm is also within the realm of technical options.

For 650 ppm and 550 ppm CO_2-eq. stabilization, it is possible to develop strategies that stabilize at these concentrations without overshooting the required target. For 450 ppm CO_2-eq., overshooting this level before returning to the target during the 22nd century seems unavoidable. For both 550 ppm CO_2-eq. and 450 ppm CO_2-eq. (and even lower levels), emissions will have to peak within the next two decades followed by strong emission reductions. Our calculations show this to be the most difficult period for climate change policy, even assuming the full participation of all countries under a climate regime. The costs of not peaking global emissions within the next two decades could include higher temperature change and/or more rapid emission reduction rates in the longer term (which can be costly if requiring premature replacement of capital).

- **Creating the right socio-economic and institutional conditions for stabilization will represent the single most important step in any strategy towards GHG concentration stabilization.**
  The types of reduction described in this chapter will require major changes in the energy system, stringent abatement action in other sectors and related large-scale investment in alternative technologies. Moreover, we have assumed that the world will find a mechanism to tap reduction potential in all parts of the world. In this context, creating the right socio-economic and institutional conditions that enable these transitions will be more important than any of the technologies discussed. This includes, for example:
  - creating a sense of urgency about emission reduction in all parts of the world in order to develop an effective global climate regime;
  - creating conditions for technology development, and more important, technology dispersal and transfer;
  - overcoming current barriers to effective/cost-effective measures for reducing GHG emissions (e.g. information to improve investment in energy efficiency).

  The impact of socio-economic and institutional conditions can also be illustrated by our analysis of the impact of alternative baseline scenarios. While stabilization at 450 ppm CO_2-eq. represents a major challenge starting from the B2 baseline, the challenge is much smaller when starting from a B1 baseline.

- **The Net Present Value of abatement costs increases from 0.2% to 1.2% of the Net Present Value of GDP (5% discount rate) when moving from 650 to 450 ppm. On**

the other hand, the probability of meeting a two-degree target increases from 0-18% to 22-73%.
Here, we have mapped out some of the costs and benefits of stabilizing GHGs at low levels. Costs clearly increase for lower levels of stabilization, but so do benefits. The net present value of stabilizing at 450 ppm CO_2-eq. at our standard assumptions are about 1.2% of GDP (accumulated over the century), but they reach a peak of around 2% in the period, 2040-2070. At the same time, stabilization also provides clear benefits at low concentration levels. In order to achieve a certainty (on average) of at least 50% in reaching a 2°C target, the CO_2-eq. concentration needs to stabilize at 450 ppm CO_2-eq. or below.

In addition to direct abatement costs, stabilization also involves indirect costs and benefits. There are, for example, the consequences for fuel trade. Stabilization policies are likely to reduce the volume and change the pattern of global trade in fossil fuels, in particular, oil and coal. This will reduce the exports of some countries, but at the same reduce imports of others. Regions that could export bio-energy may compensate some of reduced oil export by bio-energy exports. CCS does limit the impact of climate policy on fuel trade, especially for gas and coal.

- **Strategies consist of a portfolio of measures. There is no magic bullet.**
  The reductions in our stabilization scenarios are achieved through a set of measures rather than a single measure. The reasons for this include: 1) limitations in the potential of individual options, 2) regional and sub-regional differentiation, 3) increasing costs for penetration rates as a result of depletion, and 4) differentiation between different sectors. In addition to these model results, another important advantage of a strategy based on a portfolio of measures is that the reduced risk if the development of a single technology is slower than expected (even a technology may be found altogether unacceptable, which could happen to nuclear power after a major accident). There is also an important disadvantage: the dispersal of R&D capacity, learning-by-doing and economies of scale. However, we feel that this disadvantage is outweighed by the benefits mentioned above.

- **Given our default assumptions, carbon capture and storage (CCS) represents a very attractive technology to reducing greenhouse gas emissions.**
  CCS could be the single most important technology for reducing CO_2 emissions from the energy sector given its relatively low current costs estimates (IPCC, 2005) compared to technologies that are chosen in the absence of climate policy. Its contribution could be around 30-40% of total CO_2 emissions reduced in the energy sector or 25% of total emission reductions. At the same time, the role played by CCS can, if necessary, be replaced by nuclear power and/or additional use of solar and wind power (at somewhat higher costs). It should be noted that these options are subject to several uncertainties. CCS still has to be proven in large-scale applications, and for CCS, nuclear power and wind power societal acceptance can play an important role in determining their real potential.

Other important contributions to overall emission reductions (in the absolute sense) under our default scenario include energy efficiency, the reduction of CH_4 emissions, bio-energy and nuclear, solar and wind power.

- **Stringent stabilization strategies do result in co-benefits but also in additional costs.**
  The systemic changes in the energy system induced by a stringent climate policy can result in important co-benefits. Emissions of regional air pollutants, in particular SO_2 and NO_x, will be reduced substantially, leading either to the improvement of regional and urban air pollution or to reduced abatement costs for these pollutants. Another co-benefit is the likely positive impact of climate policy on energy security issues (less dependency on oil imports). However, in addition to co-benefits, there will also be additional costs. The most important is that stringent climate policies are likely to lead to increased demand for land. This, in turn, could lead to impacts on biodiversity and possibly on food security.

- **Uncertainties are important.**
  Uncertainty constitutes an important factor in the development of stabilization strategies. Here, we also focused on uncertainties relating to the effectiveness and cost of mitigation options. These uncertainties are partly caused by uncertainty with respect to technology development, but also regarding public attitudes (e.g. acceptance of nuclear power, CCS or large-scale bio-energy). Together, these uncertainties can easily double or halve the mitigation costs for a certain mitigation target, or even put certain targets out of reach. Crucial uncertainties, for instance, include those related to land use, baseline emissions, bio-energy use, and potential and technology development. Climate policies should therefore include strategies that can cope with these uncertainties.

Acknowledgements
The authors would like to thank other members of the Climate and Global Sustainability team of MNP for their contribution to this Chapter in particular Bert de Vries, Rineke Oostenrijk, Marcel Berk and Monique Hoogwijk. We would also like to thank Malte Meinshausen and Christian Azar for their comments, which helped us considerably in improving the manuscript.

Appendix 7.1 Additional information

The FAIR 2.1 model (Framework to Assess International Regimes for differentiation of future commitments) was designed to quantitatively explore the outcomes of different climate regimes in terms of possible environmental and economic impacts (including emission trading). It is a decision-support tool with at its core the option of designing rule-based systems that simulate different proposals for differentiating of future commitments (also referred to as “burden differentiation” or “burden sharing”). The model uses expert information from more complex models such as baseline emissions and marginal abatement costs curves (in particular, TIMER and IMAGE) to calculate the consequences of these proposals. The basic assumption of the model is that regions will meet their emission reduction commitments on the basis of least cost – i.e. across different mitigation options (multi-gas) and across different regions (set by certain trading rules). Recently, FAIR 2.1 has been integrated with the SiMCaP 1.0 model to allow simultaneous calculations of climate impacts based on the MAGICC model (Wigley and Raper, 2001) included in SiMCaP. Extensive documentation of the FAIR 2.1 model can be found in Elzen and Lucas (2005) and FAIR–SiMCaP 1.1 model in Den Elzen and Meinshausen (2005).

Information on reduction potentials have been transferred to FAIR, as indicated in Figure 7.1. Table A.1 (topmost rows) summarizes the reduction potentials for 2500 and 2100 according to three main categories (under default assumptions). Three cost levels (200, 500 and 1000 US$/tC) are indicated for two years (2050, 2100). A single number is provided for carbon plantations and non-CO_2 gases; while for CO_2 emissions from energy, emission reductions depend on the pathway, which is why the table provides ranges. The bottom rows provide for comparison the total emissions under the scenario (bottommost rows).

Table A.1 Overview of reduction potential under the main baseline (B2) (top) and baseline emissions (bottom)

		2050 Reduction potential			2100 Reduction potential		
		Permit price			Permit price		
		200 US$/tC	500 US$/tC	1000 US/tC	200 US$/tC	500 US$/tC	1000 US$/tC
Reduction potential (GtC-eq.)	CO_2 fossil fuels(*)	5.6/7.9	9.6/11.2	11.7/12.6	13.5/14.2	15.8/16.2	16.7/16.8
	Carbon plantations	0.3	0.4	0.4	0.4	0.8	0.9
	Non-CO_2	1.8	2.4	2.6	2.6	3.1	3.3
	Total	**7.7**	**12.4**	**14.7**	**17.1**	**20.1**	**21.0**
		2050 emissions			2100 emissions		
Emissions baseline (GtC-eq.)	CO_2 fossil fuels	19.8			20.8		
	CO_2 land use	-0.2			-0.1		
	Non-CO_2	5.3			4.9		
	Total	**24.9**			**25.6**		

(*) For CO_2 from fossil fuels, the maximum reduction potential depends on the trajectory of the carbon tax. Indicated are (left and right of the / sign) the minimum and maximum reduction potential based on a linearly increasing and block tax profile.