MNP Report 500114002/2006

Stabilising greenhouse gas concentrations at low levels: an assessment of options and costs

D.P. van Vuuren, M.G.J. den Elzen, P.L. Lucas, B. Eickhout, B.J. Strengers, B. van Ruijven, M.M. Berk, H.J.M. de Vries, M. Hoogwijk*, M. Meinshausen**, S.J. Wonink, R. van den Houdt, R. Oostenrijk

* : Ecofys BV, Utrecht, the Netherlands

**: Potsdam Institute for Climate Impact Research (PIK), Postdam, Germany

Contact:
Detlef P. van Vuuren
KMD
detlef.van.vuuren@mnp.nl

This investigation has been performed within the framework of S/550025 Methods for Sustainability Analysis

Netherlands Environmental Assessment Agency (MNP), P.O. Box 303, 3720 AH Bilthoven, the Netherlands;

Tel: +31-30-274 274 5; Fax: +31-30-274 4479; www.mnp.nl/en

Preface

This report presents the results of an extensive research project on the potential for stabilising greenhouse gas concentration in the atmosphere at relatively low levels in order to reduce climate change risks. Most studies so-far have concentrated on higher stabilisation levels, but given new insights in the science of climate change, these might not be anymore sufficient to achieve the overall target of the UN Framework Convention on Climate Change (prevent dangerous antropogenic climate change). The results of this research project have been reported in seven related articles. Four of these articles focus on potentials to reduce greenhouse gas emissions. One article focuses on the required emission reduction rates for different stabilisation levels, and finally, two articles look into the integrating aspects of the project and report results for the world and separate regions. The research has been done using MNP's Environmental Integrated Assessment modelling framework IMAGE 2.3 and the related models IMAGE/TIMER (an energy systems model) and FAIR (a climate policy evaluation tool). The seperate articles have been submitted to various journals. The purpose of this report is to bring the results together – both for documentation purposes and to provide readers a complete and comprehensive overview of latest insights in various aspects of low concentration stabilisation mitigation scenarios.

While the chapters in this report focus on climate mitigation options, it is acknowledged that this is only part of the story. First of all, adaptation to climate change impacts forms an important part of climate policy, as a substantial level of change has already become inevitable. Moreover, the climate change problem is to be considered part of the broader issue of sustainable development. Solutions to the climate problem will need to fit in with sustainable development, both to avoid creating new problems while dealing with climate change, to seize opportunities for synergies with meeting other policy objectives, and to render societal support for the implementation of climate policies. Also the way society developes will influence the challenge of mitigating climate change. This broader context is partly addressed n some of the chapters e.g. by looking at the implications of options for land use and synergies with air pollution abatement (co-benefits), and by exploring the influence of baseline developments (scenarios) on the feasibility and costs of climate change mitigation. These issues will be the subject of future research.

The results of the projects as a whole have also be summarised in a concise report also available from MNP (www.mnp.nl)

Abstract

Stabilising greenhouse gas concentrations at low levels: an assessment of options and costs

Preventing ‘dangerous antropogenic interference of the climate system’ may require stabilisation of greenhouse gas concentrations in the atmosphere at relatively low levels such as 550 ppm CO_2-eq. and below. Relatively few studies exist that have analysed the possibilities and implications of meeting such stringent climate targets. This report presents a series of related papers that address this issue – either by focusing on individual options or by presenting overall strategies at the global and regional level. The results show that it is technically possible to reach ambitious climate targets – with abatement costs for default assumptions in the order of 1-2% of global GDP. To achieve these lower concentration levels, global emissions need to peak within 15-20 years. The stabilisation scenarios use a large portfolio of measures, including energy efficiency but also carbon capture and storage, large scale application of bio-energy, reduction of non-CO_2 gasses, increased use of renewable and/or nuclear power and carbon plantations.

Key words:

climate policy, stabilisation scenarios, integrated assessment

Rapport in het kort

Stabilisatie van broeikasgasemissies op lage niveau's: een studie naar de mogelijkheden en kosten

Het voorkomen van 'gevaarlijke menselijke beïnvloeding van het klimaatsysteem' vereist mogelijk de stabilisatie van broeikasgasconcentraties in de atmosfeer op relatief lage niveau's (zoals 550 ppm CO_2-eq. en lager). In de literatuur zijn er nauwelijks studies beschikbaar die op een geïntegreerde wijze hebben gekeken naar de mogelijkheden voor en gevolgen van het bereiken van dergelijke ambitieuze klimaatdoelstellingen. Dit rapport bevat een serie gerelateerde artikelen die op dit onderwerp ingaat – enerzijds door naar de mogelijke bijdrage van individuele mitigatieopties te kijken en anderzijds door analyses van geïntegreerde strategieën op mondiaal en regionaal niveau. De resultaten laten zien dat het technisch mogelijk is om aan ambitieuze klimaatdoelen te voldoen – met reductiekosten onder standaard aannames in de orde van 1-2% van het mondiale bruto nationale produkt (BNP). Daartoe dienen de mondiale emissies wel binnen 15-20 jaar hun maximumniveau te bereiken. De scenario's tonen aan dat een brede portfolio van opties noodzakelijk is, inclusief verbetering van de energie-efficientie, CO_2-afvang-en-opslag, grootschalige benutting van bio-energie, terugdringen van niet-CO_2 broeikasgassen, meer benutting van hernieuwbare en/of nucleaire energie en het toepassen van koolstofplantages.

Trefwoorden:

klimaatbeleid, integrated assessment, stabilisatie-scenario's

Contents

Summary

Avoiding dangerous anthropogenic interference with the climate system may require stabilisation of greenhouse gas concentrations in the atmosphere at relatively low levels. Current studies on emission pathways, for instance, indicate that in order to achieve the EU 2°C climate target with a probability larger than 50% may require stabilisation below 450 ppm CO_2-eq. Unfortunately, the number of multi-gas stabilisation scenarios currently available in scientific literature exploring strategies to stabilise greenhouse gas concentration at such low levels or even at 550 ppm CO_2-eq. is severely limited. As a result, information about how to achieve these levels is mostly lacking.

In this study, we have used the IMAGE integrated assessment modelling framework, including its world energy model TIMER and the climate policy support model FAIR–SiMCaP to explore the environmental and economic effects of mitigation scenarios stabilising long-term greenhouse gas concentrations at 650, 550 and 450 ppm CO_2-eq. (compared to current literature 450 and 550 are low concentration levels; 650 is a medium stabilisation level and is added for comparison). The main research question of this study was whether and how low levels of stabilisation of greenhouse concentrations can be reached and at what costs. It focused on three different subquestions:

- What would be the required level of emission reductions needed to stabilise greenhouse gas concentration levels at 650, 550 and 450 ppm CO_2-eq. on the long-term?
- What technical potential is available to abate future greenhouse gas emissions, in particular by reducing non-CO_2 gasses, growing carbon plantations (sinks), use of renewables and use of hydrogen as a secondary energy carrier?
- What cost-effective portfolios of reduction measures could achieve stabilisation at 650, 550 and 450 ppm CO_2-eq. and what could be the abatement costs and climate and air-pollution benefits of these portfolios, both at the global and regional level?

The research was published as separate articles. This publication combines these articles in one single report.

1. Development without climate policies

In the study, updated versions of the Special Report on Emission Scenarios (SRES) scenarios of the Intergovernmental Panel on Climate Change (IPCC) were used. These updates included new insights in population trajectories (lower for each scenario), updated GDP trajectories (high economic rates in some developing regions take a long time to build up), revised energy resources (a downward revision of oil and natural gas resources) and new modeling tools (TIMER 2.0 was used as energy model). The B2 scenario, used as central baseline in the study, is developed on the basis of the International Energy Agency's (IEA)

2004 energy projection and the marker B2 IPCC scenario and and forms a medium emission scenario. The B1 and A1b scenario are used as low- and high emission alternatives.

- **Without climate policies, the scenarios explored show greenhouse gas emissions to increase significantly.** In the B2 scenario, emissions increase from about 10 GtC-eq. today to around 23 GtC-eq. in 2050 and more-or-less stabilise at this level afterwards. Compared to other studies this can be regarded as a medium estimate. The scenario results in greenhouse gas concentration in 2100 of above 900 ppm CO_2-eq. This implies that significant emission reduction is needed to stabilise concentration at the range 450-650 ppm CO_2-eq. The alternative A1b and B1 scenarios show higher, respectively lower emissions resulting from assumptions on a) higher economic growth and more energy intensive life-styles (A1) and b) sustainable development policies (B1). The B1 scenario leads more-or-less to a 650 ppm CO_2-eq. stabilisation level – but should certainly not be regarded as policy-free (as it assumes improved energy efficiency and increased use of renewable energy, but for other reasons than climate policy).

2. Pathways to stabilisation targets

Using the policy support model FAIR–SiMCaP, the study explored pathways for stabilising greenhouse gas concentrations at 450, 550 and 650 ppm taking into account uncertainties and inertia in both the climate system and the social-economic system. The emission pathways are calculated on the basis of a cost-optimal implementation of available reduction options. The main findings are:

- **There is no single clear pathway that leads to a particular stabilisation level.** Instead, there is a broad envelope of pathways containing pathways that lead to stabilisation, depending on early action or delayed mitigation action (or in between). The pathways within the envelope have almost the same probability to meet temperature targets. The 550 and 650 ppm CO_2-eq. stabilisation pathways always stay below the target concentrations. For 450 ppm CO_2-eq. pathways unavoidably first overshoot the target level and only return to the stabilisation level after 2100.

- **The costs of the envelopes show a wide range, depending on early-action or delayed response**. The delayed response pathway shows lower costs in the short-term, but in long-term the costs are higher. The early action pathways benefit from the induced technology development and the early signal to the energy system. Comparing the discounted cumulative costs, shows that at discount rates of 4-5% or less early pathways lead to lowest costs.

- **The ranges of emissions pathways for the 450 ppm CO_2-eq. and 550 ppm CO_2-eq. are relatively tight. Meeting both concentration targets requires strong emission reductions in the short-term.** For 550 ppm CO_2-eq, global emissions needs to be peak by 2025 – and then decrease rapidly. For the 450 ppm CO_2-eq. scenario global emissions need to peak by 2020 with even stronger reduction thereafter. Figure

1 summarizes the required reduction rates compared to 1990 levels and compared to baseline for the lowest two levels (450 and 550 ppm).

- **Emission reductions depicted for 450 and 550 ppm CO_2-eq. require early participation of major greenhouse gas emittors, including developing countries.** The emission reductions calculated for the different profiles in the next 20-30 years cannot be achieved by a small group of countries only. This will somehow require a broadening of developed and developing country participation in international policy regimes for the mitigation of greenhouse gases.

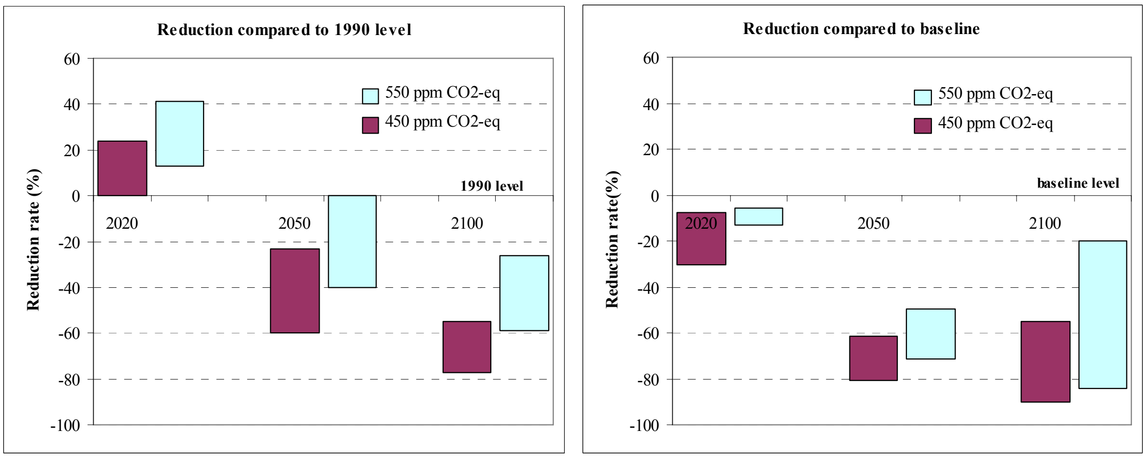


Figure S-1 Emission reduction levels required for stabilisation at 450 and 550 ppm CO_2-eq. The ranges presented are a function of the timing of reductions (particularly important for left side figure) and baseline emissions (in particular important for right side figure)

3. Studies on abatement potential

In preparation of the overall assessment of greenhouse gas abatement potential, separate analysis was performed into abatement potential of specific options, i.e. carbon plantations (sinks), non-CO_2 greenhouse gas emission reduction, renewable energy and the role of hydrogen.

Potential to sequester carbon dioxide by carbon plantations

One way to reduce greenhouse gas concentration levels is to sequester carbon dioxide by means of carbon plantations. Our analysis leads to the following conclusions:

- **Carbon plantations can theoretically sequester around 1-2 GtC annually depending on baseline developments and other uncertainties.** In the B2 scenario, the carbon sequestration potential on abandoned agricultural land increases from 60 MtC/yr in 2010 to 2700 MtC/yr in 2100, assuming that forests are harvested and used to meet the timber demand. The cumulative amount is 118 GtC. The largest contributors in the coming 20 years are South Africa and Russia. By the end of the century, the lead is taken over by China and South America. The cumulative sequestration potential goes from 17 GtC in the A2 scenario to 148 GtC in the A1b scenario, and strongly depends on the amount of abandoned agricultural land.

- **Carbon plantations provide a relatively low cost mitigation option.** Taking into account the main costs components, i.e. land and establishment costs, and *not* taking into account the revenues from timber sales, the largest part of the potential up to 2025 can be supplied below 100$/tC. Beyond 2050, more than 50% of the costs exceed 200$/tC. Compared to other mitigation options, this is still relatively cheap so a large part of the potential will likely be used in an overall mitigation strategy. However, since huge emission reductions are probably needed, the relative contribution of plantations will be small (around 3%).
- **The range of supply and costs presented falls well in the range of other (regional and global) carbon sequestration cost-supply studies.** An exception is East Asia, where the land prices might be too high and where revenues from timber extraction are more important than in other regions.
- **The largest source of uncertainty is the growth rate of plantations compared to the natural vegetation.** Especially if growth falls short, costs per ton of carbon strongly increase. A different baseline scenario than B2 has a limited impact on costs per unit of carbon sequestration, suggesting that costs do not strongly depend on the baseline scenario used.

The role of non-CO_2 greenhouse gases

Recently, considerable attention has been paid to the contribution of non-CO_2 gases to emission reduction. However, most information on abatement potentials focuses on the short-term. Here, we also explored the long-term potential of non-CO_2 greenhouse gases, finding that:

- **Over the century, the share of non-CO_2 gases in the baseline is likely to drop from 22% to around 15%, as their growth rate is slower than that of CO_2.** Non-CO_2 gases are mostly coupled to agricultural activities. These activities are strongly coupled to population growth and population will likely stabilise (or even decline) during the 21st century.
- **Assumptions about technological change and barriers for implementation play an important role in the assessment of future contributions of non-CO_2 gases in mitigation scenarios.** If the reduction potential for non-CO_2 gases is restricted to the set of reduction measures that have been identified specifically for 2010/2020, the role of non-CO_2 gases is limited. Based on a literature survey and expert judgment we estimate that the potential for the reduction of non-CO_2 gases is much larger in the long-run (up to about 70%).
- **Including non-CO_2 abatement options in strategies aiming at stabilising greenhouse gas concentrations can reduce costs by about 30% (if cumulated over the century) compared to CO_2-only strategies.** For pathways for stabilisation at 450 ppm, the share of non-CO_2 emission reduction in total abatement is about 75% in the short term. It decreases to around 15% in 2050 due to the limited potential of non-CO_2 reduction and the rapidly increasing global reduction objective. Along with the fluorinated gases, methane emission reductions from mainly fossil fuel production and landfills form the largest share in total non-CO_2 emission reduction.

Renewable energy

- **Estimates of the potential contribution of renewable energy (wind, solar, biomass) to mitigation of greenhouse gas emissions are strongly dependent on underlying assumptions.** In the literature, often technical, theoretical, economic or other potential production levels and costs are mentioned for renewable energy sources. All these categories, however, do strongly depend on assumptions (land, technology, costs etcetera) – and should therefore be used with care.
- **Theoretically, future electricity demand can be easily met by renewable energy sources in most regions by 2050 at production costs below 10 ¢ kWh^{-1}**. Major uncertainties in the estimated worldwide potential of about 200 to 300 PWh yr^{-1} below this cost level are the degree to which land is actually available and the rate and extent at which specific investment costs can be reduced. In some regions, competition for land among the three options may reduce the combined potential.
- **The potential to produce liquid biofuels is estimated in the order of 75-300 EJ yr^{-1}.** This implies that depending on the scenario, about 50-100% of world transport demand can be supplied on the basis of bio-energy. However, in that case no bio-energy would be available for use in other sectors (like electricity production).

The role of hydrogen in stabilisation scenarios

- **Hydrogen will probably not play an important role before the mid-21st century in the world energy system, neither with nor without a climate policy. Thereafter it can become a major secondary energy carrier but only under optimistic assumptions.** In our scenarios, which mainly use costs as decisive factor, high costs as a result of infrastructure, production costs and the price of fuel cells prevent hydrogen penetration in the first half of the century. These cost barriers may disappear in the second half of the century.
- **Without climate policy, CO_2 emissions from energy systems with hydrogen are likely to be higher than those of systems without hydrogen.** In our scenarios, hydrogen is mainly produced from coal and natural gas (as these form the lowest costs routes). Hence, hydrogen rich scenarios without climate policy increase CO_2 emissions up to 30% by 2100 compared to the baseline.
- **Energy systems with hydrogen respond more flexibly and at lower marginal abatement costs to climate policy.** The reason for this is related to the previous conclusion: the use of hydrogen provides new and presumably cheap carbon emission reduction options in the form of centralized Carbon Capture and Storage (CCS). As a result, the costs of reaching a given climate target may be reduced substantially.

The combined potential of different options

Taking into account the results of the specific studies on the potential of mitigation options, the study also assessed the influence of various uncertainties on the total mitigation potential related to factors such as 1) baseline developments, 2) different technology assumptions (optimistic/default/pessimistic) and 3) other factors (e.g. societal acceptance of nuclear power). It was found that the total abatement potential ranges from about 60-70% in 2050 to about 80-90% in 2100 from baseline level, for the default baseline scenario (B2).

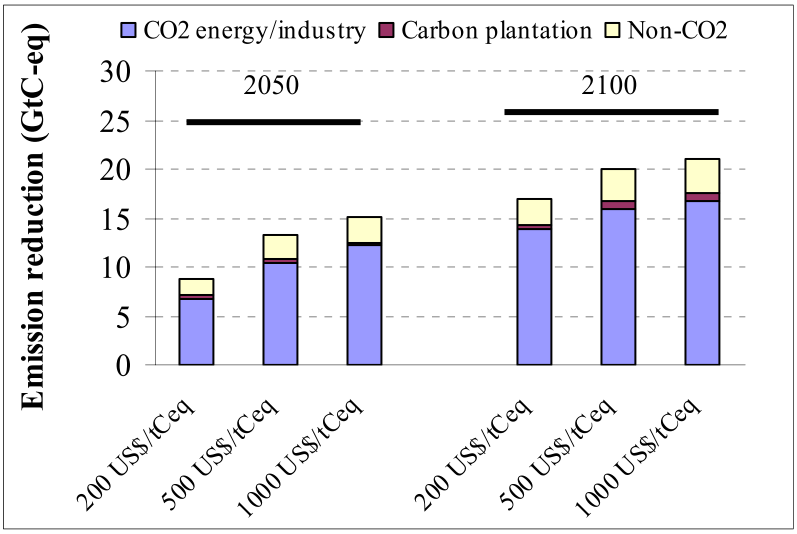


Figure S-2 Abatement potential under the B2 scenario at various marginal cost levels (using default assumptions). Horizontal line indicates baseline emissions; comparison of abatement potential and baseline emissions indicates reduction rate.

4. Integrated scenarios

Global results

On the basis of the IPCC B2, A1b and B1 baseline scenarios, mitigation scenarios were developed that stabilise the greenhouse gas concentrations at relatively low stabilisation levels. The analysis takes into account a large number of reduction options, such as reductions of non-CO_2 gases, carbon plantations and measures in the energy system.

- **The study shows that, technically, stabilising greenhouse concentrations at 650, 550, 450 ppm and, under specific assumptions, 400 ppm CO_2-eq. is feasible from a median baseline scenario on the basis of known technologies.** The study shows stabilisation as low as 450 ppm CO_2-eq. to be technically feasible. To achieve these lower concentration levels, global emissions need to peak within the first two decades. The net present value of abatement costs (2010-2100) for the B2 baseline scenario (a medium scenario) increases from 0.2% of cumulative GDP to 1.1% going from stabilisation at 650 to 450 ppm. On the other hand, the probability of meeting the EU climate target (limit global mean temperature increase to 2^{o}C) increases from 0-10% to 20-70% when going from 650 to 450 ppm. The lowest level of 400 ppm CO_2-eq. can be reached if the option of combining bio-energy and carbon capture and storage is added to the model.
- **Creating the right socio-economic and institutional conditions for stabilisation will represent the single most important step in any strategy towards greenhouse gas concentration (GHG) concentration stabilisation.** The types of reductions described in this paper will require major changes in the energy system, stringent abatement action in other sectors and related large-scale investment in alternative

technologies. Some of these changes are required on the short term (2020). Creating a sense of urgency will be required to achieve this.

- **Strategies consist of a portfolio of measures. There is no magic bullet. Given our default assumptions, energy efficiency and carbon capture and storage (CCS) contribute significantly to the overall portfolio.** All scenarios apply a wide-range of technologies in reducing emissions. Some technologies, however, contribute more than others. Efficiency plays an important role in the overall portfolio. CCS is another important technology under default assumptions – but may be substituted at limited costs against other zero-carbon emitting technologies in the power sector.
- **Uncertainties are important.** Uncertainties play an important role in the whole analysis – and thus in decision-making on mitigation strategies. Uncertainties include 1) the required reduction levels, 2) baseline emissions, and 3) availability and costs of different technologies. For a given baseline and target, the uncertainties in 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. Given this dominant role, it is important to develop strategies that are robust against these uncertainties.

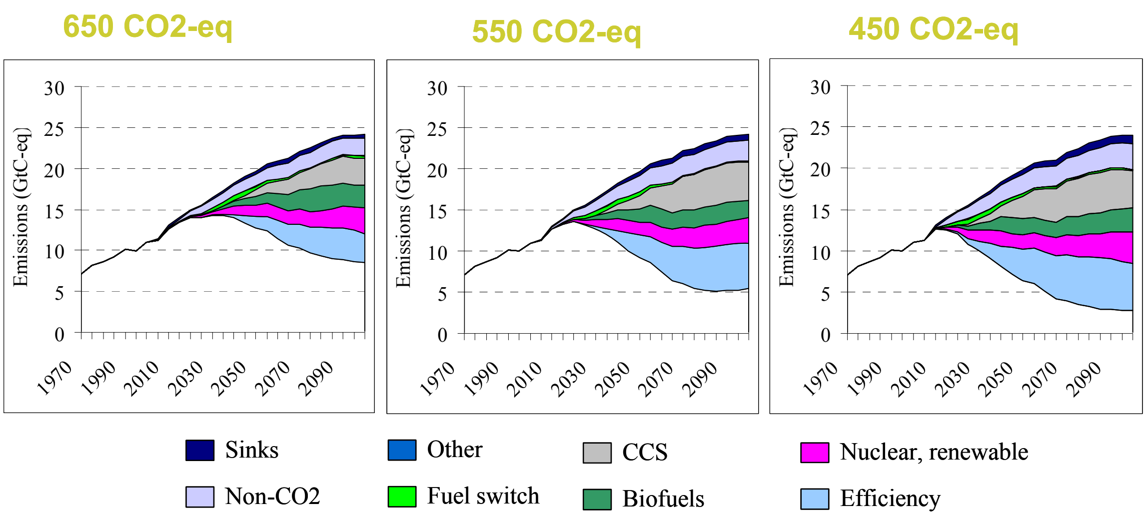


Figure S-3 Reduction measures in stabilisation scenarios for 650, 550 and 450 ppm CO_2-eq.

Regional results

Finally, the study looked into the regional abatement action and costs using the FAIR model. These mainly depend on 1) the concentration stabilisation level chosen, 2) the (regional) baseline emissions, 3) the distribution of emission reduction efforts (depending on the allocation scheme), and 4) transfers related to international emissions trading. Here, regional costs were explored for two allocation schemes: Multi-Stage, and Contraction & Convergence, and two stabilisation levels (450 and 550 ppm CO_2-eq.). The main findings are:

- **To achieve the low CO_2-equivalent concentrations, the developed regions need to reduce their emissions substantially below 1990 levels and the developing regions need to make reductions compared to their baseline emissions levels as soon as possible.** The developed countries as a group would need to adopt emissions reduction targets of 10% to 25% below 1990 levels by 2020 and 60% to 90% below 1990 levels by 2050 in order to stabilise greenhouse gas concentrations at 550 and 450 ppm CO_2-equivalent, respectively.

- **Under the regimes explored the abatement costs as percentages of Gross Domestic Product (GDP) vary significantly by region, with high costs for the Middle East &Turkey and the former Soviet Union, medium costs for the OECD countries and low costs or even gains for most non-Annex I regions.** Some developing regions gain from participating in international emissions trading. In addition to the abatement costs, fossil-fuel-exporting regions are also likely to be affected by losses of coal and oil exports. In some regions, however, these could be offset by increased bio-energy export gains.
- **Also at the regional scale, abatement strategies to meet low stabilisation targets require a portfolio of mitigation options.** Especially in the former Soviet Union and the Asia region – but also in other parts of the world, non-CO_2 abatement options are important in the short term in reducing emissions. Carbon capture and storage, energy efficiency improvements, bio-energy use and the use of renewables dominate reductions in the long term in all regions.

1 Introduction

1.1 Background for exploring low-concentration stabilisation scenarios

Climate change poses one of the most challenging environmental threats to the world. According to the Intergovernmental Panel of Climate Change in its Third Assessment Report (IPCC, 2001) mankind has demonstrably changed the earth's climate system since the pre-industrial era and – without climate policy responses – is likely to changes much further, with expected increases in global temperature in the 2000-2100 period ranging from 1.4 to 5.8 degrees Celsius. 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' (UNFCCC, 1992). However, what constitutes a non-dangerous level cannot be unambiguously determined, as this depends on both uncertainties in the cause-effect chain of climate change as well as on political choices about the level of risks viewed acceptable. In its third assessment report (TAR) (IPCC, 2001), the Intergovernmental Panel on Climate Change (IPCC) identified different dimensions of climate risks also known as 'reasons for concern' that could constitute the basis for determining dangerous levels of climate change. It made clear that already with limited temperature increase impacts of climate change could already be severe for some systems or regions (Figure 1.1).

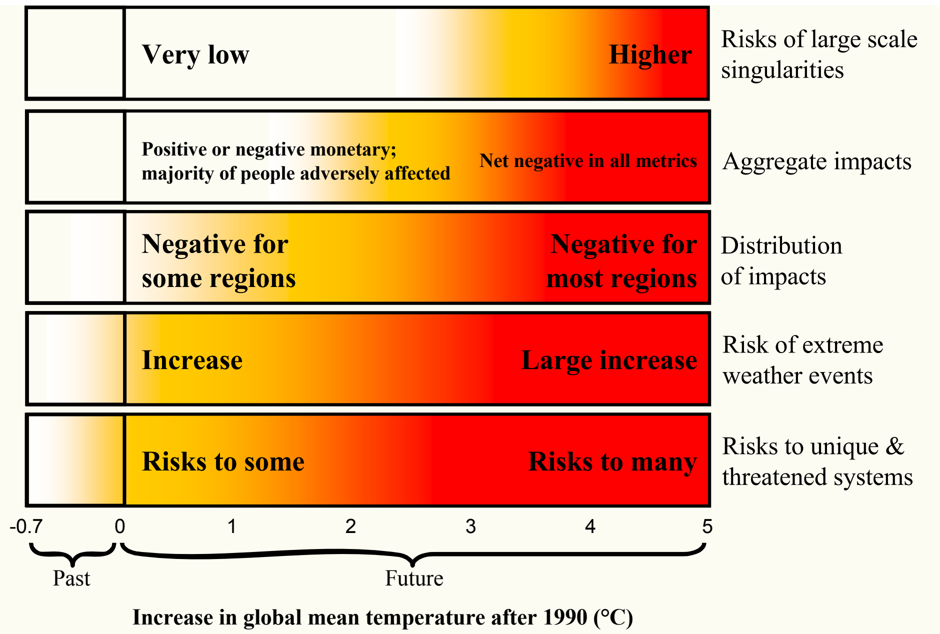


Figure 1-1 Reasons for concern (IPCC, 2001)

This finding has been confirmed by more recent research. 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, 2005). These studies point at risks such as the loss of unique ecosystems like the arctic, alpine ecosystems, and coral reefs, or an irreversible melting of the Greenland ice sheet.

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). New studies have shown that a high degree of certainty in terms of achieving a 2°C temperature target is likely to require stabilisation at low GHG concentration (for instance a probability greater than 50% requires stabilisation at least below 450 ppm CO_2-eq[1]). (Figure 1.2.). The stabilisation 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. But 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).

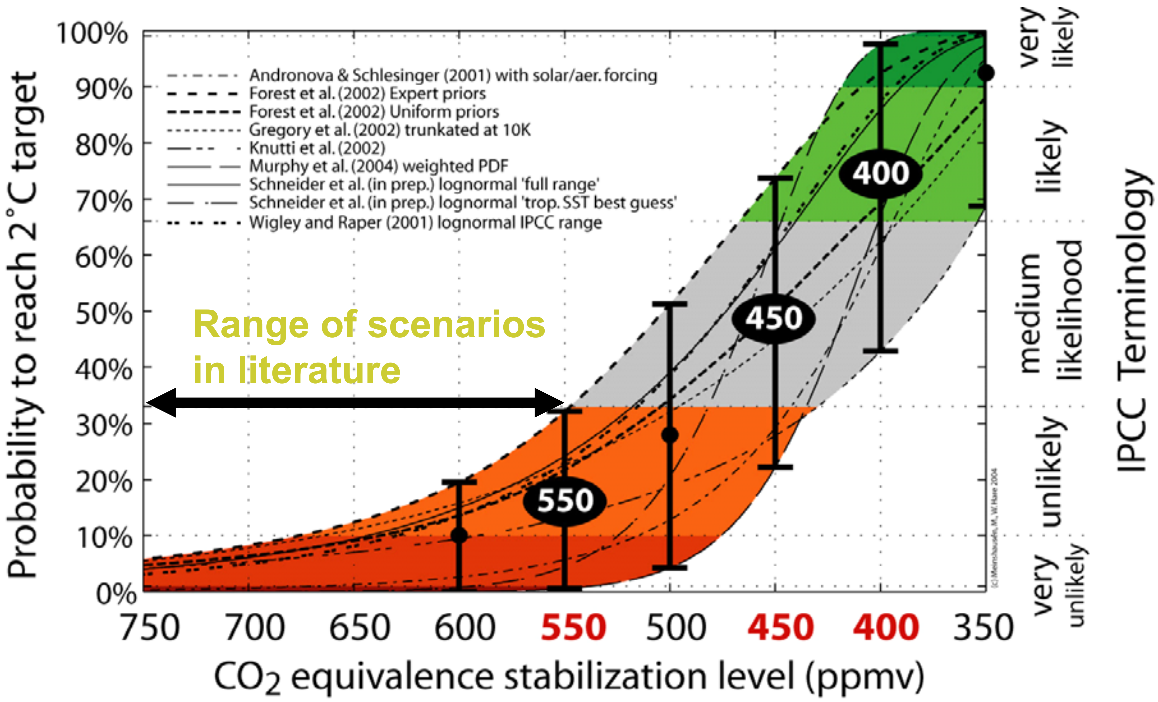


Figure 1-2 Relationship between CO_2-eq. concentration level and probability of achieving a 2°C target; the range of current (2005) multigas scenarios in literature is also indicated (Source: Meinshausen, 2006).

---

[1] 'CO_2 equivalence' expresses the radiative forcing of other anthropogenic radiative forcing agents in terms of the equivalent CO_2 concentration that would result in the same level of forcing. In this paper, the definition of CO_2-eq. concentrations includes the Kyoto gases, tropospheric ozone and sulphur aerosols.

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). Most of these studies, however, have focused on reducing only the energy-related CO_2 emissions, and disregarded options for the abatement of non-CO_2 gases and the use of carbon plantations. Furthermore, the number of studies looking at stabilisation levels below 550 ppm CO_2-eq. is very limited. Thus very little information exists on mitigation strategies that could stabilise GHG concentrations at the low levels required to achieve a 2-3°C temperature target with a high degree of certainty[2]. Given current insights into climate risks and the state of the mitigation literature, there is a very clear and explicit need for comprehensive scenarios that explore different long-term strategies to stabilise GHG emissions at low levels (Morita and Robinson, 2001; Metz and Van Vuuren, 2006).

In this context, the 'Mitigation Scenarios' project of the Netherlands Environmental Assessment Agency (MNP)– of which the results are described in this report – took on the task to explore the following three main questions:

1) What would be the required level of emission reductions needed to stabilise emissions at concentration levels 650, 550 and 450 CO_2-eq.?
2) What is the potential of various specific options to seriously reduce greenhouse gas emissions (carbon plantations, the use of hydrogen as energy carrier, non-CO_2 gases and renewables)?
3) What portfolios of reduction measures could achieve stabilisation at low-concentrations levels (650, 550 and 450 CO_2-eq.) and what could be the costs and benefits of these portfolios, both at the global and regional level?

The levels 650, 550 and 450 ppm CO_2-eq. have been chosen as a range of targets reaching from medium to low targets.

1.2 General project design and methodology

In 2001, the IMAGE model (Integrated Model to Assess the Global Environment) was used to explore potential developments in the cause-effect chain of climate change under the four storylines of the IPCC-SRES scenarios - all assuming the absence of climate policy (IMAGE-team, 2001). Integrated Assessment models like the IMAGE model and the models associated to IMAGE are also well suited to explore integrated scenarios to stabilise greenhouse gas emissions. In the context of the project ''Mitigation Scenarios' these models were used specifically to explore whether it was possible to identify stabilisation scenarios consistent with limiting global mean temperature increase to only 2-2.5°C.

[2] 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 stabilisation targets (see Morita et al., 2000;see Swart et al., 2002).

The models used are the following:

- 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 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 based on various GCM model output to project climate change at the grid level. At the grid level, land use change is described by a rule-based system driven by regional demand for, and production of food, timber and fibers. Finally, natural ecosystems are described by an adapted version of the BIOME model.
- The global energy model, *TIMER 2.0*, a part 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–SiMCaP 1.1* model is a combination of the multi-gas abatement-cost model of FAIR 2.1 and the pathfinder module of the SiMCaP 1.0 model. 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).[3] MACs for energy-related sources are derived from the TIMER 2.0 model. The SiMCaP pathfinder module uses an iterative procedure to find multi-gas emission pathways that meet a predefined climate target (Den Elzen and Meinshausen, 2005).

Calculations in all three main models are done for 17 regions[4] of the world.

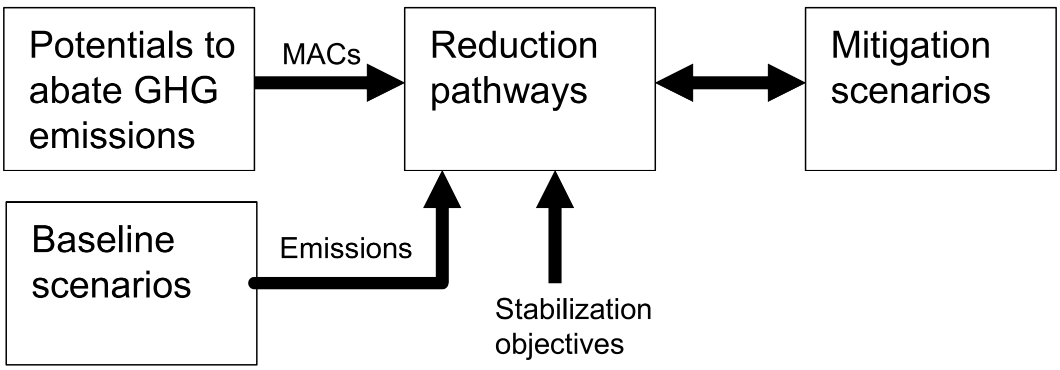


Figure 1-3 Overall project scheme.

The project has been set-up in the following steps:

- *Baseline scenarios.* First, the TIMER and IMAGE models are used to determine potential development in the absence of climate policies. This part of the project represents basically an update of the IMAGE implementation of the IPCC-SRES scenarios.

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

[4] 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).

- *Potential to abate GHG emissions.* Second, an assessment was made of the potential and costs to reduce GHG emissions for various emissions sources. In some cases, specific research was performed to update existing information such as for non-CO_2 gasses, renewables, hydrogen and carbon plantations.
- *Development of emission pathways.* The FAIR–SiMCaP 1.1 model is used to develop global emission pathways that lead to a stabilisation of the atmospheric GHG concentration.
- *Development of mitigation scenarios.* The emissions pathways are expressed in terms of specific mitigation action. These are implemented into the TIMER and IMAGE model to evaluate their impacts on the development of the energy system and land use.
- *Distribution of efforts.* The FAIR 2.1 model is used to evaluate the implications of various approaches for regionally allocating the global emission reduction effort and its implications for regional costs and emission trading.

This modeling set-up corresponds to addressing the overall questions raised in section 1.1 and is also partly reflected in the structure of the various papers that are included in this report.

Compared to the previous work (e.g. Van Vuuren et al., 2006) the new scenario analyses presented here have been improved in various ways:

- the set of stabilisation levels has been extended;
- the methodology for defining global emission profiles has been improved;
- the set of mitigation options includes more options, like hydrogen use, improved modeling of carbon sequestration and biomass use combined with carbon removal and storage;
- the analysis includes an extensive uncertainty analyses to test the robustness of results.

All in all, the analyses can be considered as ‘state of the art’ in integrated assessment modeling of mitigation of greenhouse gases at a global scale. Nevertheless, the analysis also has some limitations to be mentioned. The impacts of climate change have not been assessed, thus also not the cost of inaction. Recent insights into the relationship between global average temperature change and risks from climate change have, however, been explored in another MNP report (MNP, 2005) and by others (see the first section). Moreover, no macro-economic feedbacks of the mitigation costs on economic development pathways have been explored.

1.3 Structure of this report

This report consists of a set of articles rather than a set of chapters. The reason for this is that in addition to their contribution to the overall analysis, each of these chapters was intended to be published separately in scientific journals to be citable in existing scientific literature and the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. The publication of the findings in scientific journals also allows for peer-review of the findings presented here. All articles have been submitted to various journals; some have already been accepted. The aim of this report was to bring together the various tranches of analytical work that contributed to the integrated assessment. The report starts with a chapter on the integrated assessment of low-level stabilisation scenarios, followed by a chapter on the construction of the emission pathways for stabilisation. Next, a number of chapters explore more specific mitigation options. Finally, the aspect of the regional distribution of mitigation costs is addressed.

2 The role of carbon plantations in mitigating climate change: potentials and costs

B.J. Strengers, J.G. van Minnen, B. Eickhout

2.1 Introduction

There is mounting evidence that most of the global warming since the mid 20^{th} century is attributable to human activities, in particular to emissions of greenhouse gases (GHGs) from burning fossil fuels and land-use changes (Mitchell et al., 2001). Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC) states its ultimate objective as 'Stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system'. A large number of scenario studies have been published that aim to identify mitigation strategies for achieving different stabilisation levels of CO_2 (e.g. Morita et al., 2001). However, most of these studies concentrated on reducing the energy-related CO_2 emissions only, leaving aside abatement options that enhance CO_2 uptake by the biosphere. This lack of attention to carbon sequestration in the scientific literature has been partly compensated since the Kyoto Protocol makes provisions for Annex B countries to partly achieve their reduction commitments by planting new forests or by managing existing forests or agricultural land.

Information made available before the Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC; Metz et al., 2001) suggested that land has the technical potential to sequester an additional 87 billion tons of carbon by 2050 in global forests alone (Watson et al., 2000). Since the IPCC's TAR, many studies have addressed the possibility of carbon sequestration as part of mitigation strategies, although not many integral studies are available. Moreover, differences in terminology and scope make it difficult to compare the different carbon sequestration studies (Richards and Stokes, 2004). Several sectoral studies suggest that land-based mitigation could be cost-effective compared to energy-related mitigation strategies and could provide a large proportion of total mitigation (Sohngen and Mendelsohn, 2003; McCarl and Schneider, 2001).

However, most of these studies work on crude assumptions for future land-use change, a crucial factor determining future land availability for purposes other than carbon plantations (Graveland et al., 2002) or land for modern biofuels (Hoogwijk et al., 2005). For example, Sathaye et al. (in press) based their future projections of carbon sinks on linear extrapolation of continuing deforestation and afforestation rates, whereas Sohngen and Sedjo (in press) only considered an increase in forest product demand, discarding future food demand, which is expected to increase immensely in the coming decades (Bruinsma, 2003).

This paper presents a new methodology for constructing supply curves and cost-supply curves or Marginal Abatement Curves (MACs) for carbon plantations based on integrated land-use scenarios from the Integrated Model to Assess the Global Environment (IMAGE team, 2001; Strengers et al., 2004). This methodology builds on Van Minnen et al. (2006), which present a method for quantifying the sequestration potential of planting carbon plantations. This methodology takes land use for food supply into account and obtains a more coherent carbon sequestration potential. Moreover, by basing the MACs on the land-use scenarios of IMAGE 2 and implementing the carbon plantations in IMAGE 2 itself, overestimation of carbon sequestration potential or unrealistic overruling of the food supply chain is not possible, as in other studies. In these studies, MACs are used directly by Computable General Equilibrium models and the consequences for other land opportunities are not considered (Criqui et al., in press; Jakeman and Fisher, in press).

Section 2.2 summarises the methodology to determine the carbon sequestration potential and present the methodology for constructing cost supply curves in more detail. Section 2.3 consists of global and regional results to emphasise the regional specificity of our methodology. Here, we also show the importance of different harvest regimes. Section 2.4 elaborates on the relative importance of different parameters in our methodology via a sensitivity analysis. We draw our presentation of this new methodology to a close with an elaborate discussion that compares our results with those from other studies, and with a number of conclusions.

2.2 Methodology and scenarios

In this approach, the MACs for carbon sequestration potentials are based on geographical explicit simulations in which the availability of potential land can be assessed in different baselines. The carbon potentially sequestered is compared with the natural carbon sequestered, and the costs of carbon plantations are considered regionally, resulting in supply curves and cost-supply curves for 17 world regions. These curves can be used in an overall framework that compares different CO_2 emission mitigation options. We can also estimate how much carbon sinks can realistically add to an overall mitigation effort aimed at a certain stabilisation level. An overview of the complete methodology is shown in Figure 2.1.

Step 1: Global C-sequestration potential

In this first step, the carbon sequestration potential of carbon plantations is determined at a grid level of 0.5^o longitude x 0.5 ^{o} latitude, taking into account the agricultural land needed to meet the food and feed demand. The C-sequestration potential of the best growing trees out of six representative species is quantified by comparing their carbon uptake with the uptake of the natural vegetation that would otherwise grow at the same location. The growth of carbon plantation trees is determined by the Net Primary Production of the natural land cover type that best matches the tree species considered, times an additional growth factor (AGF), which is defined as the additional growth of existing timber plantations compared to the average growth of the natural land cover types. The value attributed to the AGF per tree species is based on an extensive literature review (see Van Minnen et al., 2006). The potential is corrected for the carbon losses due to the conversion. As such, the potential determines the additional aspects when plantations are present compared to the situation in which plantations are absent.

If no harvest takes place, a plantation will grow to a stable level of carbon storage and then provide only little further sequestration over time. If a harvest takes place, we assume that the wood is used to meet the demand for wood. If the harvest exceeds this demand, the remaining wood can then be used to displace fossil fuels. Displacing wood demand and/or fossil fuels can, in theory, last for forever. The displacement of fossil fuels is not modelled explicitly in the current version of the model, but is mimicked by 'storing' all remaining useable stems and branches of harvested plantations so that they do not decompose. Leaves, roots and the non-harvested stems and branches enter the soil carbon pools. We assume no leakage (i.e. no changes in fossil fuel demand and/or wood demand). In the default settings we apply a harvest criterion, where the moment of harvesting takes place when the above-ground biomass (AGB) has been maximised. This criterion is common in forestry and reflects the practice of harvesting a forest at the point where the mean annual increment (MAI) decreases. In the IMAGE model this option is mimicked by harvesting when the age of the carbon plantation equals the 'likely rotation length'.

Since we consider the conversion of natural ecosystems to carbon plantations as being inconsistent with broader sustainability concepts, we allow plantations only on abandoned agricultural land. In this way, the results represent the minimum carbon sequestration potential (see Van Minnen et al., 2006 for more detail on step 1 of this methodology).

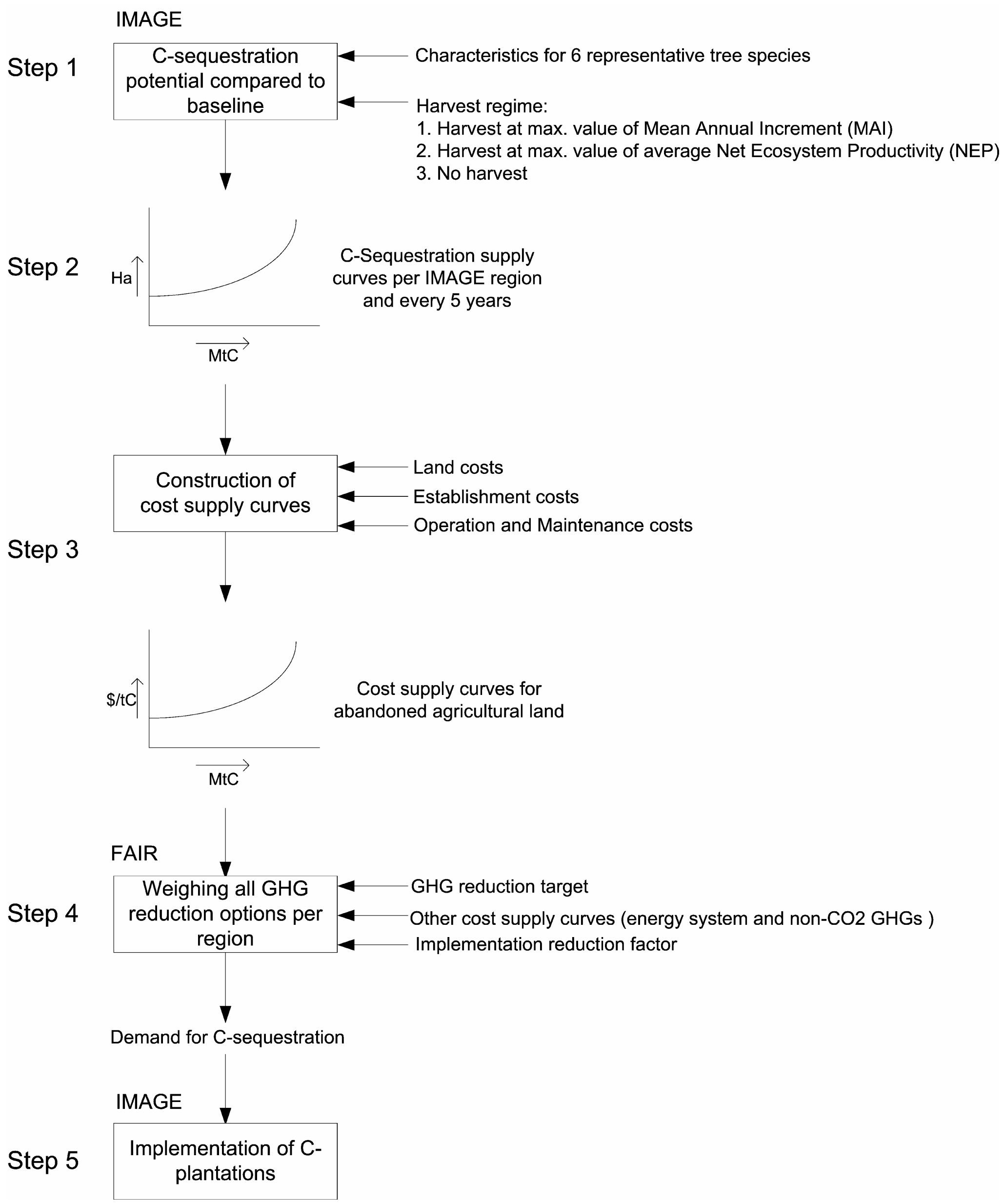


Figure 2-1 Methodology to construct MAC curves for carbon sequestration potential.

Step 2: Supply curves

Based on the carbon sequestration surplus per grid cell, supply curves are constructed for each IMAGE 2 region. The curve for year *z* is constructed using all grid cells in a region where the average carbon sequestration, corrected for climate change and CO_2 fertilisation effects, is positive in year *z*. In Figure 2.2, grid cell *i* covers the y_i hectares that potentially sequester an average of x_i MtC in year *z*. Correction for climate change effects is needed because the amount of carbon sequestered should be based on stable conditions in terms of climate and since CO_2 concentration as also prescribed in the Kyoto Protocol.

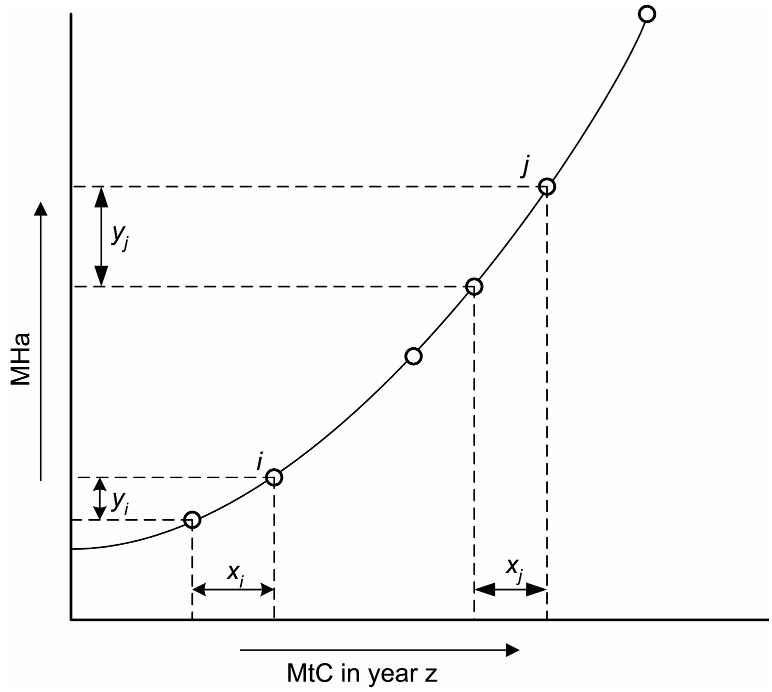


Figure 2-2 A supply curve in year z; grid cell i (y_i Mha) can potentially sequester x_i MtC

Because it is not known in advance *when* a certain potential is actually used in a mitigation effort, and to allow for comparison with other greenhouse gas mitigation options, carbon sequestration is averaged over a predefined period of time. Therefore each point in a supply curve represents the average annual carbon sequestration potential of a grid cell as assigned to a certain time interval $[t_s,t_t]$. T_s is the first year the total cumulative carbon sequestration is positive and t_t is the final year of the simulation period. This final year is 2100, or, if no harvest takes place, the first year in which the annual carbon sequestration decreases below 40% of the overall average value. When there is a harvest, the *average* carbon sequestration of a plantation between t_s and t_t equals the average value at the end of the simulation period. However, when this value at the end of the simulation period is less than 85% of the average value at the end of the last completed harvest cycle, then we assume the average carbon sequestration value at the end of the last completed harvest cycle for the entire plantation period. This situation occurs quite often because in the first years of a harvest cycle the overall average carbon sequestration can temporarily be significantly reduced, since in that period soil respiration often exceeds plant growth, especially for slow-growing species in the high latitudes.

Step 3: Cost-supply curves

The costs of carbon plantations need to be assessed in order to construct MACs out of the supply curves. When dealing with costs, one should keep in mind that vastly different cost estimates of sequestration in forests exist, even among studies that have focused on similar regions (especially the United States). In general, the single most important cost factor in producing or conserving carbon sinks is land (Richards and Stokes, 2004). Here, we consider two types of costs: land costs, and establishment costs. Various other types of costs have been evaluated but were not considered further. Operation and maintenance costs, for example, costs for fertilisation, thinning, security and other activities are not considered in most studies on forestry (for review, see Richards and Stokes, 2004). We assume that operation and maintenance costs are either low (in the case of permanent plantations), or are compensated by revenues from timber or fuel wood (in the case of harvesting at regular time intervals) (Benítez-Ponce, 2005). Likewise, transaction costs and the costs of monitoring or certification are not considered, since hardly any project experience is currently available (Trines, 2003).

Land costs

Richards and Stokes (2004) indicate that in a number of studies land costs cover a wide range of estimates. This study uses GTAP data (GTAP, 2004) for land values of agricultural land in 2001 and land costs in GTAP are defined as the sum of value added from crop production and land-based payments such as subsidies (see Table 2.1). The average value of *abandoned* agricultural land will probably be lower than the average value of *existing* agricultural land as a result of our assumption that grid cells with the lowest agricultural productivity are abandoned first. Therefore we may have (slightly) overestimated the land costs in our analysis. We compared the annual GTAP land values (GTAP, 2004) with capital values from the World Bank (Kunte et al., 1998) (see Table 2.1). These values are defined as the present discounted value of the difference between the world market value of three major agricultural crops (i.e. maize, wheat and rice) from these lands and the crop-specific production costs. The present value of the annual land values from GTAP, computed with the same discount rate as in the World Bank study (i.e. 4%), has turned out to correlate very well for 7 out of 15 regions for which World Bank data exists : USA, South America, northern Africa, southern Africa, OECD Europe, Middle East and Oceania (R^2=0.99; although GTAP values are around 1000 US$ higher than World Bank values). No data were was available for Eastern Europe and former Soviet Union): For another five regions (Canada, Western Africa, Eastern Africa, South Asia and Southeast Asia) GTAP values come to around one-third of World Bank results (at R^2=0.91). For the remaining three regions (Japan, East Asia and Latin America) GTAP values are considerably higher than the World Bank values. The sensitivity analysis shows the importance of different land costs, which are considerable.

GDP per hectare of 'useable' area (see Table 2.1) is an important indicator for estimating how land costs evolve over time. The useable area is defined as the total surface area of a region minus the surface area of hot desert, scrubland, tundra and ice. Adding other factors, such as population density or crop yields does not improve the correlation coefficient (of 0.74). Regional land costs over time ($LC_R(t)$) are calculated as:

$$LC_R(t) = C_R \times \sqrt{\frac{GDP(t)}{Area_{2001}}} \qquad (2.1)$$

where C_R is a regional normalisation factor to make land costs in 2001 equal to the GTAP-land values (see Table 2.1).

Table 2-1 GDP per ha of 'useable' area in 2000 and estimates of land costs based on two different sources: GTAP (GTAP, 2004) and the World Bank (Kunte et al., 1998).

	IMAGE 2 Region	*GTAP* 1995US\$ ha^{-1}yr^{-1}	*GTAP*[a] 1995US\$ ha^{-1}	*World Bank* 1995US\$ha^{-1}	*GDP* 1995US\$ ha^{-1}	C_R
1	Canada	87	2130	5224	960	2.8
2	USA	263	6450	6200	10,150	2.6
3	Central America	324	7950	2650	2280	6.8
4	South America	153	3760	2160	860	5.2
5	Northern Africa	152	3720	2620	1840	3.5
6	Western Africa	31	760	1990	130	2.8
7	Eastern Africa	31	760	2000	120	2.8
8	Southern Africa	45	1110	500	310	2.6
9	OECD Europe	423	10370	10,080	28,250	2.5
10	Eastern Europe	263	6440	no data	3520	4.4
11	Former USSR	52	1280	no data	280	3.1
12	Middle East	100	2460	1710	2655	2.0
13	South Asia	304	7440	16,515	1410	8.1
14	East Asia	458	11,220	5273	2790	8.7
15	Southeast Asia	289	7085	24,100	1815	6.8
16	Oceania	76	1870	1040	815	2.7
17	Japan	2150	52,720	33,470	150,350	5.6

[a] The second GTAP column contains present-day values of the first column using a discount factor of 4%.

Table 2-2 Overview of regional establishment costs.

	IMAGE 2 Region	*Establishment costs* *1995 US$ ha⁻¹* Source: IPCC, 1996	*Establishment costs* *US$ ha⁻¹* Source: Richards and Stokes, 2004[h]
1	Canada	456 (343-572)[a]	300-500
2	USA	473 (160-790)[a]	140-690
3	Central America	542 (172-890)[a,g]	387-700
4	South America	395 (290[b]-500[c])	
5	Northern Africa	No carbon plantations	
6	Western Africa	456 (33-1560)[a]	
7	Eastern Africa	343[d] (33-1560)[a]	
8	Southern Africa	456 (33-1560)[a]	
9	OECD Europe	352 (296[b]-408[e])	
10	Eastern Europe	352 (296[b]-408[e])	
11	Former USSR	389 (370[f]-408[e])	
12	Middle East	No carbon plantations	
13	South Asia	525 (420-630)[a]	367-550
14	East Asia	500 (50-950)[a]	46-828
15	Southeast Asia	515[c]	
16	Oceania	395 (290[b]-500[c])	
17	Japan	349 (290[b]-408[e])	
	World average	435	400-450

[a] Table 9.29, IPCC (1996); [b] Temperate afforestation, Table 7.9, IPCC (1996); [c] Tropical reforestation, Table 7.9, IPCC (1996); [d] Lower than African average because of lower per capita GDP; [e] Temperate reforestation, Table 7.9, IPCC (1996); [f] Boreal reforestation, Table 7.9, IPCC (1996); [g] Table C1, p. 77, Benítez (2005); [h]US$: here it is not clear to which year Richards and Stokes (2004) refer.

Note that the application period of carbon plantations is longer than the period of net sequestration. Therefore land costs over the complete period need to be assigned to the period in which carbon payments take place. Here, the period before cumulative carbon sequestration exceeds the sequestration of the natural vegetation, and is called the start-up period (sp_i). For fast growing tree species, such as eucalyptus and poplar, this period is usually 0–5 years, whereas for other species it can be 25 years or more. The *annual* land costs, $ALC_i(t)$, are calculated by the following (in 95US$/ha/yr):

$$ALC_i(t) = LC_R(t) \times \left(1 + \frac{r \cdot \sum_{j=1}^{sp_{i-1}} (1+r)^{sp_i - j}}{1 - (1+r)^{-lt}} \right), t_s \le t \le t_t \qquad (2.2)$$

where i is the index for a grid cell, r the discount rate (i.e. 4%), and lt the length of the period from t_s to t_t in years (see also step 2).

Establishment costs

Establishment costs include costs for land clearing, land preparation, plant material, planting and replanting, fences and administrative and technical assistance. Costs of land clearing depend on the original type of vegetation and other (landscape and soil) factors. Estimates on establishment costs as summarised by IPCC (1996) have been translated to the IMAGE 2 regions (Table 2.2). These costs fall well within the range of the initial treatment costs, as reported in Table IX from Richards and Stokes (2004).

Since relatively small variations exist between the regions compared to the ranges within the regions, we decided to use one single average value (435 1995US$/ha), both in time and space. This assumption is supported by the overview study of Sathaye et al. (2001), who state that the cost of planting is relatively uniform and stable in time: here, costs are found from 150 US$/ha to 500 US$/ha.

The establishment costs are translated to annual establishment costs at the grid level as follows:

$$AEC_i(t) = 435 \times \frac{r \cdot (1+r)^{sp_i}}{1 - (1+r)^{-lt}}, t_s \le t \le t_t \qquad (2.3)$$

Step 4: Computation of a multi-gas abatement strategy

The MACs developed from carbon sequestration are used as input in the FAIR model (Framework to Assess International Regimes) for differentiation of commitments (see Den Elzen and Lucas, 2003), along with MACs from the energy system and non-CO_2 GHGs (Van Vuuren et al., 2006). The FAIR model was developed to explore and evaluate the environmental and abatement cost implications of various international regimes for differentiating future commitments to meet long-term climate targets. An implementation factor in the FAIR model (see Figure 2.1) mimics the fact that a shortage of planting material, limited availability of nurseries, lack of knowledge and experience, unavailability of credit facilities, land tenure, distrust in governmental policies, and other priorities for the land (e.g. biofuels) may reduce the potential area that can actually be planted. Nilsson and

Schopfhauser (1995) estimated, for example, that only 275 Mha of carbon plantations will actually be available out of the global total of 1.5 billion ha (=18%). Likewise, in a study on Clean Development Mechanisms (Waterloo et al., 2001), eight implementation criteria are distinguished, including additionality, verifiability, compliance and sustainability. If all eight criteria were to be applied, they estimated that only 8% of the potential area would actually be available. Benítez et al. (2005) indicate that if 'country risk considerations – associated with political, economic and financial risks' are included, then carbon sequestration will be reduced by approximately 60%.We use an implementation factor of 1; the consequences of lower values are assessed in Van Vuuren et al. (2006).

Step 5: Implementation of carbon plantations

Finally, the carbon sequestration as demanded by a multi-gas mitigation simulation with FAIR is realised in the IMAGE model by simulating the actual establishment of carbon plantations. Since grid cells can only be converted entirely, the implementation factor determines the number of the available grids being converted to C-plantations. Logically, the C-sequestration achieved will be checked to see if it is indeed at least equal to the amount required.

Scenarios implemented

We used the four IPCC SRES scenarios (Nakicenovic et al., 2000) to assess the importance of different baselines (Table 2.3). These scenarios (A1b, A2, B1, and B2) explore different possible pathways for greenhouse gas emissions in the absence of climate policy on the basis of two major uncertainties: the degree of globalisation versus regionalisation, and the degree of orientation with respect to economic objectives versus an orientation focusing on social and environmental objectives. New insights have emerged for some parameters: for example, both population scenarios and economic growth scenarios in low-income regions have been lowered (Van Vuuren and O' Neill, 2005). In general, the B2 scenario focuses on possible events under medium assumptions for the most important drivers (i.e. population, economy, technology development and lifestyle). In terms of its quantification, the B2 scenario used here roughly follows the reference scenario of the World Energy Outlook 2004 in the first 30 years. After 2030, economic growth converges to the IPCC B2 trajectory. The long-term UN medium population projection is used for population. The demand for biofuel crops is determined according to Hoogwijk et al. (2005). Trends in the regional management factors for agriculture, which reflect the difference between potential attainable yields and the actual yield level, have been taken from the 'Adapting Mosaic' scenario of the Millennium Ecosystem Assessment (MA, 2005). The assumptions for population, economic growth and management factors in the A1b and B1 scenarios have also been taken from the respective scenarios, 'Global Orchestration' and 'Technogarden', in the Millennium Ecosystem Assessment. All other assumptions are based on the earlier implementation of the SRES scenarios (Strengers et al., 2004; IMAGE team, 2001).

Table 2-3 Five indicators in the year 2100 of the IMAGE implementation of four SRES scenarios.

	Indicator	Unit	A1b	A2	B1	B2
1	GDP per capita	US$ (1995)	75,100	17,690	54,232	36,000
2	Population	x billion	6.9	12.6	6.9	9.1
3	CO_2 equivalent	ppmv	1057	1341	675	928
4	Temp. increase	^oC	3.3	3.7	2.5	3.0
5	Agricultural land	Mha	2004	4512	1859	2671
6	Biofuel crop area	Mha	356	237	618	405
7	Potential CP area	Mha	938	109	724	790

The differences in socio-economic conditions and environmental conditions (see Table 2.3) have considerable effects on the demands for and growth rate of food, fodder, and biofuel crops and wood, thus on the area needed for agriculture. These different trends result in different areas being potentially available for carbon plantations, both cumulative and over time (Figure 2.3). These areas are used as input for simulating different carbon sequestration potentials.

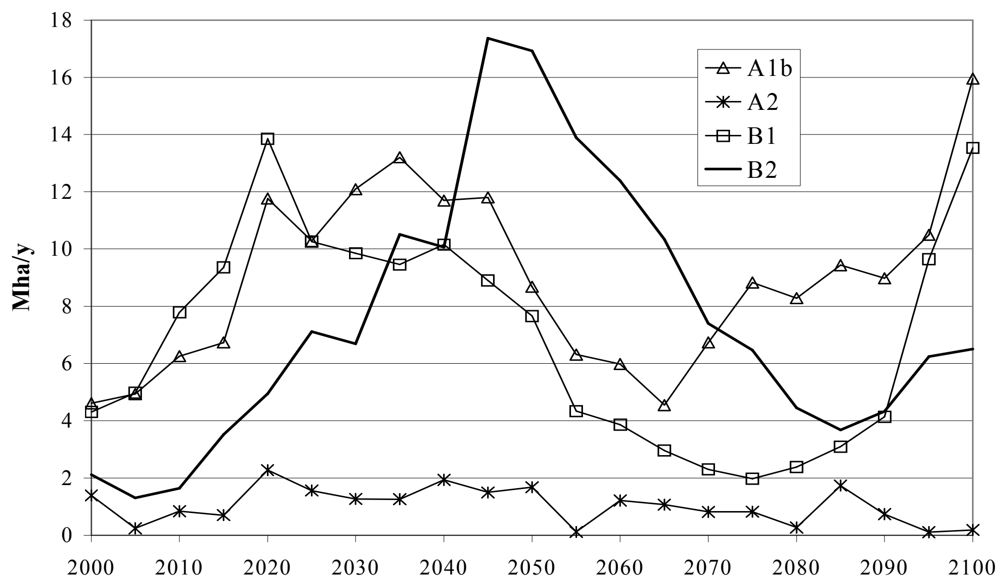


Figure 2-3 Increase of abandoned agricultural land in the IMAGE implementation of four SRES scenarios, which can potentially be used for carbon plantations.

2.3 Results

Global potential for carbon sequestration on abandoned agricultural land

The global sequestration potential on abandoned agricultural land is defined as the amount of carbon sequestered if *all* abandoned agricultural land in the world (that remains abandoned until the end of the century) were covered *entirely* by plantations, excluding locations where the plantations sequester less carbon than the natural vegetation. Figure 2.4 shows the global potential annual carbon sequestration in the baseline scenarios used to construct the supply curves: i.e. based on average carbon sequestration values (see Step 2) and corrected for climate change effects.

The sequestration potential is especially low in the A2 scenario, because of the limited amount of abandoned agricultural land. Compared to B2, the A1b and B1 scenarios have relatively high potential sequestration rates in the first part of the century, which is a direct consequence of relatively high land availability in this period (see Figure 2.4).

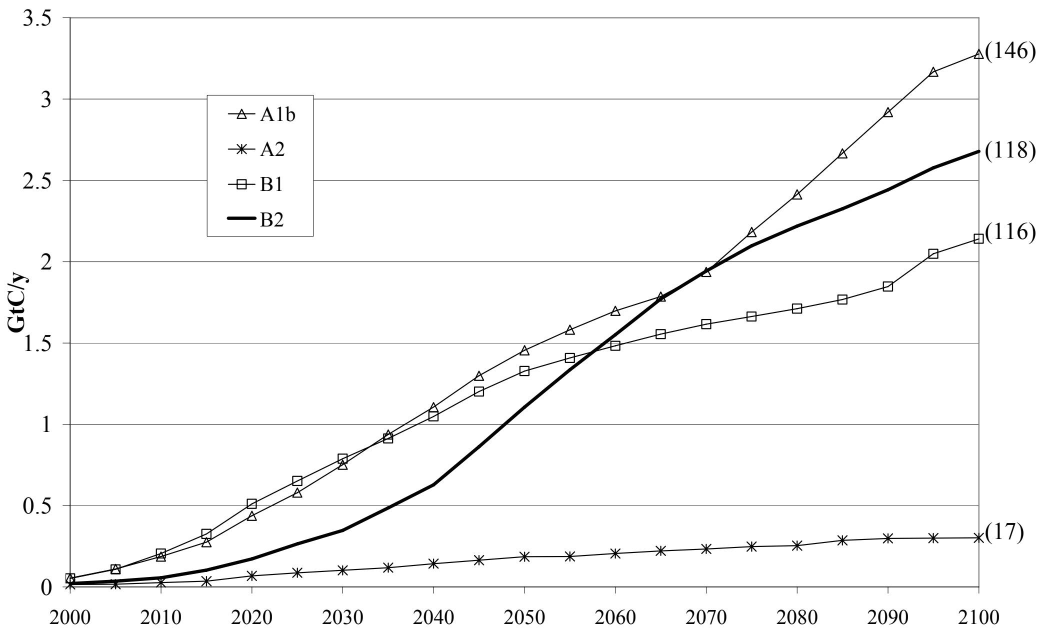


Figure 2-4 Global potential annual carbon sequestration of plantations on abandoned agricultural land for four SRES scenarios, assuming harvest at Likely Rotation Length (LRL). The numbers between brackets equal the cumulative carbon sequestration in GtC.

Supply Curves

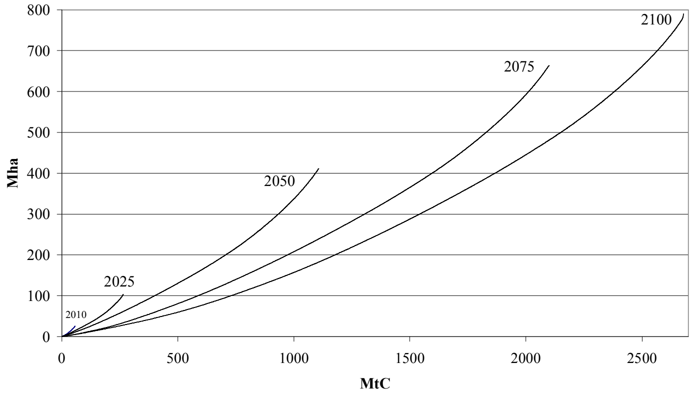
This section shows only the supply curve results for the B2 baseline scenario, since it contains medium assumptions for the most important drivers (see chapter *Scenarios*).

Figure 2.5 shows the global supply curves for the B2 scenario at five different moments in time. As explained in Figure 2.2, the curves go from grids cells with a high sequestering potential at the beginning (i.e. a gentle slope) to low sequestration at the end (i.e. a steep slope). The *average* sequestration rates for the subsequent supply curves increase from 2.2 tC/ha in 2010 to 3.4 tC/ha in 2100. This is due to more productive areas becoming available later in the century. Note that the increase is *not* caused by climate change, since the carbon sequestration rates have been corrected for this.

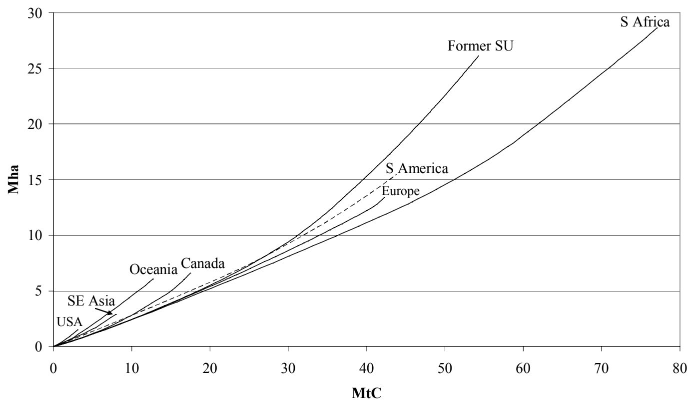
At the regional level (Figure 2.5b), four regions make up the lion’s share of the supply in 2025: these are Southern Africa, the former Soviet Union, South America, and Europe (sum of OECD Europe and Eastern Europe). Southern Africa has the largest potential due to crop yields that increase faster than food and fodder demand, resulting in a decreasing need for agricultural land from 226 Mha in 2000 to 168 Mha in 2025. The large potential available in the former Soviet Union is mainly due to decreasing population numbers (-6%) and slightly increasing crop yields, again both resulting in less land needed for agriculture. The relatively high potential of Europe is due to stabilising population numbers while yields go up, especially in Eastern Europe (+23%). In South America, slowly decreasing population growth, combined with a relatively fast increase in crop yields, results in a decreasing need for agricultural land, starting in 2020. This trend continues in the remainder of the 21st century making South America the second largest supplier of carbon sequestration in 2100 (see Figure 2.5c). In our analysis, the largest supplier in 2100 is East Asia (mainly China). Population size peaks in 2030 at almost 1.6 billion and decreases to 1.3 billion in 2100, while average crop yields increase by 22% in the same period. This results in a 65% decrease in agricultural land. Over 220 Mha becomes available for carbon plantations, which potentially sequester 1 GtC per year. In 2100 the former Soviet Union, Africa (excluding North Africa), USA, and Europe supply around 200 MtC each. Europe shows the highest sequestration potential per hectare, comparable to East Asian levels. Relatively fertile agricultural land is abandoned in Europe, potentially supporting fast-growing plantations (mainly poplar).

The potential in southern Asia (including India) is zero during this century because population growth remains high up to 2075 and only decreases slowly afterwards.

a)



b)



c)

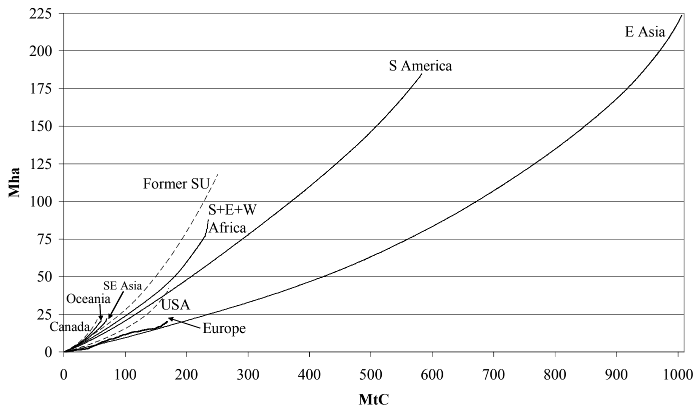


Figure 2-5 Supply curves in the B2 scenario for: a) the world in 2010, 2025, 2050, 2075 and 2100, b) regional supply curves in 2025 and c) in 2100. Northern Africa, Southern Asia, Central America, the Middle East and Japan are omitted because they have low or zero potentials. Eastern Asia, Eastern and Western Africa are omitted in 2025 because their potentials are zero or close to zero in that year

Cost-supply curves

Figure 2.6 shows the global carbon sequestration cost-supply curves for abandoned agricultural land in the B2 scenario. For 2010 and 2025 the largest part of the carbon sequestration potential can be supplied at costs of less than 100 $95/tC. This is relatively cheap compared to other mitigation options (Van Vuuren et al., 2006). In 2050, this fraction decreases to 29% of the potential, but 75% can be supplied below 200 $95/tC. Even these costs are still reasonably low compared to other options. Beyond 2050 the costs of carbon plantations decrease considerably. In 2075 only 14% of the sequestration potential is achievable for less than 100 $95 and 54% for less than 200 $95/tC. In 2100 these fall to 8% and 44%, respectively. Prices will therefore go up early in the second half of this century.

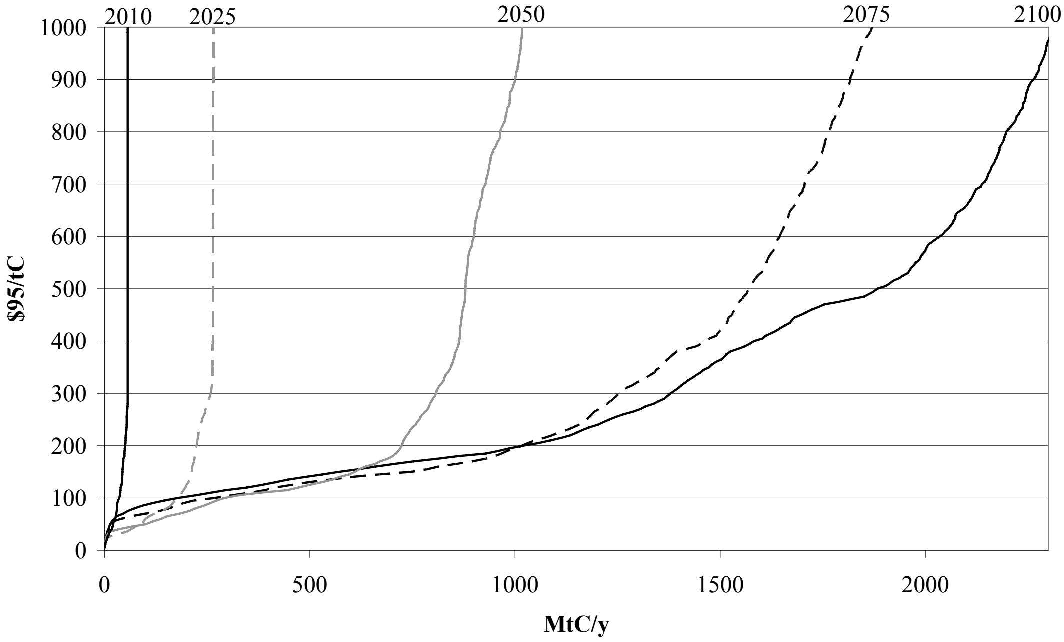


Figure 2-6 Carbon sequestration cost-supply curves for abandoned agricultural land at global level in the B2 scenario for 2010, 2025, 2050, 2075 and 2100.

With respect to the costs of sequestering carbon, large differences exist between world regions (Figure 2.7). These differences are mainly driven by land costs and differences in growth rates. For example, in 2025 the full potential of the largest supplier, Southern Africa, can be obtained at the lowest costs (see Figure 2.8a). This is due to the low land costs in Southern Africa (see Figure 2.7) and the highest average carbon plantation sequestration rates (see Figure 2.8b). On the contrary, although European growth rates are higher than in the former Soviet Union and South America (see Figure 2.8b and 2.5c), costs per hectare are much higher as land is relatively expensive. A general trend is that higher availability of land coincides with lower land costs and higher carbon sequestration rates, and thus larger potentials against lower costs result. A remarkable exception is East Asia. In 2025 the sequestration potential is almost zero due to the lack of available land, resulting in high costs. But in 2100, the C-sequestration in plantations will remain expensive, despite the large increase in land potential available. Costs start around 300 $95/tC and less than 50% can be obtained below 500 $95/ha. This is because land costs are already high in 2025 and increase relatively fast in the course of the century, even if more land becomes available. One could argue that land costs in East Asia should not keep going up so much, since deceasing land scarcity should result in lower land prices. In this case, the assumed relationship between GDP and land costs (see equation 2.1) should be reconsidered for that region. On the other hand, since East Asia remains very densely populated and land is needed for many more purposes, land prices might indeed remain high.

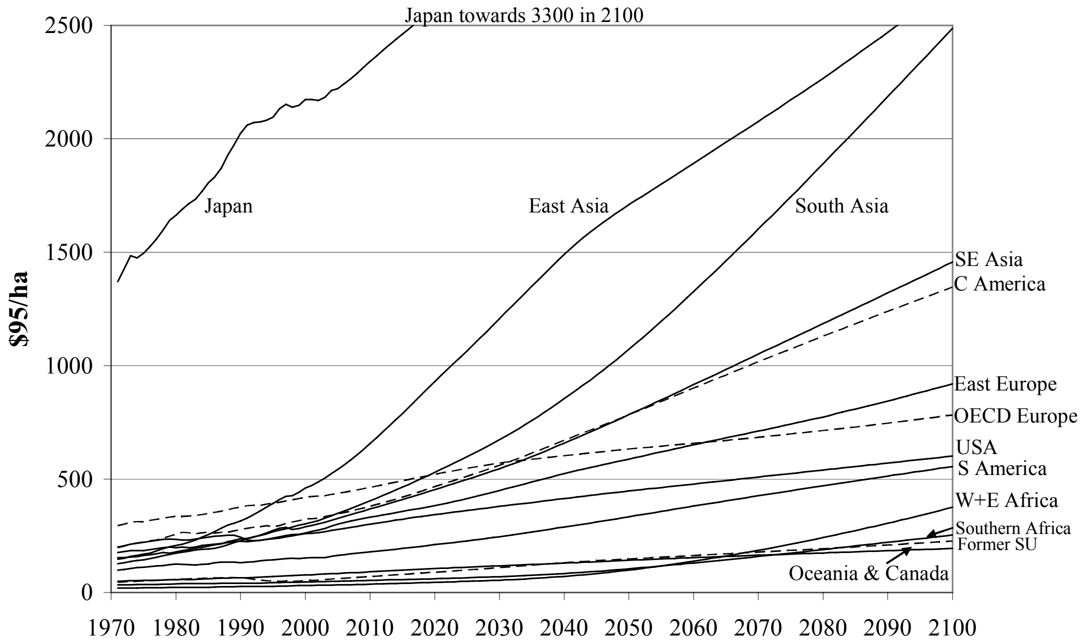
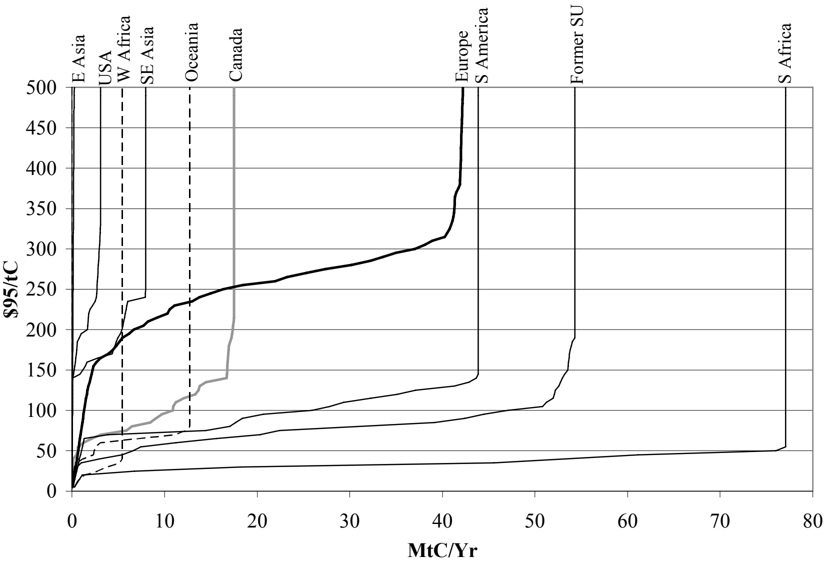


Figure 2-7 Land costs of some major regions in the B2 baseline scenario.

a)



b)

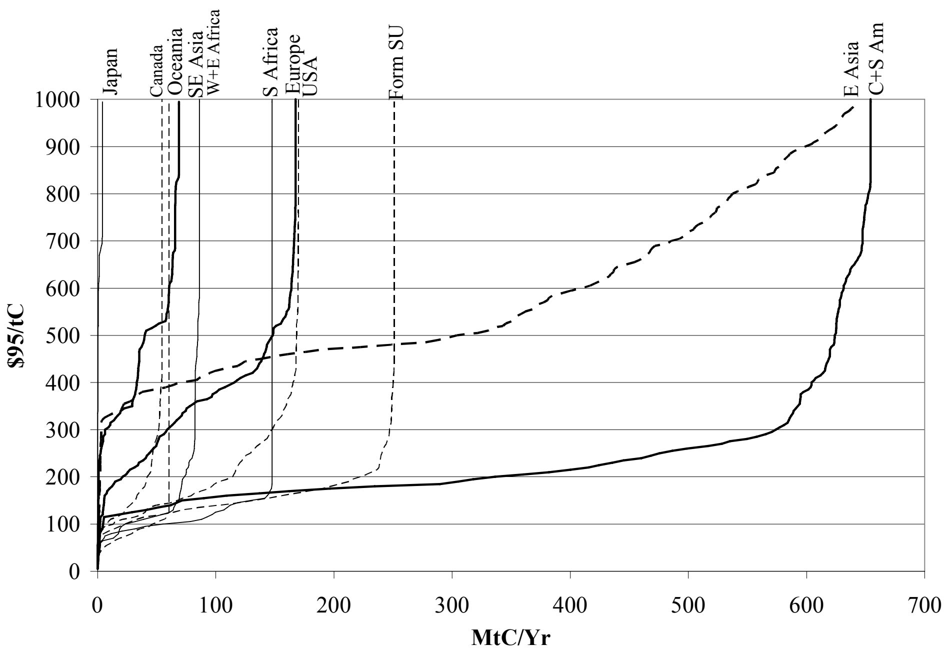


Figure 2-8 Regional cost supply curves in the B2 scenario in: a) 2025 and b) 2100. The potentials of North Africa, South Asia and the Middle East are zero this century and are therefore not mentioned, while Eastern Africa and Central America have zero potentials in 2025. In 2100 the (low) potentials of the latter two regions have been added to Western Africa and South America, respectively.

Carbon plantations in a multi-gas abatement strategy

Carbon sequestration on plantations is a fairly cheap option compared to other mitigation options. For example, Van Vuuren et al. (2006) show that in a 650 ppmv CO_2 equivalent stabilisation scenario carbon prices could be between 150 and 200 $/tC in the period in which the largest reductions are needed. In a 550 ppmv stabilisation scenario these prices are between 250 $/tC and 450 $/tC, while a stabilisation level of 450 ppmv results in prices of 500$/tC to 1000 $/tC. Given these prices, 50–100% of the useable carbon sequestration potential will be utilised. However, since large emission reductions are needed, the relative contribution by carbon plantations in an overall mitigation strategy will always be low. Van Vuuren et al. (2006), starting from the same B2 baseline scenario as in this analysis, show that a 450, 550 and 650 ppmv stabilisation level need a cumulative emission reduction in this century of 1200, 850, and 650 GtC, respectively. Only 37, 29, and 19 GtC respectively of these amounts (or around 3%) can be achieved by establishing carbon plantations, given an implementation factor of 0.1 in 2005, increasing to 0.4 in 2030 and thereafter. Note that although the contribution in the mitigation effort might be limited, harvested wood from these carbon plantations could cover up to 40% and more of the global wood demand in 2100 (assuming no leakage effects).

2.4 Sensitivity analysis

Table 2.4 shows the consequences of varying seven crucial parameters on the supply and costs of carbon sequestration in plantations in the B2 baseline-scenario:

1) the CO_2 fertilisation factor, which has been shown being as one of the most sensitive parameters of the carbon cycle (Leemans et al., 2003);
2) the additional growth factor (AGF), which is the crucial parameter in the growth rate of a carbon plantation (see Step 1);
3) the management factor, which has a strong impact on the actual yield of agricultural crops;
4) the harvest regime, which has a significant effect on the global potential carbon sequestration (see Figure 2.4);
5) establishment costs;
6) land costs, and
7) the discount factor, which influences both annual establishment and land costs through equations 2 and 3.

CO_2 fertilisation

We evaluated the consequences of lowering the CO_2 fertilisation factor on *natural* ecosystems by 50% to 100% (i.e. no fertilisation at all). The reason for doing this is the current scientific debate on the large-scale response of ecosystems to increasing atmospheric CO_2 levels (e.g. Heath et al., 2005; Körner et al., 2005). The CO_2 fertilisation in *agriculture* has been left unchanged, because (to our knowledge) this has not been questioned in the literature. Reducing the fertilisation factor lowers the global Net Primary Production to 10–24%, resulting in 23–50% reduced C-net uptake of natural ecosystems. This is equivalent to more than 6 GtC per year by the end of the century. The potential carbon plantation area increases by 2–6% because slightly less agricultural land is needed to cover the food and feed demand. This is because the atmospheric CO_2 concentration is substantially higher, which stimulates agricultural production. The total potential carbon sequestration in carbon plantations (‘Total supply’ in Table 2.4) increases less than the potential area because the lower CO_2 fertilisation factor reduces the additional carbon sequestration of carbon plantations compared to the natural vegetation. Costs per tC (for the first Gt reduction potential) substantially change for the same reason. In fact, this factor has the least impact on costs compared to the other factors. On the other hand, the mitigation effort will be much higher if CO_2 fertilisation is lower than we now assume in IMAGE.

Additional growth factor

As previously mentioned, the additional growth factor (AGF) is defined as the growth rate of a plantation compared to the average growth of the natural land cover type that best matches the tree species considered. It is one of the most sensitive variables in our model in assessing the global sequestration potential and its costs. This is in line with the findings by Richards and Stokes (2004) and Benítez and Obersteiner (2005).

When changing the AGF values by -20%, the cumulative net carbon sequestration up to 2100 decreases by 37%, whereas it increases by one-third when assuming a 20% higher additional growth. This large effect is caused mainly by a changed uptake of the plantations. These uptake changes are larger than the changes in AGF, because what counts is the additional uptake of a carbon plantation compared to what the underlying natural vegetation would do. For example, if the AGF is increased from 1.8 to 2.16 (= +20%) this implies a 45% increase in the uptake of a plantation compared to the natural land cover (2.16-1=1.16 instead of 1.8-1=0.8). The potential plantation area also slightly decreases under a lower AGF, because a plantation becomes less effective and might no longer be able to sequester more carbon than the natural vegetation. Costs per tC more than double when the additional growth factor is reduced by 20%, which shows its extremely high sensitivity to the AGF.

Management factor

The management factor reflects the difference between potential attainable and actual yields. This factor therefore has an impact on the agricultural land needed to produce the food and feed demanded, and thus on the abandonment of agricultural areas. In the sensitivity runs, we used management factors from the ‘Global Orchestration’ and ‘Order from Strength’ scenarios taken from the Millennium Assessment. ‘Global Orchestration’ has a higher management factor than ‘Order from Strength’.

Table 2.4 Sensitivity analysis of crucial parameters and their impact on costs in the B2 scenario in 2100.

Parameter	Range of values	Agric. land *Mha*	Pot. CP Area *Mha*	Total supply *MtC*	Costs per tC[a] *$95*	CO_2 eq. *ppmv*
Baseline values		*2671*	*790*	*2679*	*138*	*928*
CO_2 fert. (excluding. Agriculture)	-50% -100%	-0.7% -1.3%	+1.9% +5.9%	+0.2% +1.7%	+1.2% +3.8%	+6.7% +15%
Additional growth factor	-20% +20%		-2.2% 0.0%	-37% +33%	+126% -35%	
Management Factor	High Low	-17% +7.6%	+14% -14%	+15% -13%	-12% +12%	-2.4% +0.8%
Harvest regime	No harvest NEP		-19% +0.1%	-20% +7.5%	+10% -11%	
Establishment costs	-20% +20%				-0.5% +0.4%	
Land costs	-20% +20%				-19.5% +19.6%	
Discount factor	2% 8%				-10% +22%	
Baseline scenario	A1b B1 A2	-25% -30% +69%	+19% -8.4% -86%	+22% -20% -89%	0.0% +11% +200%[b]	+14% -27% +45%

[a]Costs per tC refer to the average costs of the cheapest first GtC. In the baseline scenario this is up to 200 $95/tC.

[b]The supply in A2 is 250 MtC., therefore average costs have been compared with the average costs of the cheapest 250 MtC of the B2 baseline scenario.

‘Order from Strength’ results in 200 Mha (or almost 8%) additional agricultural land needed in 2100, leading to a decrease of around 110 Mha (or -14%) potential available for carbon plantations. The latter is lower because the additional agricultural land comes not only from avoiding abandonment, but also by clearing new land in some regions. ‘Global Orchestration’ shows a substantial decrease in agricultural land demand of 450 Mha (-17%), while the potential plantation area increases by 125 Mha (+16%). This difference occurs because large areas never become agricultural land at all and are therefore never abandoned. Both total potential carbon sequestration ('Total Supply') and costs per tonne C change by about the same percentage as the change in potential plantation area, where high management factors also significantly reduce the eventual atmospheric CO_2 concentration, implying less mitigation effort.

Harvest regime

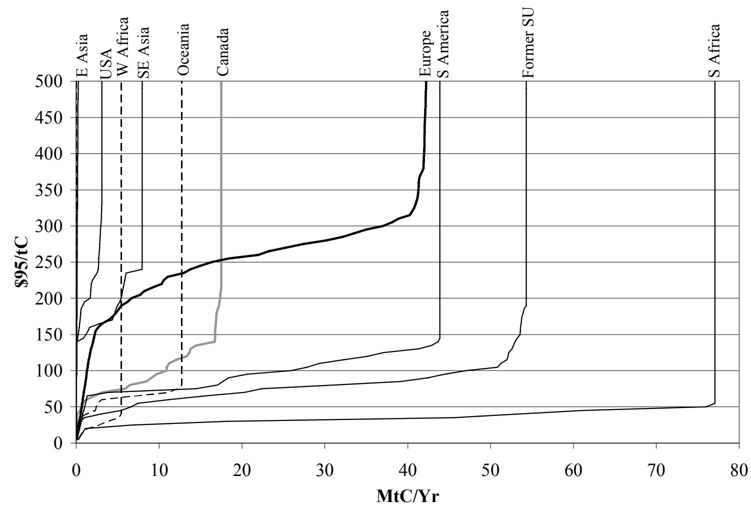
Two alternative harvest criteria are used to determine the importance of harvesting: 1) no harvest and 2) harvest when the net carbon sequestration of the plantation (or NEP) averaged over stand age decreases. The pattern of the potential sequestration rate is similar between the three harvest regimes (compare Figure 2.9 with Figure 2.5), but the total sequestration amounts differ considerably. The highest potential will be achieved when harvesting at the moment NEP decreases (Figure 2.9b). The lowest sequestration potential is reached if plantations are permanently grown (Figure 2.9a). The differences (in terms of GtC/yr) between the harvest options occur mainly in the second half of the century. Permanent plantations have the highest sequestration rates at 25–50 years after an initial period of 0–10 years. After these 25–50 years the sequestration potential decreases, while it remains high or even increases when harvest takes place. Table 2.4 shows that harvesting when NEP decreases leads to an additional supply of 7.5% compared to harvesting when MAI decreases, while costs per tC decrease by 11%. Therefore, harvesting when NEP decreases is most logical from the incentive of mitigating climate change, but is hard to implement in practice because the NEP of a plantation is almost impossible to verify.

It should also be realised that regularly harvested plantations sequester more carbon than permanent plantations only if the wood harvested does not disturb the wood market (i.e. leakage) and if the displacement factor is not (much) smaller than 1. As indicated by Schlamadinger and Marland (1997) and Nabuurs et al. (2003), in time horizons up to 100 years, the net C-benefit can actually be higher in cases that consider reforestation only.

Establishment and land costs

As indicated earlier, both establishment costs and land costs are uncertain. Since establishment costs are much lower than land costs (see Step 3), varying establishment costs changes costs per tonne C only marginally. On the contrary, varying land costs have an almost linear effect on the total costs per tonne C.

a)



b)

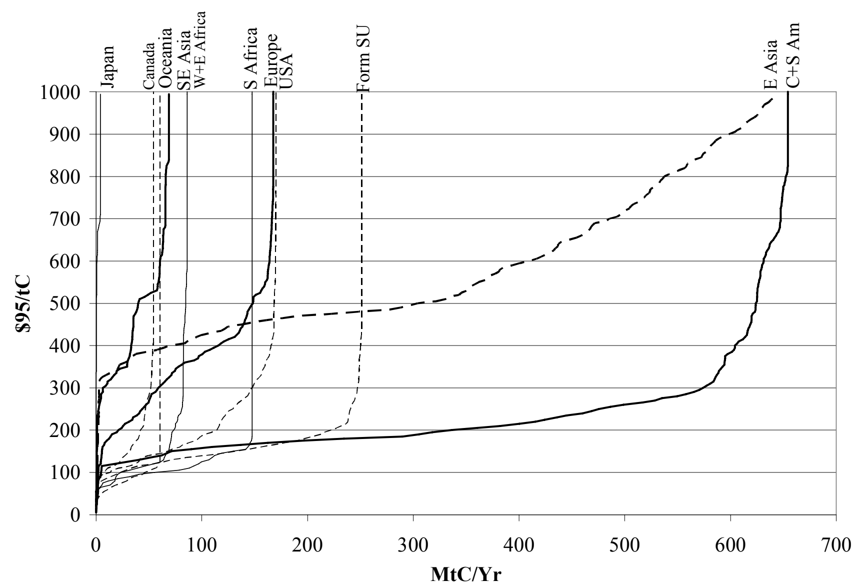


Figure 2-9 Global potential annual C-sequestration of plantations on abandoned agricultural land for four SRES-scenarios: a) No Harvest, b) Harvest when NEP decreases. The numbers in brackets equal the cumulative carbon sequestration in GtC

Discount rate

The discount rate determines how annual land costs in the start-up period are valued thereafter, and how establishment costs are translated to annual costs during the sequestration period (see equations 2 and 3). Since the costs of carbon sequestration programs occur early and the carbon sequestration benefits are substantially delayed, high discount rates produce higher unit costs of sequestration. Choosing an appropriate discount rate is always a major source of discussion. Nilsson and Schopfhauser (1995), for example, suggest discount rates in the range of 0–10% for long-term forestry projects, but there is no rational consensus on how to set the rate. They even propose using an array of interest rates in global analysis in order to catch regional specifics. To get an idea of the importance of the discount rate for the results shown above, we repeated the calculation with a discount rate of 2% and 8%, instead of 4% in the B2 baseline scenario. Table 2.4 shows that the costs per tC change around 5% for each percentage change in the discount rate.

Baseline scenario

Although the potential area for carbon plantations, and thus the potential carbon sequestration supply, is different in the A1b and B2 scenarios, the impact on costs is very limited. In the case of A2, costs increase by a factor 2. However, this is an extreme scenario where high population numbers and low crop yields result in only 109 Mha being available for carbon plantations. This area has probably been taken out of production because of very low yields and will also result in low carbon sequestration rates and thus (very) high costs.

2.5 Discussion and conclusion

We constructed supply curves and cost-supply curves for carbon sequestration for plantations in 17 world regions. This section synthesises our results and places them in a broader context by comparing them with other global and regional studies.

C-sequestration potential and costs

Using the IPCC B2 scenario, and assuming harvest at the moment that the mean annual increment (MAI) decreases, we observed the carbon sequestration potential on abandoned agricultural land to increase from almost 60 MtC/yr in 2010 to 2700 MtC/yr in 2100. Geographically speaking, the largest contributors in the coming 20 years are South Africa and the former Soviet Union. By the end of the century, the lead is taken over by East Asia (China) and South America.

Assuming permanent plantations, the potential carbon sequestration substantially decreases (up to 44%). However, as explained in several studies, for time horizons up to 100 years, the net C-benefit can actually be higher in cases considering reforestation only. The potential would increase from 55% to 75% if carbon plantations were allowed on harvested timberland. It is, however, questionable whether this can be considered as a sustainable option. If harvest takes place when average Net Ecosystem Production decreases then the potential increases by 8% to 10%, but in practice the NEP criterion is almost impossible to verify.

Up to 2025 the largest part of the (limited amount of) carbon sequestration potential can be supplied at costs of less than 100 $95/tC, although the costs are projected to rise during this century. We project that in the second half of this century more than 50% of the potential can be supplied at costs over 200 $95/tC. Compared to the costs of other mitigation options in the energy system (including biofuels) and for non-CO_2 emissions this is still a fairly cheap option. As a result, a large part of the carbon sequestration potential will probably be used in an overall mitigation strategy (Van Vuuren et al., 2006). However, since large emission reductions are needed, the relative contribution by carbon plantations will be low.

Cost comparison at the global level

Richards and Stokes (2004) provided a comprehensive overview by comparing 36 forest carbon sequestration cost studies. A major problem highlighted is that a comparison is often difficult to make due to 'inconsistent use of terms, geographic scope, assumptions, program definitions, and methods'. Nevertheless, 'after adjusting for variations among the studies', they concluded that in the cost range of 10–150 US$ per ton of carbon it may be possible to sequester 250–500 MtC/yr in the USA and up to 2 GtC/yr globally. It is, however, not directly clear how they adjusted data for variations among studies, which complicates any comparison with our results. When looking at the underlying studies in more detail it seems that:

- the time frame of most studies is between 50 and 140 years;
- land costs form the most important cost factor and are always included;
- initial treatment costs (or establishment costs) are almost always included;
- revenues from timber have been included to a limited extent;
- administration costs and maintenance costs have either not been included or only to a limited extent;
- most studies refer to afforestation of former agricultural land *and* reforestation of harvested or burned timberland;
- most ecosystem carbon components are included;
- additionality of the carbon sequestration is *not* taken into account;
- secondary benefits have not been taken into account.

Unfortunately, it remains unclear to what extent:

- their estimate applies to the full time frame, or whether this level is reached at the end of the period;
- the baseline scenarios used differ from the baseline scenarios in the study presented.

A major difference between most other studies and our methodology is the exclusion of timberland. However, if we were to also include harvested timberland, the global potential between 10 and 150 US$ would rise from 75 MtC in 2010 to around 1.2 GtC/yr in 2075 and 2100. More than 2 GtC would be obtained only at costs above 235 $/tC. The potential for the USA in the same cost range rises from 3 MtC/yr in 2010 to almost 150 MtC/yr in 2100. A potential of 250–500 MtC/yr can be obtained in 2100 at cost levels around 300 $/tC. This would bring our results to the low end of the range in these other studies. The main reasons for this are that we:

1. largely excluded revenues from harvested wood;
2. only account for the *additional* carbon sequestration compared to the natural vegetation; and
3. do not convert *existing* agricultural land to carbon plantations, that is, there is no interference with the food and feed production.

Benítez and Obersteiner et al. (2005) present a global country-risk adjusted[5] cost-supply curve based on a grid cell analysis for the next 20 and 100 years. These authors consider croplands, grasslands, shrublands and savannas, excluding (potentially) highly productive land, and show that in the next 20 years, around 9 GtC can be sequestered below 400 $/tC. In the next 100 years, this will be around 65 GtC. If we include these land classes in our analysis and also apply a country-risk adjustment of minus 60%, our cumulative potential carbon sequestration in the first 20 years is almost 9 GtC below 400 $/tC, and 108 GtC in the first 100 years. Thus the results are almost equal in the first 20 years and will differentiate in the longer term. The difference is caused mainly by the differences in method: that is, an analysis based on land cover changing over time, instead of using the land cover as it is now. Furthermore, we explicitly model the carbon cycle, while Benítez and Obersteiner(2005) use the carbon uptake from spatial databases.

Cost comparison at the regional level

Differences are more pronounced at regional levels due to the reasons mentioned by Richards and Stokes (2004). For example, on the basis of a study from Xu et al.(1995), both Sathaye et al. (2001) and Richards and Stokes (2004) indicate that China has a reasonable potential at *negative* costs. Up to 2060, the computed sequestration potential for China (or actually East Asia) in our analysis is comparable to theirs (see Figure 2.5), but only for considerably higher costs (Figure 2.6). The negative costs in Sathaye et al. are caused by high timber prices in

[5] Benítez et al. assess that risks associated with political, economic, and financial circumstances reduces the global carbon sequestration potential by approximately 60%.

China, something that is not included in this study. On the other hand, they might have underestimated land costs.

Another interesting region is South Asia (including India), which our analysis shows to have practically no potential. However, Sathaye et al. (2001) estimated for India that plantations can sequester around 300 MtC until 2030, whereas Richards and Stokes mention a potential of 3.7 Gt, based on a study from Ravindranath and Somashekar (1995). The main reason for our much lower estimate is the fundamental requirement of not allowing interference with agriculture. Benítez and Obersteiner (2005) conclude that 'most least-cost afforestation projects are located in Africa, South America and Asia'. Our analysis confirms this result for Africa and South America (see Figure 2.8). For Asia we only show low-cost projects in the former Soviet Union. As discussed above, the remainder of Asia is relatively expensive.

Summary

We have presented supply curves and cost-supply curves for carbon sequestration at plantations in 17 world regions. These curves have been used in an overall framework comparing different CO_2 emission mitigation options. We have shown that a potential of up to 2700 MtC/yr by the end of the 21st century is possible, depending on assumptions made. The associated costs are low up to 2025, but are projected to substantially increase thereafter. Still, the costs remain low compared to those of other mitigation options in the energy system (including biofuels) and for non-CO_2 emissions.

Although direct comparison with other studies is not straightforward, the range of supply and costs presented falls well within the range of other (regional and global) carbon sequestration cost-supply studies. An exception is East Asia, where our land prices might be too high and where revenues from timber extraction are more important than in other regions.

The largest source of uncertainty for the projected sequestration potential and associated costs is the assumed growth of carbon plantations compared to the natural vegetation, as expressed in the Additional Growth Factor (AGF). If growth falls short the costs per ton of carbon will increase considerably. Using a different baseline scenario to B2 has a limited impact on costs, suggesting that costs do not strongly depend on the baseline scenario used.

The next steps will deal with comparing the potential of biofuel crops and carbon plantations, including revenues from harvested wood and their impact on the wood and land market (i.e. leakage) and the inclusion of other cost components such as maintenance and monitoring. Regional consequences will also be evaluated in more detail, especially for East Asia.

3 Renewable energy sources: their global potential for the first half of the 21st century at a global level: an integrated approach

H.J.M. de Vries, M Hoogwijk, D.P. van Vuuren

3.1 Introduction

Decision-makers, societal groups and scientists have at various moments in time expressed their interest in renewable energy sources such as power from wind, sun and biomass-derived fuels. Recently, this interest has been on the rise again. Several reasons are mentioned for this: the risk of energy supply insecurity and the corresponding need for resource diversification, the prospect of depletion and hence cost increases of conventional oil and gas and the adverse impacts of climate change and local air pollution[6] as a result of emissions related to burning fossil fuels. The concerns show up in questions asked by policymakers, citizen groups and industrial firms: How fast can renewable energy sources expand? When will they be competitive with conventional energy options? Which role can they play in reducing greenhouse gas emissions and which are the best policy instruments to stimulate their introduction? To answer such questions adequately, it is necessary to have proper insight in the potential availability of renewable energy sources at different cost levels, and also in the evolution of the energy system in which these resources have to be implemented.

The potential availability of wind, solar and biomass energy varies over time and between locations. This variation is not only caused by the resource characteristics (wind/solar regime, soil) but also by geographical (land use and land cover), techno-economic (scale, labour cost) and institutional (policy regime, legislation) factors. Some of these factors cannot or can only approximately be quantified. As a consequence, an assessment of the long-term role of renewable energy sources has to rely on a combination of data from observations, mathematical models and narratives – that is, on scenarios. In the past, several estimates of the worldwide potential of renewable energy options have been made, for instance for wind energy (Grubb and Meyer, 1993; WEC, 1994, Fellows, 2000; Rogner, 2000; Sørensen, 2000), solar energy (Rogner, 2000; Sørensen, 2000; Hofman et al*.,* 2002) and biomass energy (Rogner, 2000; Berndes et al*.*, 2003). These studies mostly focus on one specific source only or, when including several sources, lack a well-defined generic approach. They also use different regional aggregation. Also, most studies concentrate on ‘technical potentials’ and do not consider the economic potential. Besides, the underlying assumptions are often not clearly stated. All these factors make a comparison of various analyses across regions and resources quite complicated. A clear description of the calculation procedure and assumptions is therefore crucial to reach more consensus on the renewable resource potential.

---

[6] A comparative environmental advantage does not necessarily apply for biomass applications.

In this paper we present a new assessment of future costs and technical potential of electricity from onshore wind, solar-photo voltaïc (PV) and modern biomass in centralised generation units and fuel from biomass (we refer to these collectively as WSB (Wind, Solar, Biomass)), using a generic and integrated approach across the different resources.[7] It permits an integrated, comparative analysis of the three WSB options and of the role of uncertainties, in particular land availability and technology. An additional reason to provide new estimates of the potential of renewable energy options is the availability of better data on resource characteristics and technological and economic performances and prospects. Hydropower, geothermal power, tidal power and other techniques to capture solar energy directly have significant potential in some regions, but are not considered in this paper.

We use worldwide geographical data on wind speed, solar radiation and biomass yields. These are combined with estimates of constraints on land availability and on existing and future costs. The resulting regional cost-supply curves for different scenarios and for the period 2000–2050 are compared with projected energy demand and with other estimates found in the literature. The possible interface between wind, solar-PV and biomass is explored in order to find interesting high-potential locations.

3.2 Renewable energy potentials: definition and methodology

3.2.1 Definitions

We distinguish the following definitions for renewable energy potentials, based on the World Energy Council report (WEC, 1994; Hoogwijk, 2004)[8]:

The *geographical potential* is the energy flux theoretically extractable in areas that are considered suitable and available for this production, that is, in areas which are not excluded by other incompatible land cover/use and/or by constraints set on local characteristics such as elevation and minimum average wind speed;

The *technical potential* is the geographical potential after the losses of the conversion from the extractable primary energy flux to secondary energy carriers or forms (electricity, fuel) are taken into account; and

The *economic potential* is the technical potential up to an estimated production cost of the secondary energy form which is competitive with a specified, locally relevant alternative. A flexible way to represent the economic potential is in the form of the energy production potential as a function of the production cost, the so-called long-run supply cost curve (LSCC).

---

[7] The method applied for each individual electricity resource has been published earlier in individual papers (Hoogwijk et al., 2005; Hoogwijk et al., 2004; Hoogwijk., 2004).

[8] The *theoretical potential* is the energy flux theoretically extractable from the renewable resource; it is rather arbitrary and has not much practical value so we leave it out here;

While the potentials are often presented as 'objective', most of them are strongly influenced by assumptions on average values and trends. The *geographical potential* contains by its very definition a number of assumptions on land suitability and resource availability. Some of these are, within the time period concerned, given – such as wind speed and solar radiation regime and soil characteristics.[9] Other assumptions are more of a socio-cultural or political-economic nature – such as land availability and the need for agricultural land to produce food. The *technical potential* is derived from the geographical potential and assumptions on the development of conversion efficiencies. For instance, for solar-PV electricity, assumptions need to be made on how conversion efficiency may develop from around 10% today to potentially much higher efficiencies in the future. Finally, for the *economic potential* it is necessary to estimate the average cost at which the secondary energy carrier (electricity, fuel) can be produced at a given locality. This depends on a variety of mostly techno-economic factors such as investment costs of available technology, labour wages and skills, and interest rates.

Whether a potential is realised and how fast – the *implementation potential* for any given year – depends on many of the assumptions underlying the geographical as well as the technical and economic potential calculations. Moreover, policies and preferences in society (subsidies, feed-in tariffs and other policy incentives), perceived urgency of issues such as climate change or import dependence will all play a role in this respect. There may be some confusion as to the difference between economic and implementation potential. What we calculate as economic potential is the potential production of WSB-based energy at a given production cost. The implementation potential not only depends on these production costs, but also on system factors such as the production costs of alternative options to produce fuel, specific implementation barriers such availability of knowledge and the costs of integrating WSB energy into the larger energy system.[10] Despite clear definitions, the estimates of these potentials, and in particular of the geographical and implementation potentials, require a set of context-related additional assumptions. As we will show further in this article, coupling potentials to scenarios is one way of making these additional assumptions transparent.

3.2.2 Generic procedure to assess renewable resource potentials

The assessment methodology of a renewable energy potential can be formulated in a rather universal way. The relevant physical and geographical data for the regions considered are first collected on a sufficiently high resolution. We use the soil and land-use land-cover data from the IMAGE 2.2 model, available at grid-cell level (0.5° x 0.5°). The wind and solar characteristics are from the digital database at the same resolution constructed by the Climate Research Unit (CRU) and adjusted to the coordinates of the IMAGE-grid (New et al. 1997,

---

[9] For the possible change in wind speed due to climate change, see (Alcamo et al., 2002).

[10] These broader system considerations will be included in subsequent analyses with the energy model TIMER 2.0 and the land-use land cover sub-model of IMAGE 2.2 (see Hoogwijk et al., 2006).

1999).[11] This resolution is still too coarse for local assessments, but it has the advantage of global coverage.

Firstly, an assessment is made of which part of the area considered can be used for energy production given the physical-geographical characteristics, that is, of the average suitability/availability. This yields the *geographical potential* which is for a geographical unit (grid cell) *i* with an area surface A_i (in m^2). This is the general form:

$$EG_i = f_i A_i E_i \qquad \text{W} \qquad (3.1)$$

with E_i the theoretically extractable energy output per unit surface area (in W m^{-2}). The suitability/availability factor f_i typically depends on physical-geographical factors (terrain, habitation) but also on socio-geographical parameters (location, acceptability). The theoretically available primary energy E_i can only partly be extracted in the form of useful secondary energy carriers. This is accounted for in the expression for the *technical potential* ET_i:

$$ET_i = f_i \cdot A_i \cdot \Phi[\eta_i, D_i, \lambda_i] \cdot E_i \qquad \text{W} \qquad (3.2)$$

with Φ a function of the over-all conversion efficiency η_i, which depends on technology characteristics, and of the power density D_i. The latter represents constraints posed by technical factors such as turbine interference or biomass yields for the area f_iA_i under consideration, but also by social constraints such as the preference for dense or less dense wind parks and the associated visual impact. The parameter λ_i represents an aggregate of other parameters such as operational details. A next and final step is to relate this technical potential to the on-site production energy carrier costs. This results in the *economic potential* EE_{ic}:

$$EE_{ic} = ET_i \cdot \Psi[c, S_i, CP_i, \mu] \qquad \text{W} \qquad (3.3)$$

with *c* cut-off cost, that is, the maximum cost level considered. The symbol Ψ is a function converting technical to economic output. It contains two factors which are assumed to influence production costs: the conversion equipment scale, S_i, and the cumulated output for the area, CP_i. These two parameters take into account economies of scale (upscaling and

[11] The geographical co-ordinates of the CRU-data do not match completely with the grid cell definition of the IMAGE 2.2 database. The CRU database has been converted to the raster of the IMAGE 2.2 database from which all the land-use data are taken. There are also differences in the definition of land cells versus sea cells. This was the case for 4200 (border) grid cells. These data have been converted by means of linear interpolation. Cells that border the shore are included in this study if more than 10% is defined as land. We have included only the onshore area fraction in these cells.

series production) and learning-by-doing which both tend to lead to lower specific investment costs (see e.g., Junginger et al., 2005). The parameter μ consists of operational parameters which in this analysis are all considered to be site-independent, as will be discussed later.

To get the regional potential in energy units per year, one has to convert to GJ unit^{-1} y^{-1} or kWh unit^{-1} y^{-1} assuming that all energy flow densities are annual averages, and then sum over all the geographical units (grid cells) in the particular region. Summing up over all regions gives the worldwide (or global) technical potential. Arranging the outcome across the grid cells in order of ascending costs yields the regional and global LSCC and, for any cut-off costs *c*, the regional and global economic potential. We now proceed with the application of this generic approach to the three renewable sources: first biomass, then wind and solar-PV. The quantification of the assumptions is given in Appendix A.

3.2.3 Diesel fuel and electricity from biomass

Out of the many possible conversion routes from primary biomass to commercial energy carriers, we have selected only two:

- liquid biofuel (ethanol and Fisher-Tropsch diesel) for which we assume that it can be produced from three different crop categories: woody biomass (grown in short rotations), maize and sugar cane; and
- electricity, for which we consider woody biomass only

Together, these categories give a reasonable representation of the potential biomass production in a region given grid-cell level information on temperature, soil and precipitation. Other considerations are that there is plentiful information on all these three categories and that they, and in particular woody biomass, can be converted into all types of secondary energy carriers.[12] For moderate climates a typical crop is probably willow or poplar, whereas eucalyptus is often the most suitable perennial woody biomass crop in more tropical climates. However, the species of energy crop is not specified further because, among other reasons, in the IMAGE 2.2 model the productivity of energy crops is parameterised in a generic way by assuming optimal photosynthesis efficiency (e.g., optimal water use efficiency) at grid-cell level.

The *geographical potential* of biomass from energy crops thus becomes for a grid cell *i* (cf. Equation 1):

$$EG_i = \sum_{i=1}^{n} f_i \cdot A_i \cdot Y_i \cdot MF \qquad \text{GJ grid cell}^{-1} \qquad (3.4)$$

[12] The fact that non-woody, C4 grasses have not been included causes an underestimation of the potential in the tropical regions where higher productivity levels can be expected when herbaceous crops are used (Hall *et al.* 1993).

with the suitability/availability factor f_i accounting for competing land-use options, Y_i the harvested rainfed yield of energy crops in grid cell *i* based on IMAGE 2.2 (GJ m^{-1} y^{-1}), and MF the management factor representing the development of the management and technology (-). We have used the IMAGE 2.2 implementation of the IPCC SRES scenarios (IMAGE-team, 2001; Strengers et al., 2004) as the basis for evaluating the amount and quality of land which could become available for biomass-derived energy – hence, our potentials are scenario-based upper limits. The scenarios will be discussed in more detail in the next section.

The important step is to decide which of the various land categories (A_i) are available for energy crops and to which extent (f_i). We use the IMAGE-based estimates of the average productivity Y_i in any grid cell I and given year to choose areas to be considered: cropland is not available, forest lands are to be preserved and low-productivity land will not yield competitively-priced biomass.[13] Hence, the categories abandoned cropland and rest land are the interesting ones.[14] The exogenously set management factor is assumed to increase over time (cf. paragraph 3.3). Besides the differences in land availability, this is the other major reason why the calculated biomass potentials will differ for the scenarios. Given these assumptions, we calculate the scenario-dependent potential for primary biomass. The next step is then to estimate the *economic potential* in the form of an LSCC. The cost of primary biomass $C_{\text{prim},i}$ is calculated for grid cell *i* as:

$$C_{prim,i} = CL_{i \subset R} / Y_i + a \cdot \lambda_{Bprim} \cdot K_{Bprim} + w \cdot \lambda_p \cdot L \quad \text{US\$ GJ}^{-1} \qquad (3.5)$$

with $CL_{i \subset R}$ the region-dependent land costs (US\$ ha^{-1}) taken from Hoogwijk (2004), *a* the annuity factor (yr^{-1}), $\lambda_{B\text{prim}}$ the learning coefficient and $K_{B\text{prim}}$, *L* the specific capital (US\$ GJ^{-1} yr^{-1}) and labour (hr GJ^{-1}) requirements respectively.[15] The ratio *K*/*L* is made dependent on the relative cost ratio (wages/interest rate, or *w/r*) according to a Cobb-Douglas production function to take into account that capital will be substituted for labour if wages rise.

Primary biomass is converted into liquid biofuel or feedstock for electricity production, for which in both cases the same equation but a different parameterisation is used:

$$C_{\sec,i} = CP_i / \eta + a \cdot I_{B\sec} \cdot \lambda_{B\sec} / LF_s + OM_s * \lambda_{B\sec} \quad \text{US\$ GJ}^{-1} \qquad (3.6)$$

---

[13] For the definitions of crop productivity as used in the IMAGE-model, see Alcamo et al., 1998 and Hoogwijk et al., 2005.

[14] Rest land here is the leftover of the other categories (cropland, abandoned cropland, bioreserves, forest and low-productivity lands) corrected for grassland, forest land, urban area and bioreserves and includes mainly savannah, scrubland and grassland/steppe. Tundra area is excluded as it is considered to be unsuitable for energy crop production.

[15] As is seen from this formulation, the cost reduction from learning-by-doing is assumed to be factor-neutral in capital and labour.

with η the conversion efficiency, $I_{B\text{sec}}$ the specific investment costs, $\lambda_{B\text{sec}}$ the learning factor, LF_s the load factor (hr yr^{-1}) and OM_s the operation and maintenance costs (US\$ GJ^{-1}) for the conversion equipment under consideration. Conversion efficiency and capital requirements are crop-specific and based on Damen and Faaij (2004), Hamelinck (2004) and Hendriks et al. (2004). In the case of biofuels, in each grid cell the crop with the lowest production costs is chosen from the three different feedstock crops. If the biomass is used to generate electricity, two different dedicated power plant types are considered (conventional and gasification) and in each grid cell the plant type with the lowest costs is chosen. Until 2030 the conventional plant is generally the cheaper option; after 2030–2050 the gasification plant is (cf. section 3.3.3). The expression for the resulting electricity generation cost is:

$$C_{Belec,i} = C_{\text{sec},i} / \eta + a \cdot I / LF_{elec} + OM_{elec} \qquad \text{US\$ GJe}^{-1} \qquad (3.7)$$

3.2.4 Electricity from on-shore wind

The resource data are monthly wind speed data in m s^{-1} at a height of 10 m from climatic average measured values (1961–1990) from 3615 stations covering the world and adjusted to the IMAGE-grid (New et al., 1997, 1999).[16] The function used to convert wind speed data at grid-cell level into the *technical potential* (cf. Equation (1); (2)) can be written in condensed form as:

$$ET_i = [(A_i - u_i)a_i w_i b_i r_i / A_i] \cdot A_i \cdot \eta_a \cdot \eta_{ar} \cdot D \cdot h_{f,i} \qquad \text{W grid cell}^{-1} \qquad (3.8)$$

with the first term between brackets the suitability/availability factor f_i in the area A_i. The parameter r_i indicates whether the wind regime in grid cell i is viable for which we use the criterion that the adjusted average wind speed should exceed 4 m s^{-1} at a height of 10 m.[17] This leads to regional r values in the range of 0.01 (Southern Africa) to 0.55 (USA). The other geographical constraints: exclusion of urban land (u_i), land above 2000 m (a_i) and constraints due to land use such as agriculture (w_i) and bioreserves (b_i) have been taken from IMAGE-data for the year 1995 (IMAGE-team, 2001). The second group of variables/parameters consist of η_a, the average availability of the wind turbine (-), and η_{ar}, the wind farm array efficiency (-). D_i is the power density[18] (MW km^{-2}) and $h_{f,i}$ indicates the full-load hours the average wind turbine in this area is assumed to operate (hr). We take a 1 MW

[16] The coverage of the stations is highest in Europe and lowest in Oceania. There are various sources of errors, for attempts at correction have been made (New *et al.* 1999). Adjustment, (also for solar irradiance) was necessary because the co-ordinates of the CRU wind speed data do not completely match with the definition of grid cells in IMAGE 2.2, especially with regard to the definition of land versus sea.

[17] Other analyses have used stricter criteria, for example, a wind regime above 6.0 m s^{-1}, or 5.1 m s^{-1} at 10 m (Grubb and Meyer, 1993; World Energy Council, 1994), partly on economic grounds. In our approach such sites would show up in the upper end of the LSCC. Also, the database we use (see note 2) gives one single number for the annual average wind speed at the specified resolution of 0.5° x 0.5°. Such values are rather low (80% of the land area has an annual average wind speed lower than 4 m s^{-1} at 10 m in the CRU database) and neglect the potential large spatial and temporal fluctuations which could make wind turbines attractive.

[18] The assumption on power density D implies that on any given area designated as 'suitable' (f_i), one can either install many small or a few big installations. For instance, D = 1 MW km^{-2} can be as a single 1 MW turbine in the centre of a grid-square or as 4 250 kW turbines at halfway between the square centre and square corner.

turbine with 69 m hub height as the reference and adjust the wind speed data for this hub height of 69 m according to the standard height correction formula and estimates of the roughness length for each grid cell. We have used the assumption that $h_{f,i}$ is a linear function of the annual average wind speed (based on Abed and El-Malllah, 1997). The other parameters in equation (8) concern efficiency and spacing. The value of η_a is set at a conservative 0.95. The value of η_{ar} depends on the configuration of wind turbines in a farm; we have chosen 0.9, which is consistent with the placing of four 1 MW turbines 500 m apart. We have not differentiated across grid cells, that is, we make one parameter choice for the whole world. Of course, at this level of aggregation any assumption on these variables can be contested so we add a sensitivity analysis in the next paragraph. For instance, extreme wind speed distributions may yield results quite out of the range of our regression-based relationship.

The third and last step is an estimation of the on-site generating costs. We use the standard engineering cost approach:

$$C_{Welec,i} = \frac{a \cdot (1 + OM_w) \cdot I_w \cdot D}{E_i} \quad \text{US\$ kWh}^{-1} \qquad (3.9)$$

with $C_{Welec,i}$ the production cost of electricity in grid cell i (US$ kWh^{-1}); a the annuity factor (yr^{-1}), and OM_w the cost of operation and maintenance as a fraction of the investment cost.[19] We use site-independent estimates for the various parameters (cf. Appendix A). The cost for grid connection and infrastructure are set at US$ 0.01 kWh^{-1}, based on EWEA/Greenpeace (2002).

3.2.5 Electricity from solar-PV

We confine ourselves to centralised grid-connected PV systems: medium to large-scale systems (10 kWp to many MWp)[20], installed on the ground. As primary resource data we use the average monthly irradiance I_i (W m^{-2}) for a surface grid (0.5° x 0.5°) constructed from measurements at 4040 stations covering the world in the period 1961–1990 and adjusted to the IMAGE-grid (New et al., 1997).[21] Values in between the stations are determined using an interpolation method as a function of longitude, latitude and elevation. Yearly average values range from a low 60 W m^{-2} at the highest latitudes to a high 250 W m^{-2} in some desert areas in Western and Northern Africa and Australia. Since the absorption of radiation in the atmosphere is included in the CRU data, the results differ from the numbers derived theoretically.

---

[19] Annuitising is done in the usual way: $a = r/[1-(1+r)^{-L}]$ with r the interest rate and L the economic lifetime.

[20] The unit Watt-peak (Wp) refers to the produced power under standard test condition (STC), that is, a module is illuminated with light characterised by an AM1.5 spectrum at a total intensity of 1000 W m^{-2} while held at a temperature of 25ºC.

[21] The data represent the irradiance at a horizontal plane and include both direct and diffuse irradiance. See also note 7.

The conversion from solar irradiance data at grid-cell level into the *technical potential* – extractable solar-PV based electric power – is similar to the one for wind energy (cf. equations 1; 2):

$$ET_i = [f_i A_i] \cdot 8760 \cdot I_i \qquad \text{Wh grid cell}^{-1} \qquad (3.10)$$

with I_i the annually averaged irradiance in cell *i* (W m^{-2}) and 8760 hours in a year.[22] The first term between brackets equals the product of suitability/availability factor f_i and cell area A_i and indicates the area considered suitable for solar-PV. Some considerations in estimating the f_i for centralised systems are: cropland area is restricted to small parts next to infrastructure or fallow areas; extensive grassland is given a higher suitability/availability factor than agricultural areas; nature-protected and forest areas are excluded, as well as urban areas for which we assume decentralised systems to be preferred over centralised ones. We have also used estimates made in other analyses (Weingart, 1978; Sørensen, 2000).[23] The final step, the calculation of the economic potential, is done similarly to the procedure for wind.

3.3 Renewable energy potentials: uncertainties and scenarios

3.3.1 Dealing with uncertainties

Any assessment of the potential supply of renewable energy at a regional/global scale implies significant uncertainties. Using a grid-cell level analysis, one has to balance the availability of data and the local variation on the one hand and their relevance for the WSB potentials on the other. An additional complication is that most parameters are time-dependent in ways that are difficult to forecast. Our approach has been to identify those parameters which are largely physical in nature and to analyse the uncertainties generated by extrapolating limited observations across large areas and over time. The remaining parameters often depend on rather complex, location- and time-dependent developments in society. For these, we use the scenario approach. That is, we estimate plausible 'best' values in the context of a narrative (storyline) about the future. Thus, we distinguish three uncertainty categories in the parameters:

- those that are totally or largely based on scientific measurement/observation; for these one can use conventional sensitivity analysis and their values can be expected to improve in quality over time;
- those that depend on complex interactions between social, economic and technical variables but for which different values can be used to make meaningful

[22] The orientation of the installed PV modules towards the sun is important for the output. We have assumed horizontally placed modules; this probably has no large influence on the outcome.

[23] In IMAGE 2.2 values for the urban area were derived from the 1 km x 1 km DIScover database (Loveland and Belward, 1997). This database, in which urban area is defined as land covered by buildings and other human-made structures, has been converted to 0.5° x 0.5° grid cells to construct a database giving the fraction of urban area in each IMAGE grid cell.

differentiation within a scenario storyline context and on the basis of existing literature; and

- those that also depend on complex interactions between social, economic and technical variables, but for which no direct argument could be made to connect their values to scenario storylines; for these parameters, one value has been chosen across all scenarios.

Table 3.1 indicates which factors have been considered in the analysis, and in which uncertainty class they are placed. The most obvious and relevant class 1 parameters are the average grid-cell values for wind speed and solar irradiation. These are assumed to be homogeneous within any grid cell and constant over time. Important class 2 parameters are yields, conversion efficiencies and costs, learning coefficients and typical scenario variables such as population and economic growth paths and management factors. Usually, they vary with scale, manufacturer, location and time and one would like to have a representative average value at any given place and time.

In practice, we have tried to strike a balance between feasibility on the one hand and available data and insights on the other. This has resulted in regional, but not local differentiation in conversion efficiencies (η_i) and power densities (D_i) and in some economic parameters (cf. Appendix A). The most important class 3 parameters are the land-use suitability/availability factors. Indeed, one could imagine linkages between f_i and a scenario storyline. For instance, a majority of people may in an environment-oriented scenario (B1 or B2, see below) wish to restrict biodiversity impacts of WSB, which would make low f_i values a consistent choice. However, if one assumes a global orientation (B1, see below), the seriousness of global environmental problems like climate change could justify the acceptance of more widespread introduction of WSB options c.q. high f_i values. Given this ambiguity and in order to increase comparability across the scenarios, we have decided to use the same set of f_i across the scenarios in this paper.

Table 3-1 Different uncertainties determining WSB potential. The three uncertainty categories are indicated in plain: class 1; italic: class 2; and bold: class 3.

Category	Wind	Solar	Biomass
Population and GDP	*SRES scenarios (IMAGE, 2001)*		
Land-use land cover [change] including food trade and meat consumption	*SRES scenarios (IMAGE, 2001)*		
Resource Base	Average wind speed Roughness factor Land suit./avail. Factors	Solar irradiation Land suit./avail. factors	*Energy plantation yield* Land suit./avail. factors
Technology	*Average turbine size* *Conversion efficiency*	*Average solar-PV plant scale* *Conversion efficiency*	*Management factor* *Conversion efficiency*
Economic	*Specific investment cost* Interest rate *Transport cost*	*Specific investment cost* Interest rate *Transport cost*	*Specific investment cost* *Wage rate* Interest rate *Transport cost*

3.3.2 The four scenarios and the land-use land cover changes

The scenario analysis in this paper focuses on uncertainties in land-use land cover and in specific techno-economic WSB parameters. We used the four land-use scenarios that were developed using the IMAGE-model (IMAGE-team, 2001; Strengers et al., 2004), based on the four qualitative storylines developed in the context of the IPCC (Nakicenovic et al. 2000). These four storylines can be represented along two axes, one indicating people's orientation towards economic/material issues and one reflecting the tendency towards globalisation/regionalisation. From this, four scenario 'families' have been constructed (Figure 3.1: A1, A2, B1, B2).[24] Land-use land cover differs in the scenarios due to different growth rates for regional population and economic activity (i.e., Gross Domestic Product (GDP)) as well as meat consumption, agro-technological changes and food trade.

[24] For more details on these scenarios, see: www.mnp.nl or www.ciesin.org. We have used the parameter settings of the A1B storyline.

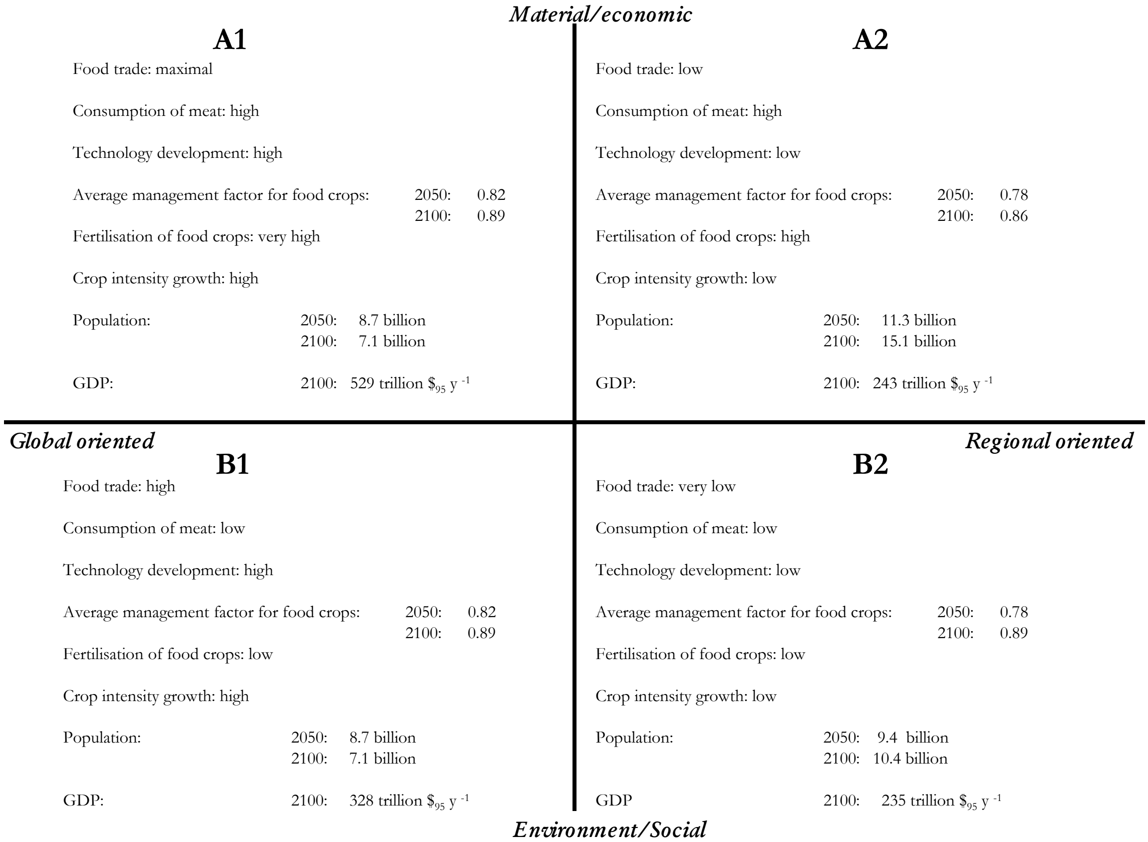


Figure 3-1 Schematic overview of the scenarios used and of the main assumptions to simulate the land-use dynamics in the IMAGE 2.2 SRES implementation (IMAGE-team, 2001).

The A1 storyline, which is the one used here as the reference, describes a trend towards a high-tech and increasingly globally interconnected world, driven by an orientation on markets, deregulation and the removal of trade barriers. It is assumed that such a world would lead to high economic growth, and, partly as a consequence, a low population pathway. The A2 storyline describes an alternative development path, dominated much more by economic and cultural protectionism, driven by factors such as resistance against 'modernisation' and concern about regional identity. It is assumed that such a world would experience low economic growth and high population growth. The B1 storyline describes a pathway of increasing global interdependence combined with increasing concern and policies for environmental integrity and social justice. Here economic growth in currently low-income regions would be high, and population growth relatively low. Finally, the B2 storyline describes a development path with a strong orientation on local/regional well-being in a broad sense, with medium assumptions for economic and population growth.

The scenario families are best interpreted as archetypical futures along which the world system might evolve. Real-world developments could follow any combination of these, in the sense that over time and across the many facets of the world system the emphasis may shift from one scenario to another. Unexpected and/or extreme events such as terrorist attacks, oil supply crises, or a severe and sudden disease outburst or climate disruption could cause an enduring shift from one scenario family to another – and hence change the prospects for WSB options.

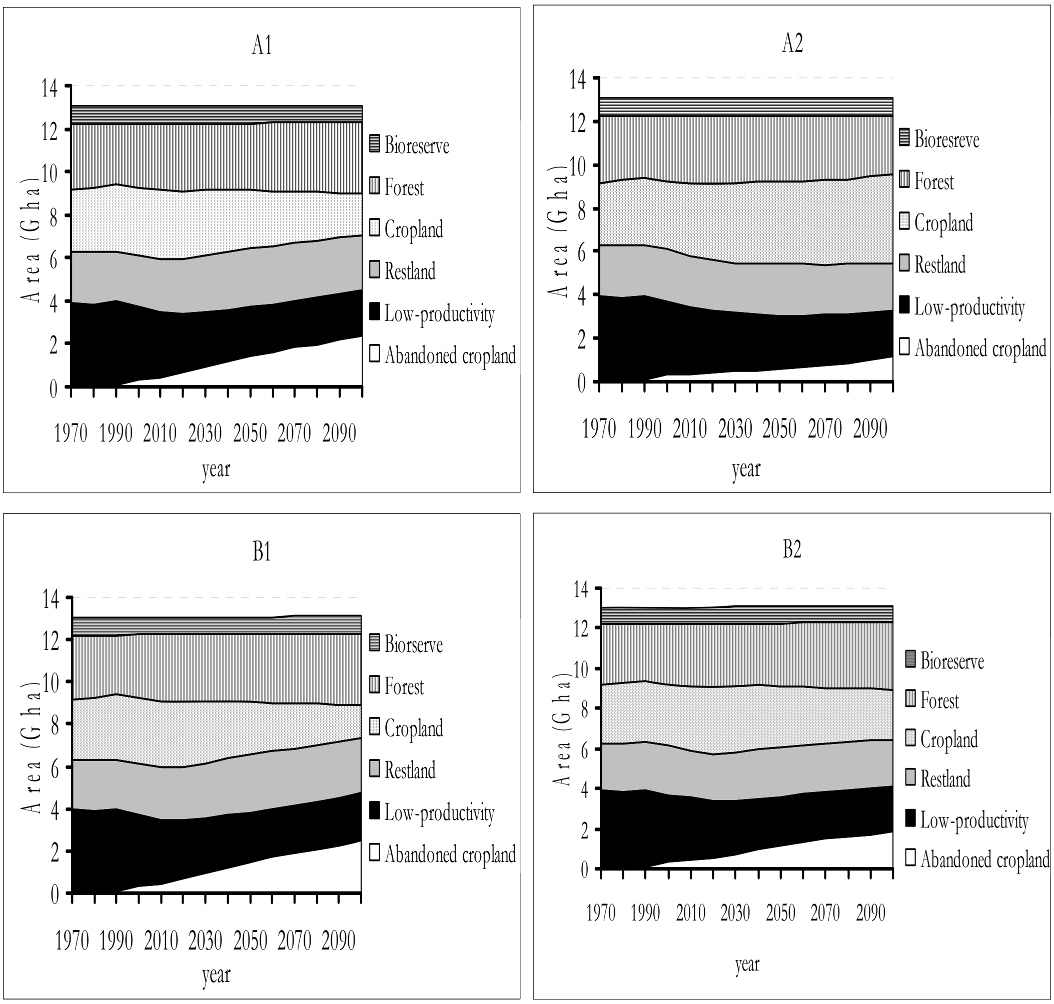


Figure 3-2 Land-use land cover changes in the IMAGE 2.2 IPCC SRES scenarios, used as the basis for the estimation of the primary biomass production potential.

Figure 3.1 summarises the assumptions for the four narratives used in this analysis to simulate the land-use dynamics in the IMAGE 2.2 model. The four scenarios lead, for the period considered (2000–2050) to divergent land-use land cover projections (Figure 3.2). In all scenarios agricultural land is taken out of production, either because of surplus agricultural land or shifts in production patterns. The area of abandoned agricultural land is highest in the B1 and A1 scenarios, mainly due to surplus agricultural land as a consequence of a stabilising world population and fast and widespread yield improvements. At the other extreme, high population growth and slow technological improvements in the A2 scenario result in a higher demand for land-for-food and, subsequently, in less abandoned agricultural land and less forested land due to the production of food and fodder.

Table 3-2 Assumed suitability fraction in % by land-use category: default values and (between parentheses) maximum values.

Land-use category included	Wind	Solar-PV	Biomass
Agricultural land	60(30/90)	0	0
Abandoned agricultural land	80(50/90)	80(50/90)	80(50/90)
Extensive grassland, grassland and steppe, scrubland, savannah	20(10/25)	10(5/15)	20(10/25)
Hot desert, wooded tundra	10(5/20)	5(2.5/10)	10(5/20)
Temperate deciduous/mixed forest, Warm mixed forest, regrowth forest (timber)	0(0/5)	0	0
Considered inaccessible and/or not permissible:	0	0	0
Ice, Boreal forest, cool coniferous forest, tropical woodland/forest			
Urban area, nature reserve/development	0	0	0

To assess the WSB-potential we assigned values to the suitability/availability factors f_i, the same for all four scenarios (class 3; cf. Table 3.2). Certain land-use/cover classes are completely excluded – such as urban areas, nature reserves and inaccessible ice. Also forested areas are (almost) completely excluded. The huge grassland ecosystem areas, including the scrublands and savannahs, are considered to be available for all three WSB-options for a quarter or less. The hot desert and tundra areas are considered to be less accessible under normal circumstances. For all these land areas, we reckon that after initial penetration in the more favourable locations – based on criteria such as demand proximity, landscape features, and so on – counteracting forces will make further penetration more difficult. Such forces may have to do with nature conservationists' resistance, transport barriers, interference with other land functions such as nomadism and tourism/recreation.[25] Here, the most interesting category is that of the abandoned agricultural lands. We consider these to be available up to 80–90%.[26] Besides these considerations, the values are based on estimates and arguments used by other authors (BWEA, 2000; Cabooter et al., 1997; EIA, 1999; Elliot and Schwarz, 1993; WBGU 1999; WCPA, 2000). The divergence in scenario drivers leads to different land-use land cover patterns and thus to different calculated WSB potentials.

3.3.3 Future technological development

Our assessment of the economic potential in the form of long-run supply cost curves (LSCC) requires assumptions on future technological changes, notably in specific investment costs

[25] Recently, a vigorous debate has grown about the trade-off between conservation of biodiversity on the one hand and large-scale introduction of biofuel plantations on the other, see Brink *et al.* 2006.

[26] The inhabited parts are excluded: the areas refer to uninhabited parts that are at any given time no longer used for agriculture.

and conversion efficiencies and yields. For the WSB energy sources, energy production costs have significantly declined in the past decades. Conceptually, one often deals with future cost developments by using a learning curve which postulates that the cost/performance parameter of the *i-th* unit, C_i, is a downward sloping function of cumulated output, $C = aY^{-b}$, with b the learning coefficient and C usually the specific investment costs – in the case of WSB € kWe^{-1} installed or € GJ^{-1} yr^{-1} capacity. Such a relationship reflects aggregate trends in upscaling and mass production, incremental innovations and technological breakthroughs (IEA, 2000; Junginger et al., 2005). An overview of some current and future cost estimates published in literature is given in Table 3.3. Our assumptions for this analysis have been based on these estimates and on estimates of the progress ratios from literature sources. Following the scenario storylines we assume technology progress in the A1 and B1 scenarios to be rapid – and thus consistent with the lower cost estimates mentioned in Table 3.3. In contrast, we assume technological progress in the A2 and B2 scenario to be slow and medium respectively, and thus consistent with the upper and medium values, respectively, of the range in Table 3.3. The cost trajectories over time have been translated into specific, exogenous parameter assumptions. The Appendix A presents all assumptions for each of the scenarios.

For energy from biomass, technological progress has been introduced via the management factor (MF) and via improvements in both production and conversion equipment. A change in the MF implies a change in the yield of energy crops Y_i through better management, biotechnology and fertilizer use (cf. equation 4). We assume an exogenous increase of MF from the 2000 value of 0.7 to values between 1.3 and 1.5 by 2050, depending on the scenario. For wind energy, the cost decline stems largely from increasing turbine size, from 200 kW in 1990 to about 1.5 MW in 2002 (EWEA and Greenpeace, 2002). Progress ratios for wind energy have been found of 0.85–0.96 or 15–4% reduction per doubling (EWEA and Greenpeace, 2002). For solar-PV, the declining specific investment costs come from innovations in conversion efficiency and module-based production techniques. The module selling price has been falling continuously, from about 55 US$ Wp^{-1} (Harmon, 2000) in 1979 to world average PV module prices of 3–6 US$ Wp^{-1} in 2002 (solarbuzz, 2002). Past experience suggests a 20% cost decline with every doubling of cumulated generating output, that is, a progress ratio of about 0.8. We assume a further drop, in one scenario to as low as 0.5–1 US$ Wp^{-1} after 2015 (Turkenburg, 2000). For biomass-based electricity generation we assume similar learning-by-doing progress as for wind power.

Table 3-3 Estimates of future cost range of WSB electricity options (sources: Rogner, 2000; IEA, 2000; WEA, 2000; Nakicenovic et al., 2000; Ericsson and Nillson, 2003; ATLAS, 2005; Kobos et al., 2005; Nemet, 2005).

	Current $ kWh^{-1}	Short term (2010/2020) $ kWh^{-1}	Medium Term (2030) $ kWh^{-1}	Long Term (2050) $ kWh^{-1}
Wind	0.05–0.13	0.03–0.08	0.03–0.05	0.03–0.10
Solar-PV	0.25–1.25	0.25–0.40	0.15–0.30	0.06–0.25
Biomass	0.05–0.10	0.03–0.08	0.03–0.04	0.03–0.10

3.4 Worldwide renewable energy potentials

In the previous section we sketched the generic methodology, the parameter choices and their uncertainties – we are now ready to present the results. We first discuss the potential for each of the WSB options. Next, we present the summed potentials taking into account interactions. Finally, these results are examined in the context of existing developments and policy regimes and longer-term penetration dynamics.

3.4.1 The worldwide potential for liquid biofuels for transport

Figure 3.3 shows the global potential production of liquid biofuel at different cost categories by scenario. In the year 2000 this potential amounts, after conversion to the final energy carrier, to 30–40 EJ yr^{-1} according to the methodology applied. Figure 3.4 shows the regional breakdown for the scenario with highest (A1) and lowest (A2) potential. Most of this potential comes from abandoned agricultural and grassland areas in Europe, the USA and the former Soviet Union (FSU). In addition, savannah and grassland areas in South America, Africa, Southeast Asia and Australia add to this, in fact giving the lowest production costs. This stems largely from woody biofuels and maize in the temperate zones and from sugar crops in the tropical zones.

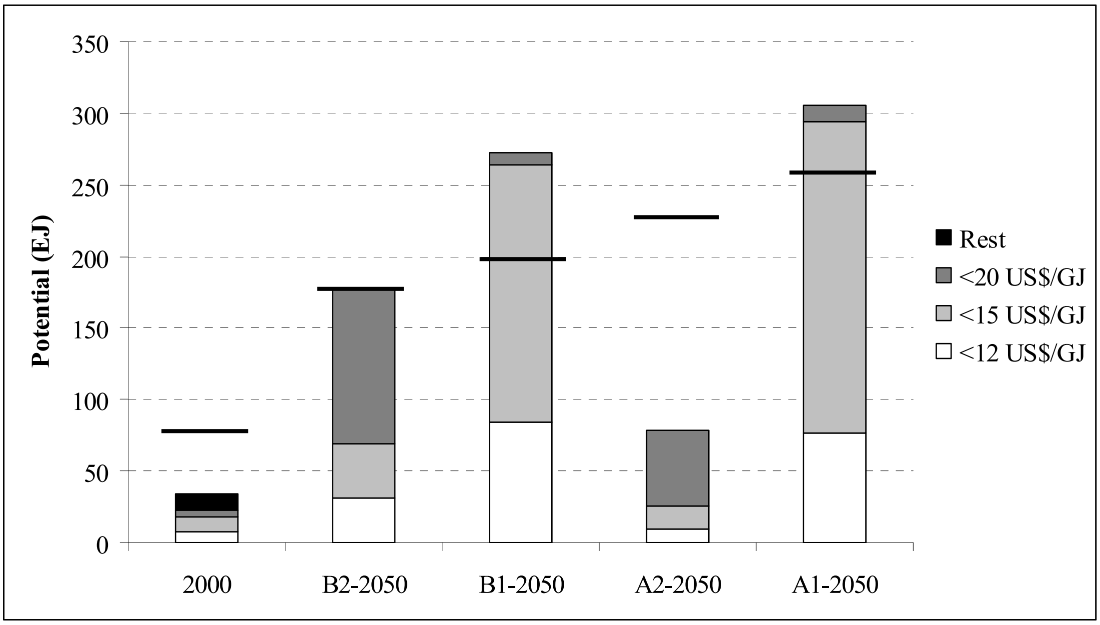


Figure 3-3 Potential global biofuel production for four production cost categories (IMAGE-team, 2001). The horizontal line indicates historical c.q. estimated future transport energy demand.

By 2050, in all four scenarios the total potential has expanded – to about 75 EJ yr^{-1} in A2, 175 EJ yr^{-1} in B2 and 250–300 EJ yr^{-1} in A1 and B1. The expansion is mainly driven by an increasing area of abandoned agricultural land, and, to a far lesser degree, increasing conversion efficiencies. In the two high-tech high-growth scenarios (A1 and B1), some 80 EJ yr^{-1} can be produced at costs between 10–12 1995US$ GJ^{-1} and about 200 EJ yr^{-1} between 12–15 1995US$ GJ^{-1} or two to three times the costs at which transport fuels are currently produced from oil. This high potential in A1 and B1 is mainly from modest population c.q. food demand growth and increasing agricultural yield and trade. In contrast, slow yield improvement and high population give a low potential in A2. In addition to the changes in total potential, Figure 3.3 and 3.4 also show that costs are assumed to come down substantially in most scenarios. While costs range from 10 to over 20 US$ GJ^{-1} in 2000, in both the A1 and the B1 scenario more than 25% of the potential is assumed to be available by 2050 at costs below 12 US$ GJ^{-1}. As a comparison of the potential production to global transport fuel demand in each of the scenarios shows (Figure 3.3), biofuel could by 2050 technically speaking supply 100% of global transport fuel demand in three out of the four scenarios if all the land considered suitable/available for biomass plantations were to be used for the production of transport fuel.

The regional breakdown (Figure 3.4) suggests that in particular South America, the FSU, East Asia, Oceania and the USA could by 2050 contribute to the potential biofuel expansion under the A1 scenario. However, low-cost biofuel production options are restricted to the tropical regions (South America, Africa, and Southeast Asia), making these regions attractive for biofuel export. The difference between the A2 and the A1 scenario is largely the reduced potential in South and Central America and West and East Africa: whereas the potential in the temperate regions is halved, it falls by over 80% in the tropical regions. The lower potential estimate in the A2 scenario is a direct consequence of more people hence higher food demand and lower yield (improvement) hence more land demand – one aspect of the food vs. energy nexus.

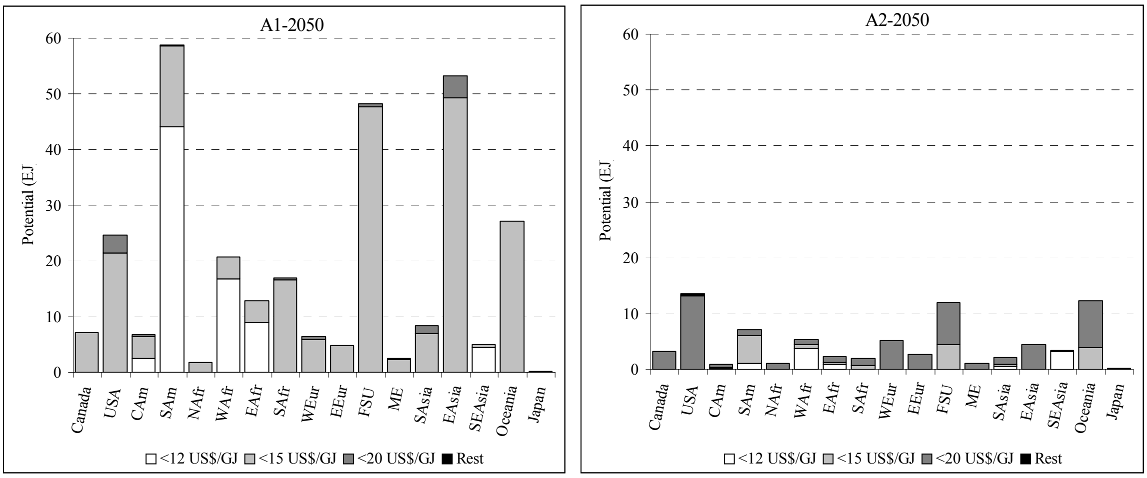


Figure 3-4 Regional biofuel production potential for the A1 and A2 scenario in 2050. The same colour code is used for the production cost categories as in Figure 3.3 (white: <12 US$ GJ^{-1}; grey: <15 US$ GJ^{-1}; dark grey: <20 US$ GJ^{-1}; black: other).

3.4.2 The worldwide potential for electricity from WSB (individual options)

Electricity can be generated from all three WSB energy sources – but they do compete for land as all three are land-intensive, though to varying degrees. This can already be shown with a 'back-of-the-envelope' calculation. Let us put the average solar irradiation at 150 W m^{-2}, the average wind speed at 6 m s^{-1} at hub height and the average biomass production at 10 tonne ha^{-1} y^{-1}. Using these values and a suitability/availability factor of 1, we find a theoretical electricity production density of about 18 (solar-PV), 7 (wind) and 2 GWh yr^{-1} km^{-2} (biomass).[27]

The worldwide technical potential is the product of electricity production density and the suitable/available land area. Calculating this for all cells and summing up over regional areas yields the regional technical potentials for 2000 and 2050. It is shown in Table 3.4 for the land cover according to the A1 scenario and the assumptions presented in Table 3.2. The technical potential for the world as a whole is largest for solar-PV; the technical potential for wind is only some 2% of it. This is partly compensated by the higher land suitability/availability for wind (Table 3.2). Biomass-based electricity is limited in 2000 by the agricultural land abandoned – but becomes comparable to wind in 2050.

[27] Other assumptions are: conversion efficiencies of 14% (for solar-PV) and of 40% (for biomass) and a Lower Heating Value (LHV) of 15 GJ $tonne^{-1}$. The electricity production density in GWh yr^{-2} km^{-2} can be seen as the inverse of the land productivity in km^{-2} GWh^{-1} yr^{-1}.

Table 3-4 Estimated technical potential of the three WSB options in PWh yr–1 for the 17 regions.

	2000			2050		
	Wind	Solar-PV	Biomass	Wind	Solar-PV	Biomass
Canada	3	18	0	4	82	2
USA	16	73	1	22	255	5
Central America	2	12	0	2	84	1
South America	3	64	1	5	505	8
Northern Africa	1	62	0	1	148	0
Western Africa	0	96	1	0	333	3
Eastern Africa	1	52	0	1	240	3
Southern Africa	0	60	0	0	336	3
OECD Europe	3	19	0	5	46	2
Eastern Europe	0	5	0	1	42	1
Former Soviet Union (FSU)	8	146	1	11	556	11
Middle East	1	85	0	1	174	1
South Asia (incl. India)	1	54	0	1	192	2
East Asia (incl. China)	1	58	0	2	640	11
Southeast Asia	0	17	0	0	25	1
Oceania	4	118	1	6	443	5
Japan	0	1	0	0	2	0
Total	43	939	7	61	4105	59

Using the cost formulas discussed in section 3.2 and arranging the grid cells according to generation costs for the regions, one gets the economic potential for different cut-off levels of electricity production cost. The maps in Figure 3.5 show for the three options the locations at which electricity can be produced at a given cost, now and as estimated for 2050. In most of the scenarios, the situation changes considerably between 2000 and 2050 (Figure 3.5; 3.6; 3.7). The strongest increase in potential for wind and biomass occurs in the A1 scenario and is driven by great improvements in yield and a stabilising population and hence the lowest need for agricultural land. By 2050, the potential for electricity from wind is about two times the estimated potential in 2000 and the potential for electricity from biomass is about six times the estimated potential in 2000, largely confined to a few highly productive regions. In the B1 and B2 scenarios the potential also grows but more slowly. Wind power costs come down on average by about US$ 0.02–0.03 kWh^{-1} and is in some places generated at cost below US$ 0.04 kWh^{-1} in the A1 and B1 scenarios. Similarly, electricity from biomass in some places can be generated at less than US$ 0.06 kWh^{-1}. The prospects for biofuel will increase in temperate regions and grassland ecosystems. Our estimate of the WSB potential for the year 2000 at less than US$ 0.08 kWh^{-1} – which is about twice the cost of fossil-fuel based power – is about 7 PWh yr^{-1} for wind and for biomass. Below US$ 0.10 kWh^{-1}, these numbers are 20 and 7 PWh yr^{-1} respectively. The higher cut-off cost level hardly affects the biomass potential – which is restricted by available land – whereas it improves the prospect for electricity from wind. This difference in supply elasticity is reflected in the supply cost curves (Figure 3.6). For solar-PV, the potential for the year 2050 depends crucially on cost-reducing innovations: for our cut-off cost level of US$ 0.10 kWh^{-1}, a non-zero potential only emerges in the A1/B1 future, but at higher costs the solar-PV is huge in all scenarios (Figure 3.6).

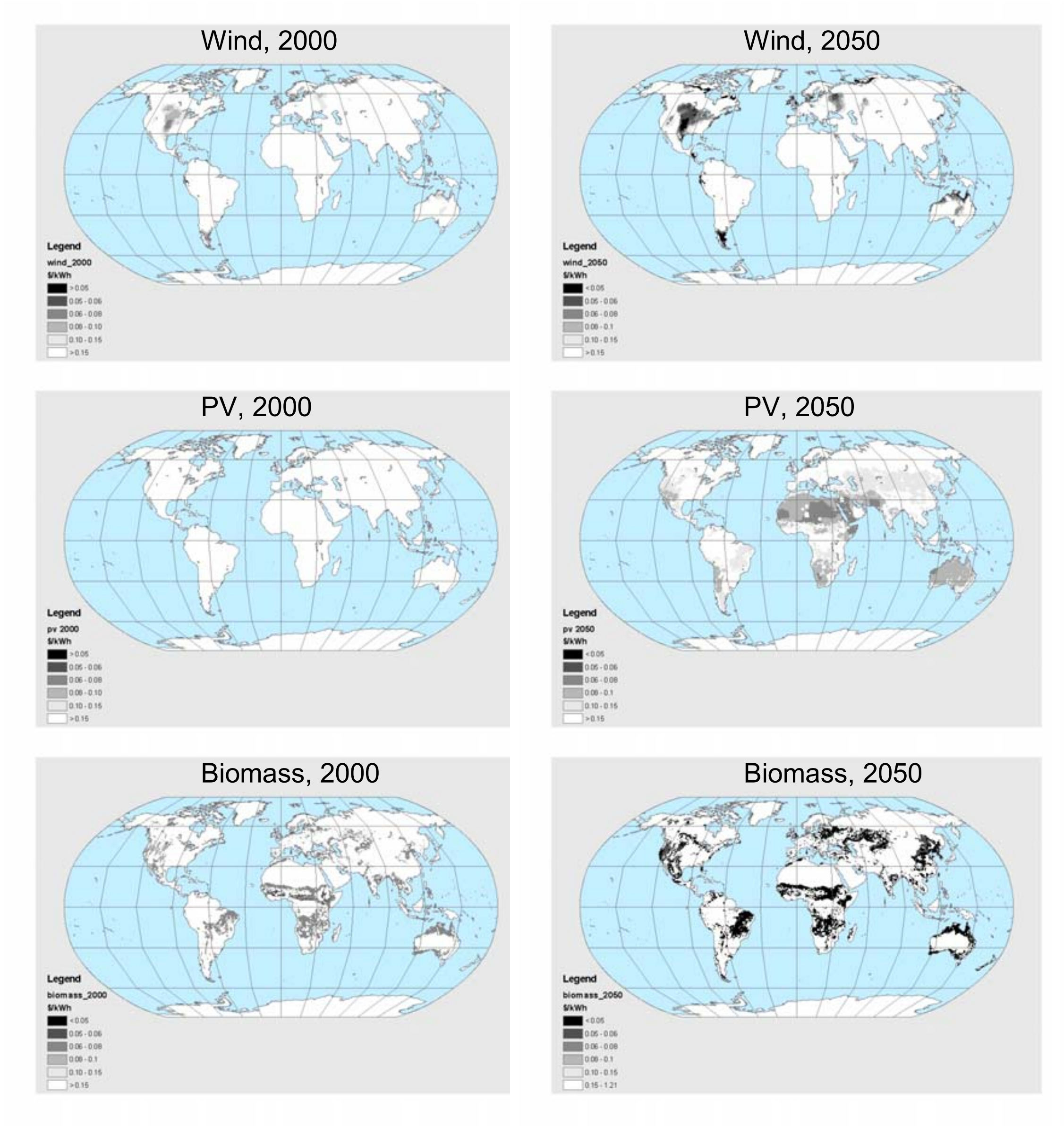


Figure 3-5 Estimated costs of producing electricity in the A1 scenario for wind, biomass and solar-PV in 2000 and in 2050.

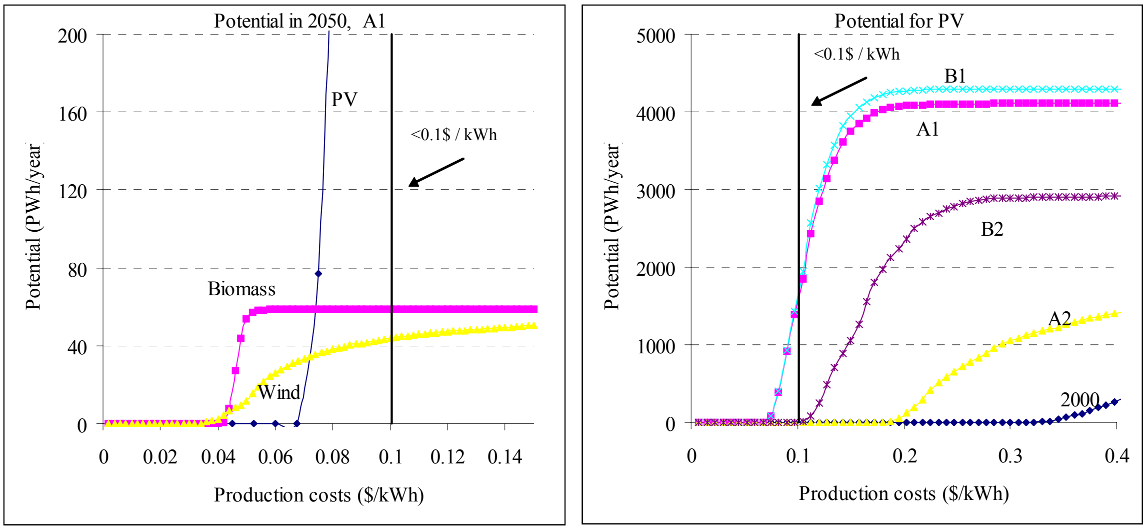


Figure 3-6 Cost supply curve for the WSB options in the A1 scenario in 2050 (left) and in all four scenarios for PV (right). The figure also shows the '0.1$/kWh' line used in this paper as an arbitrary cut-off cost in determining the economic potential (cf. Equation (3)).

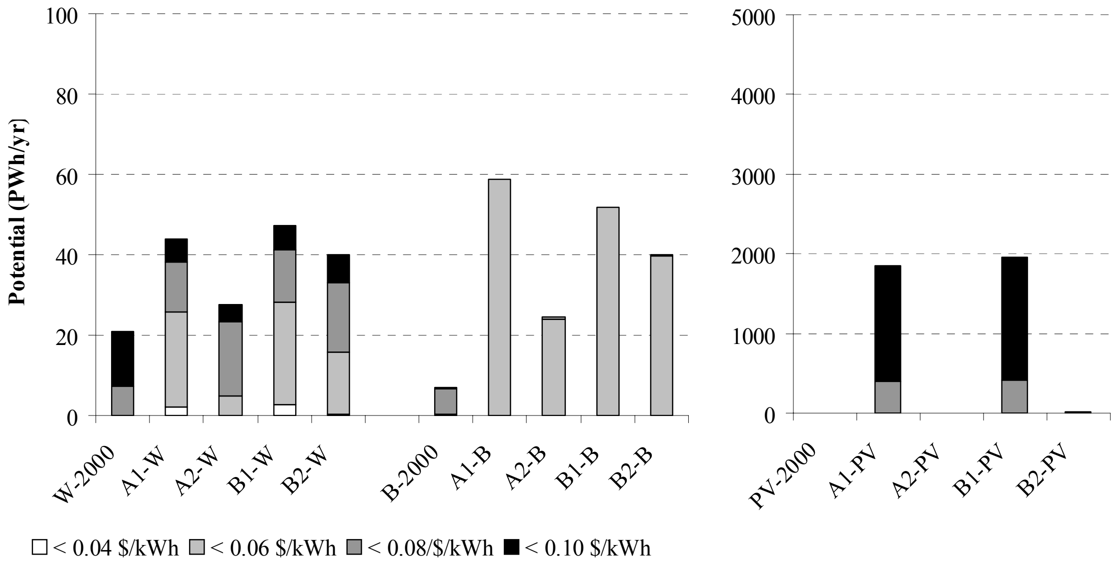


Figure 3-7 The global technical potential for electricity from wind and biomass (left) and solar-PV (right) in the year 2000 and in the four scenarios for the year 2050 for four production cost categories.

3.4.3 The worldwide potential for electricity from WSB (combined)

Because all three WSB options require land for their operation, one cannot simply add the potentials. In qualitative terms one can imagine several forms of interaction due to competition for land, some of them negative and some positive. Operation of more than one WSB-option may cause additional costs due to physical exclusion and interference, but also lower costs due to economies of scale in construction, operation and infrastructure. In order to identify potentially attractive areas for renewable energy production and to determine the overlap in the potential of the individual sources, we will now focus on those areas (grid cells) where one or more of the WSB options can produce electricity at less than US$ 0.10 kWh^{-1} in 2000 and 2050 (Figure 3.8). We restrict the discussion to the scenarios with the highest and lowest potential, A1 and A2.

Figure 3.8 (upper) shows that in the A1 scenario some form of WSB potential is available below US$ 0.10 kWh^{-1} in almost all areas of the world. Electricity from solar-PV is available in vast tropical areas; electricity from wind is concentrated in the temperate zones – but also some smaller areas in the tropical zones. Biomass can be produced on vast tracts of abandoned agricultural land in the USA, Europe and the FSU and on grasslands and savannah elsewhere. The figure also indicates that in large areas more than one form of WSB potential is available below this cost level. This is particularly the case for parts of the Western USA, the Eastern coast of South America, several savannah zones in central Africa, parts of India and China and coastal areas of Australia. Also in many areas of India, China and Central America and Africa south of the Sahara at least one, and often two, forms of WSB is available below US$ 0.10 kWh^{-1}. This potential is the more interesting because it is available in areas where there is already now or in the near future a large demand for electricity – and nearby demand centres may diminish investment costs and operational system costs of WSB. The calculations also show that there are large and sometimes densely populated regions where renewable energy sources are hardly or not at all available, given our assumptions.

In the A2 scenario (Figure 3.8, lower), the situation is much less favourable. There are still large areas in Africa, Australia and India where two or even three of the WSB-options can contribute, but outside these regions the potential to produce electricity below US$ 0.10 kWh^{-1} is quite local and limited. Now areas with two different options are restricted to the Western USA, parts of Western Europe, some parts of the FSU, South Asia and the northern part of Australia. Comparison of the two maps shows that in particular the slower decline in solar-PV costs and the higher demand for land-for-food are causing the difference.

In trying to combine the different potentials we need to establish which options compete for the same land. For instance, biomass plantations make it impossible to install solar-PV panels and in some places wind turbines may combine badly with solar-PV. On the other hand, a combination of wind turbines and local electricity from biomass or solar-PV may yield economies of scale in transport and storage systems, particularly in urban areas where infrastructure costs may be shared. We have used two methods for summing up the technical potentials across grid cells and regions: in *method 1* we use our best guess: it is assumed that wind turbines can be combined with biomass plantations or solar-PV modules but only on half of the suitable/available area; and that the production of biofuel-based and solar-PV-based electricity cannot be combined and therefore we consider only the lowest cost option in the grid cell considered. In *method 2* we are conservative: we assume that no dual land use is possible and in each cell only the lowest-cost option can be implemented.

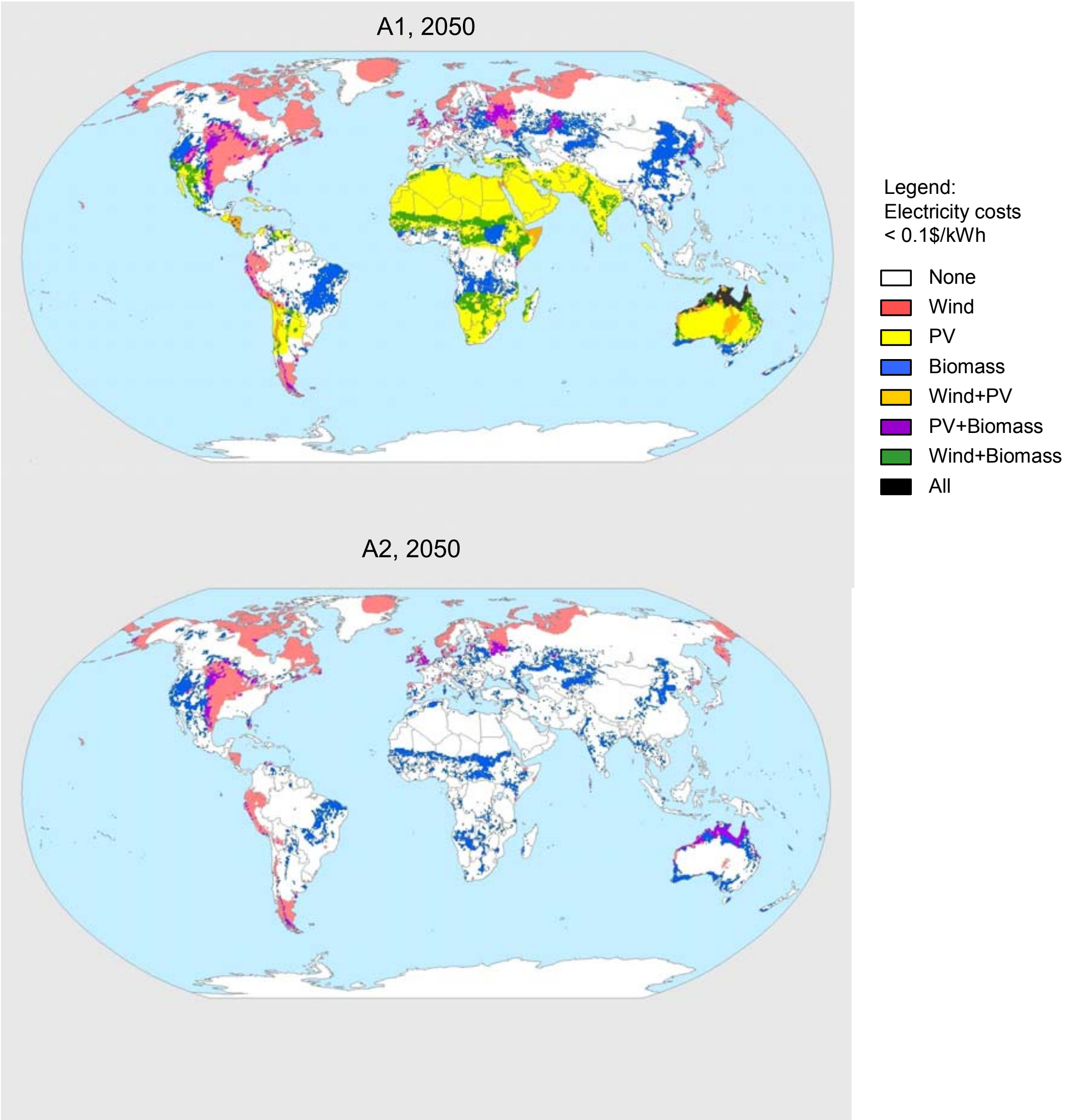


Figure 3-8 Areas where in the A1 scenario (upper) and A2 scenario (lower) one or more of the WSB options is estimated to be able to produce electricity in 2050 at costs below US$ 0.10 kWh^{-1}.

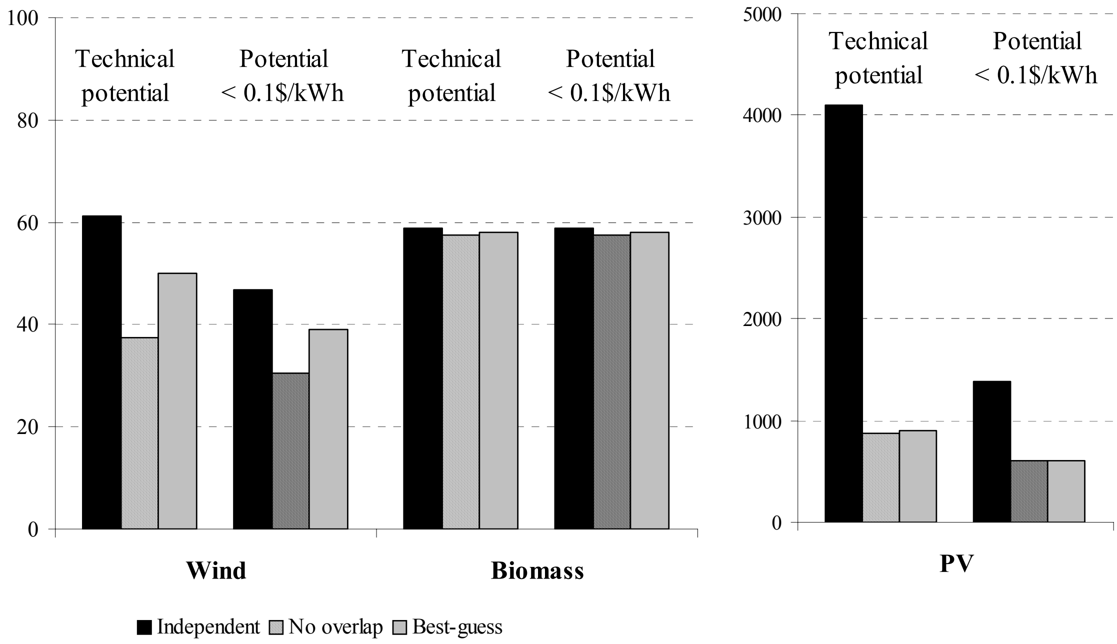


Figure 3-9 The global technical and economic (<US$ 0.10 kWh–1) potential for wind, biomass and solar-PV in 2050 based on a) independent assessment (cf. section 3.4.2), b) selecting only the cheapest option (cf. section 3.4.3, method 1) and c) allowing some overlap between wind potential and the two other options (cf. Section 3.4.3, method 2). Note that the solar-PV potential is indicated on a separate y-axis.

The results are shown in Figure 3.9. It turns out that competition for land with total exclusion of more than one option can for wind bring down the technical and economic potential by over one-third. For solar-PV the decline is even larger, in the range of 75% (technical) and 55% (economic) because under our competition rules solar-PV is excluded almost everywhere except in the desert areas. For biomass the interaction with the other two options is minor. There are, however, significant differences in the competition effects across the regions. They are in absolute (<3 PWh yr^{-1}) terms small or negligible in Central America, OECD and Eastern Europe, Southeast Asia and Japan. On the other hand, they are large in absolute (>25 PWh yr^{-1}) or relative (>2) terms in South America, all of Africa, the FSU, South and East Asia and Oceania. This shows the importance of having a closer look at the nature of such competition and the associated (dis)advantages.

3.4.4 Regional WSB potentials and electricity demand

The WSB potential to generate electricity at costs below US$ 0.10 kWh^{-1} is shown in Figure 3.10 for the 17 regions and three options for the A1 scenario in the year 2050. The aggregate outcome is also shown for the other three scenarios. The outlook is dominated by solar-PV, particularly in the desert-rich regions of Africa, the Middle East and Australia. Wind and biomass have globally a similar economic potential but in different regions: whereas wind could become a major energy source in the temperate zones of North America, Europe and the FSU, the biomass potential is largest in the tropical regions of Africa, South America and Asia – although North America and the FSU have a significant potential, too. Evidently, if interregional fuel trade is hampered by constraints, as in an A2 future, and technological innovations do not occur and spread, the WSB potential will be significantly lower or even vanish in quite a few regions (Figure 3.10).

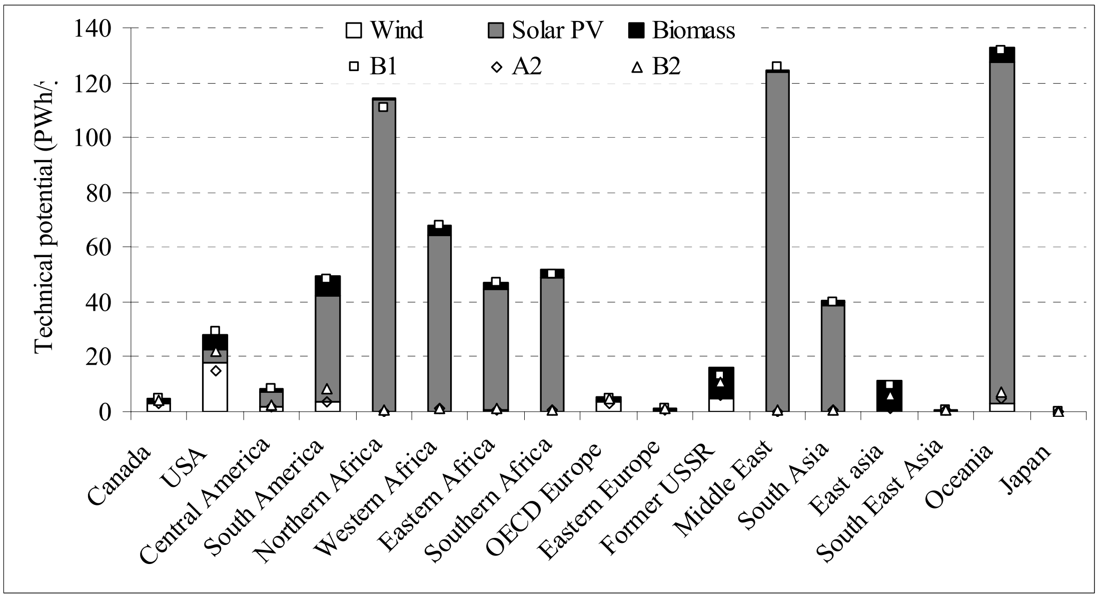


Figure 3-10 The regional potential in 2050 (i.e. the technical potential at electricity production costs below US$ 0.10 kWh–1) for wind, solar-PV and biomass in the A1 scenario, using the best-guess method. The corresponding values in the three other scenarios are also shown.

Can electricity production from renewable resources in theory satisfy anticipated electricity demand? In Figure 3.11 we present the ratio between the <$US 0.10 kWh^{-1} technical potential and the projected electricity demand in 2050 for the four scenarios. Globally, WSB potential is about two times higher than electricity demand under the A2 scenario and about seven times higher than demand under the B1 scenario. Thus, theoretically, WSB potential is enough to meet global electricity demand. At the regional scale, there are marked differences. In many of the densely populated regions in the world, with consequently a high electricity demand per area, the WSB potential cannot cover the total demand even theoretically. Southeast Asia and Japan can, in all scenarios, provide around 10% of regional electricity demand, and also in OECD Europe, Eastern Europe and South Asia the potential is insufficient to meet demand if one were to include the intermittence of supply.

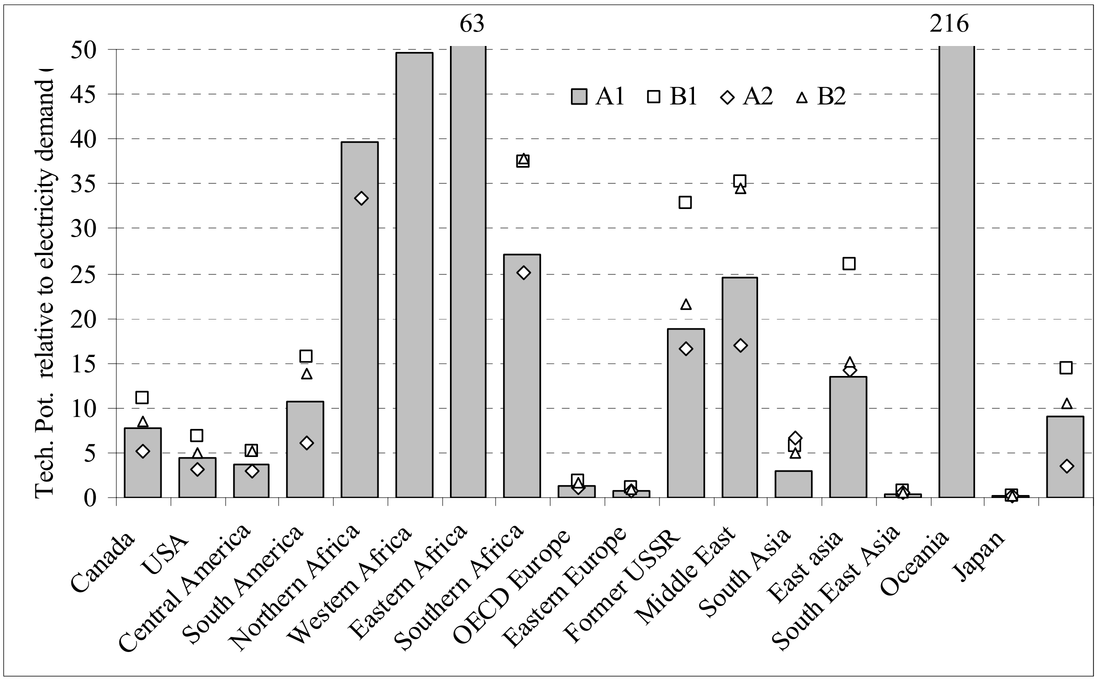


Figure 3-11 Ratio between the potential supply of WSB below US$ 0.10 kWh–1 in 2050 and the electricity demand according to the A1 scenario (bars) and the other three scenarios (marks).

For the other 12 regions the ratio of potential supply and expected demand remains above 1 in all scenarios. The highest ratios are found for the B1 scenario, due to the relatively lower electricity demand. The lowest ratios are found in A2, mainly explained by a relatively low WSB potential below US$ 0.10 kWh^{-1} which is in turn caused by a high demand for agricultural land and low technology development. Some regions – Canada, eastern Africa and Oceania, and to a lesser extent Western Africa and the FSU, have exceptionally high ratios due to a combination of high potential and low demand. These results suggest that, if the economic resources are available, the prospects for WSB options for electricity supply within the region – in line with the A2/B2 future – are quite good to excellent in most of the less densely populated regions in the world.

3.4.5 Sensitivity analysis

From the previous analyses it will be clear that any estimation of the WSB potential has a large margin of uncertainty. Therefore, we add a one-factor sensitivity analysis for the A1 scenario to better understand the role of uncertainties. In section 3.3.1 we discussed uncertainties and selected some for the scenario construction. Previous estimates of WSB technical and economic potentials turned out to be quite sensitive for assumptions on scenario-dependent class 2 parameters like conversion efficiencies and specific investment costs and interest rates (cf. Table 3.1). From the equations presented earlier, assumptions on land-use land cover change and suitability/availability are clearly important as well. Calculations show that for the low-end and high-end values of the suitability/availability factor f_i (cf. Table 3.2) the WSB options may have up to 50% less (wind) or 35% more (wind, biomass) economic potential – a difference of several times the present global electricity use in absolute terms. Nevertheless, as set out above, we have not included the f_i in the scenario differentiation and therefore confine the sensitivity analysis now to the following parameters:

- Land cover: use A2 and B2 land-use patterns instead of default A1;
- Implementation fractions: 25% above and below the default value;
- Technology: use high and medium technology assumptions (cf. Table 3.3);
- Interest rate: variations between 5% and 20% around the default value;

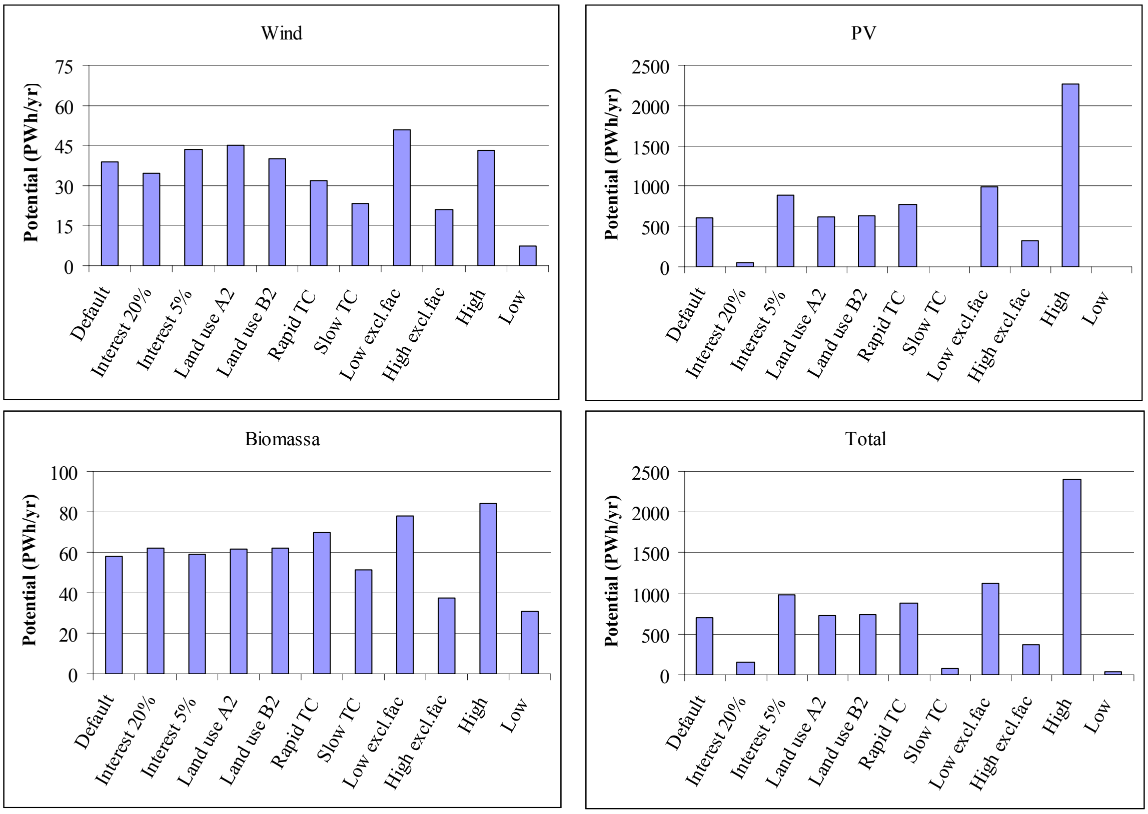


Figure 3-12 Sensitivity analysis for the potential below <US$ 0.10 kWh–1 based on default aggregation method for the A1 scenario in 2050. Results show 1) interest (5% and 20%), 2) land-use patterns (A2 and B2), 3) technology assumptions (highest and lowest assumptions on the basis of Table 3.3), 4) the land-use implementation fraction (50% higher and lower), and 5) the impact of all factors (upper and lower range).

We explored the full uncertainty range if all factors considered were varied within these ranges. The results (Figure 3.12) show that wind remains in all cases an important contributor to the worldwide economic potential at less than US$ 0.10 kWh^{-1}, with a potential between 8 and 43 PWh yr^{-1} – or 50–300% of the 2000 world electricity demand. Electricity from biomass can be equally important, with a contribution of 30–85 PWh yr^{-1}. The availability of the land and the cost reduction from technological progress are the most influential. High exclusion rates for land reduce both the wind and biomass potential significantly. A lower rate of innovations also affects the potential, as it invalidates the A1 standard assumption of rapid technology development. Changing land-use patterns due to different economic and population growth (A2/B2) cause only minor changes. The impact of the interest rate is also small, because in the range considered wind generation costs remain below the cut-off cost of US$ 0.10 kWh^{-1}.

The largest potential contribution is from solar-PV but its economic potential (<US$ 0.10 kWh^{-1}) is very sensitive to the cost determinants, as discussed before (cf. Figure 3.6). When the technological breakthroughs are not happening, a large part of the huge potential will never cross this cut-off cost boundary and even bring it below those of wind and biomass. Its capital-intensive nature also makes it sensitive to changes in the interest rate, for the same reason. High or low exclusion factors also affect the solar-PV potential, but land does not seem to be the constraint here: even with the high exclusion factor the potential is over 20 times the 2000 world electricity demand (Figure 3.12).

3.5 Renewable energy outlook: implementation potential

Elsewhere we have compared our results with previous studies by others (Hoogwijk et al., 2004; 2005). In Table 3.5, we compare our results to the figures presented in the World Energy Assessment (WEA, 2000) and to estimates of the implementation potential (period 2020–2030) in some recent scenarios. What do these potentials say about the possible and probable future of renewable energy in regional and world energy systems? It first has to be realised that a proper assessment of the role of WSB in the regional and world energy systems requires the implementation of the supply cost curves into an integrated assessment (energy and land-use land cover) model such as IMAGE/TIMER in order to get an idea of over-all system costs (De Vries et al., 2000, 2001; Palmer and Burtrow, 2005). Here, again, there are major uncertainties which will influence the technical, economic and in particular the implementation potential.

What will be the costs of the alternative competing energy supply and land-use options, what is the future energy demand, which are the costs of system expansion in order to guarantee reliability, how will fuel trade influence competitiveness, how does public perception of WSB and alternatives such as nuclear energy influence the penetration rate? Such questions may actually dominate the WSB potential in some situations.[28] Taking this ‘renewable energy environment’ into account implies a dynamic scenario for such variables as land use for food, cost/price development of other energy carriers and the prevailing value orientations and risk attitudes of people. This will be pursued in a subsequent paper.

[28] For instance in the UK, where Scottish electricity producers plan to sell 2000 MWe wind power to the more profitable market in the south. This would require € 730 million to upgrade the existing network. Similarly, development of the mid-western USA potential would necessitate major transport investments as they are far from the big load centres - a ‘wind pipeline’ of US$10-20 billion for >10 GWe transport capacity has been proposed (www.windpower-monthly.com).

There are at least three forces that will to a large extent determine the realisation of any WSB-potential:

environmental impacts, notably climate change: fossil fuel combustion is a major culprit and less use and/or clean use of fossil fuels (mitigation) is needed in addition to adaptation;

socio-economic considerations: half of the world population still lives in rural areas and for them considerations of local employment and autonomy as well as development and introduction of decentralised options may be of paramount concern besides cost per se;

energy supply security, in particular oil and gas: rising demand and depletion will contribute to economic, political and social instabilities, for example, in the form of rising and fluctuating prices.

All three may help to overcome the existing gap in generation costs. Rising fossil fuel costs and controversies about large-scale use of nuclear power will tend to advantage WSB – but counteracting forces will come into play, such as public resistance to land-use impacts.

Table 3-5 Comparison of the long-term technical potential of WSB options as reported in the World Energy Assessment (WEA, 2000), this study and some recent scenarios.

Study	Scenario	*Wind*	*Biomass*	*PV*	*Total*
		$PWh\ y^{-1}$	$PWh\ y^{-1}$	$PWh\ y^{-1}$	$PWh\ y^{-1}$
This study (2005)[a]	A1	80/39	72/58	1188/607	1341/705
	A2	62/23	25/20	317/0	403/38
	B1	80/38	63/51	945/603	1089/692
	B2	74/32	49/39	623/0	745/62
Techno-economic potential					
WEA (2000)		53	35–62	438 - 13844	526 -13959
SRES (Nakicenovic et al., 2000)[b]		2–3/>36	20–38/>361	4.5–6/>720	26.5–47/>1117
Scenario Studies (Implementation Potential)					
RIGES (Johansson et al., 1993)	Renewable Intensive Energy Scenario				10
Sørensen (2000)	Renewable Intensive Centralised 2050				15
SRES (Nakicenovic et al., 2000)[c]	A1				100
	A2				31
	B1				39
	B2				59

[a] Technical potential and economic potential at production costs <US$ 0.10 kWh–1.

[b] Potential by 2020–2025 and long-term technical potential.

[c] Includes both fuel and electricity.

The actual penetration dynamics of WSB will depend on the interplay of these forces which can be woven into the previously discussed scenario narratives. In the OECD region most governments and (big) businesses consider the energy security issue the most challenging and important one. Much research and development (R&D) effort is directed to this issue. Environmental risks are a second or at times, after an alarmingly hot summer or fierce storm, first priority. This has led, notably in the EU, to a set of ambitious targets for WSB sources, which seem to fit best in a B1-scenario. Job security is from an industrial point of view not really important in this capital-intensive sector, but providing alternative income opportunities for farmers or a genuine desire for local/regional autonomy in rural Europe or Indian and African villages may become decisive considerations in some situations, which would explicitly fit in a B2 future.

What does this mean for energy policy? A variety of policies has been implemented to stimulate the development and penetration of WSB options. Many countries (at least 48) have some kind of renewable energy policy and have introduced renewable energy targets, usually in the range of 5–30 % of total electricity use within the next 10–20 years (REN21, 2005). A variety of rules and regulations is being attempted: direct financial transfers (subsidies, R&D), preferential tax treatments (e.g., biodiesel), trade restrictions, energy-related services by governments at less than full cost (including infrastructure and public R&D), regulation of the energy sector and imposition of external costs ('negative subsidy'). Most countries and states use the feed-in policy and renewable portfolio standards, but direct investment subsidies are also often used (REN21 2005). Yet, only 7% of energy subsidies in the EU-15 2001 budget and only 18% of the on- and off-budget energy subsidies of € 29.2 billion in 2001 in the EU-15 went to renewable energy (www.eea.eu.int) . This fraction has been rising slowly, at the expense of fossil fuel and nuclear subsidies, and this could be accelerated considerably if a stringent climate policy is emerges with a permanent and rising carbon tax on all forms of energy.

3.6 Discussion and conclusions

In this paper we have presented the results of an integrated assessment of the potential to produce electricity from wind, solar-PV and biomass (WSB) and to produce liquid fuel from biomass. Unlike most earlier assessments, a well-defined methodology was used to estimate the potential of these renewables – making the results comparable across different types of renewables and regions and over time. We conclude from our analysis that:

Assessment of the future potential for renewable power at different cost levels should be done using an explicit scenario context. Many parameters in geographic and techno-economic estimates of renewable energy potentials are uncertain and dependent on broader developments such as future land use. Scenario-based assessment can provide some consistency ('logic') in assumptions and thus communicate the broad range of outcomes resulting from divergent pathways for, for example, land use and technology.

Competition for land between the WSB options may significantly affect their potential to produce electricity. The WSB options will, to some degree, use the same land types to produce electricity, that is, abandoned agricultural land and grass-type natural ecosystem. Therefore, it is not possible to determine the combined potential by simply adding up the individual potentials. Interaction effects could reduce the WSB potentials by up to 70%.

There are other important uncertainties, coming in particular from the assumptions on the suitability/availability of land and on technology-induced cost reductions. If much land turns out to be unavailable, for example, due to public resistance, or if technological breakthroughs do not occur, the WSB potential could be reduced by a factor of five to ten.

More specific conclusions are:

The potential to produce liquid biofuels from primary biomass exceeds the potential transport fuel demand in three out of four scenarios. Under the four scenarios analysed, the potential to produce liquid biofuels from biomass varies between 80–300 EJ yr^{-1} in 2050, the range coming from both different land-use patterns and different assumptions on technology development. This would suffice to supply an estimated worldwide transport fuel demand of 180–250 EJ yr^{-1}.

Wind power seems to be the most interesting of the WSB options to produce electricity. In most scenarios, wind power is able to produce electricity at somewhat lower costs in 2050 than biomass – up to US$ 0.04 kWh^{-1}. The potential of power from wind and biomass below US$ 0.10 kWh^{-1} ranges from 20–80 PWh yr^{-1}. Solar-PV costs are higher, at the cheapest sites costs may be just below US$ 0.10 kWh^{-1}; its technical potential, however, is much higher than the technical potential of the other options.

Whether solar-PV becomes available at costs below US$ 0.10 kWh^{-1} depends largely on the assumed technological development. Our results showed that in the more technology development conservative scenario A2, in 2050 the costs of centralised solar-PV have still not reached US$ 0.10 kWh^{-1}. Nevertheless, solar-PV may be increasingly competitive in some small niche markets.

The combined potential of the WSB options can in most regions supply future electricity demand at costs below US$ 0.10 kWh^{-1}. Regions with a high WSB potential over electricity demand ratio include Canada (mainly wind), the African regions (solar-PV and wind), FSU (wind and biomass), Middle East (solar-PV) and Oceania (all sources). In other regions, WSB supply is significantly lower than electricity demand (Southeast Asia and Japan). Ratios around one are found for OECD Europe, Eastern Europe and South Asia.

It should be borne in mind that our evaluation has some limitations, which also indicate directions for further research. Firstly, our data on wind speed, solar irradiation and land characteristics are rather coarse and this may, besides not permitting site-specific judgments, bias the regional estimates. Comparison with local studies can make the results more robust. Secondly, we did not consider the additional system costs occurring at high (>15%) wind and solar-PV and penetration, for instance for back-up capacity and the cost of discarded electricity in moments of supply-demand mismatch. To assess these costs, electricity system simulation is required (see e.g., Grubb and Meyer, 1993; Fellows, 2000, Hoogwijk et al., 2006). Thirdly, some assumptions are rather arbitrary, given the difficulty of forecasting long-term societal and technological dynamics. We have used the scenario approach to deal with this problem, but further elaboration of the storylines will provide more insight into uncertain parameters such as land availability.

4 Long-term reduction potential of non-CO_2 greenhouse gases

P.L. Lucas, D.P. van Vuuren, J.G.J. Olivier and M.G.J. den Elzen

4.1 Introduction

In the past, the focus in climate mitigation studies was mainly on CO_2 from energy-related sources, with many studies using a single gas approach (see among others Hourcade and Shukla, 2001; Morita et al., 2001). However, over the last few years the attention to non-CO_2 greenhouse gases (GHGs) has been rapidly increasing. Studies that consider both CO_2 and non-CO_2 mitigation options generally report important advantages of so-called multi-gas mitigation strategies[29], including: 1) major cost reductions compared to a CO_2-only strategy due to relatively cheap abatement options for several of the non-CO_2 GHG sources (Blok et al., 2001; EPA, 1999); 2) an increase in the flexibility in abatement options (Hayhoe et al., 1999; Hyman et al., 2002; Jensen and Thelle, 2001; Lucas et al., 2005; Manne and Richels, 2001; Reilly et al., 1999; Tol, 1999; Van Vuuren et al., 2003); and 3) the fact that non-CO_2 GHGs can contribute to a more rapid response in avoiding climate impacts by focusing on short-lived gases (Hansen et al., 2000). Moreover, it has been suggested that reductions in methane emissions are nearly twice as effective in reducing radiative forcing (i.e. two-thirds larger) than its Global Warming Potential (GWP) value suggests, due to its indirect effects via tropospheric ozone and stratospheric water vapour (Shindell et al., 2004). Hansen et al. (2005) estimate total effective forcing from direct and indirect methane for 1750–2000 at around 50% of the CO_2 forcing in that period. The quick response to methane reductions result from both the limited lifetime of methane and the fact that the impacts of CO_2 emission reductions are partly offset in the short term by simultaneous reduction of energy-related aerosol emissions. It is therefore no surprise that policy-makers have already acknowledged these potential benefits through the GHG basket approach adopted in the Kyoto Protocol targets and the US Administration GHG intensity strategy, thereby allowing full substitution among these gases.

In order to construct long-term multi-gas mitigation scenarios, information is needed about the abatement potential for the different GHGs and the cost at which the various abatement options can be implemented. In addition, information is needed on barriers other than costs that might prevent mitigation measures being implemented – and how both these barriers and the mitigation measures themselves change over time. This paper focuses on long-term non-CO_2 mitigation potential and its role in the construction of multi-gas mitigation scenarios.

The Energy Modelling Forum (EMF) organised a model comparison study to further enhance the understanding of multi-gas abatement strategies (EMF-21). The study aimed to provide a

[29] This set of greenhouse gases includes carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and the so-called fluorinated gases (hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6)).

consistent set of abatement potentials and costs for the major non-CO_2 GHGs and to provide the opportunity to compare the results of multi-gas mitigation scenarios across a range of different models. Furthermore, the study aimed to explore how a multi-gas strategy differs from a CO_2-only approach. Overall, they concluded that – on average and across all models – a multi-gas strategy could lead to a cost reduction of 30–60% compared to a focus on CO_2 only (Van Vuuren et al., 2006c; Weyant and De la Chesnaye, 2006). The set of abatement potentials and costs provided within the EMF-21 project in the form of Marginal Abatement Cost (MAC) curves concentrated on the year 2010. That implies that they left the question open of how to deal with changes in reduction potential after 2010.[30] The focus on 2010 also resulted in two other limitations. First, the data set focuses, in particular, on those emission sources for which currently available technologies could be identified and whose implementation was foreseeable; abatement potential was not identified for all emission sources. Second, the potential reduction measures have only been identified for a maximum cost level of 200 US$/tCeq (1995 US$). In the longer term, however, it is very reasonable to assume that new technologies could emerge and implementation barriers might vanish, certainly under the high carbon prices that are currently foreseen for more ambitious climate policy scenarios. This would result in larger possible cuts in GHG emissions. Several individual modelling groups within the EMF included technology developments in their analysis (see for instance Van Vuuren et al., 2006b), although they focused on sources reported in the EMF-21 MAC curve set and did not include abatement potential above 200$/tCeq.

In order to explore the long-term non-CO_2 abatement potential, we first perform a literature survey on future non-CO_2 abatement potentials and costs to see whether information is available on potential technology change and reduction of implementation barriers (section 2). This information is used to extend the EMF-21 marginal-abatement curves for non-CO_2 gasses to 2100 (section 3). Next, we combine this set with cost estimates for energy-related CO_2 emissions and assessed the role of the non-CO_2 GHGs and technology development in the construction of multi-gas mitigation scenarios (section 4). For the analyses we use the FAIR 2.1 model, including the multi-gas abatement costs model with the new developed set of non-CO_2 MAC curves as described here.[31] We then analyse the sensitivity of our model results towards the main assumptions on the non-CO_2 MAC curves extension (section 5). We also explore uncertainties with respect to different multi-gas emission scenarios and emission pathways for stabilising the GHG concentration. Finally, we discuss our results and draw general conclusions (section 6).

[30] Although the EMF-21 data set includes both 2010 and 2020 numbers, relative reductions are the same for both years.

[31] The FAIR 2.0 model is a policy decision-support tool developed to explore and evaluate the environmental and abatement costs implications of various international climate regimes for the differentiation of future commitments for meeting long-term climate targets (Den Elzen et al., 2005). The FAIR 2.1 model is an updated version of FAIR 2.0, differences being the marginal abatement costs curves and baseline emissions, as described briefly here.

4.2 Non-CO_2 abatement potential and costs

The most extensive set of abatement potentials and costs currently available for non-CO_2 GHGs is the EMF-21 data set. The EMF-21 set of MAC curves includes curves for CH_4 and N_2O from industrial and energy-related sources (Delhotal et al., 2006) and from agricultural sources (DeAngelo et al., 2006), and MAC curves for the fluorinated gases, i.e. HFCs, PFCs and SF_6 (Schaefer et al., 2006). In an earlier analysis the set was extended with curves for CH_4 domestic sewage and N_2O transport (Graveland et al., 2002). Figure 4.1 indicates the global 2010 emission levels and the identified maximum abatement potentials according to this set.[32] A large share of emissions can be abated for several sources. This is particularly the case for CH_4 emissions from landfills and coal production, and for N_2O emissions from adipic and acidic acid production, for which about 80% can be abated worldwide. For most other sources, a more modest reduction potential is identified, such as for CH_4 emissions from wetland rice production and for emissions of F-gases (approximately 40%). Furthermore, there are some sources that can (almost) not be abated according to this set; in particular, CH_4 emissions from sewage, enteric fermentation and animal waste, and N_2O emissions from animal waste and fertiliser use. Finally, the figure also shows baseline emissions for the category 'other sources', which includes all sources which are assumed to be impossible to abate or too small (compared to other sources) to be of any significance.

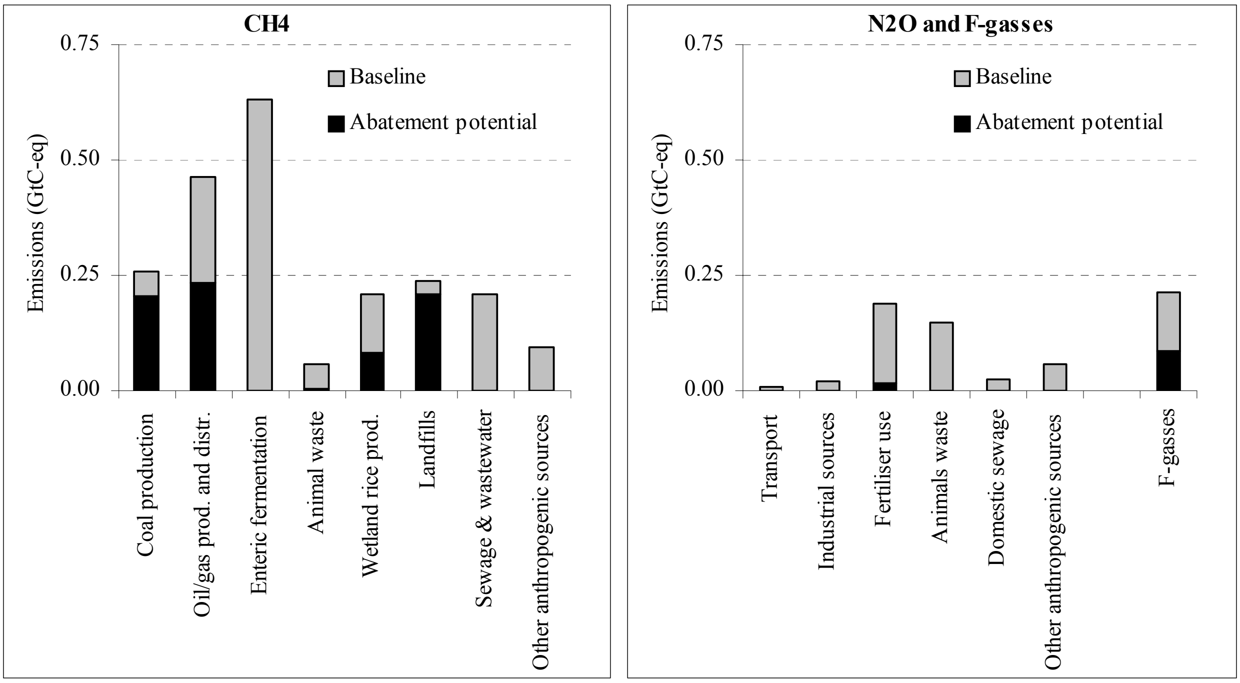


Figure 4-1 Emission baseline and reduction potential in 2010, according to the EMF-21 set of MAC curves.

[32] The baseline used is the baseline reported in the EMF-21 database, which was constructed mainly on the basis of National Communications in combination with expert judgement.

Table 4-1 Estimated maximum reduction potential and the accompanying marginal price in 2050 and 2100.

		2050		2100	
		Maximum possible reduction compared to baseline (%)	Marginal price of maximum reduction (US$/tCeq)	Maximum possible reduction compared to baseline (%)	Marginal price of maximum reduction (US$/tCeq)
CH_4	Coal production*	70	50	90	500
	Oil/gas prod. and distr.	90	500	90	500
	Enteric fermentation	50	1000	60	1000
	Animal waste	50	1000	60	1000
	Wetland rice production	70	350	70	350
	Landfills	70	10	90	500
	Sewage and waste water	90	1000	95	1000
	Other anthropogenic sources	-	-	-	-
N_2O	Transport	80	500	80	500
	Adipic acid production	98	5	98	5
	Nitric acid production	90	5	95	5
	Fertiliser use	35	1000	40	1000
	Animal waste	40	500	45	500
	Domestic sewage	20	500	35	500
	Other anthropogenic sources	-	-	-	-
F-gas	HFC-23 as byproduct	90	1	98	500
	HFC uses	90	500	95	1000
	PFC as byproduct	80	20	95-100	500
	PFC uses	50-80	100	95-100	500
	Sulphur hexafluoride	80-90	500	90-95	1000

* This only accounts for underground coal.

This section focuses on literature estimates of long-term reduction potentials and abatement costs of the non-CO_2 GHGs. The reduction potentials, presented in Table 4.1, are taken as percentage reductions compared to baseline emission levels. The information on post-2010 abatement is obviously speculative, to a certain degree. This is amplified by the fact that compared to CO_2, a very limited number of studies have looked into long-term potential for non-CO_2 abatement options. In assessing future reduction potential, we have estimated reductions against current technologies – and focused on technological potential and rough costs levels. We assume that specific implementation barriers such as limited capital turnover rate and lack of information in developing countries would disappear over the assessment period (2010–2100). If no cost estimates were available we use the upper boundary of marginal costs that can be used in our costs model, namely 1000 $/tCeq. Measures with costs clearly above a 1000 US$/tCeq, or those that require a scientific breakthrough that is not foreseeable today, have not been considered; for example, we did not include possible systemic changes in food production. As such, our estimates should be considered as rough, lower boundary estimates of the maximum reduction potential in the second half of the century. The second half of this paper includes a sensitivity analysis of these estimates on the overall annual costs of long-term multi-gas mitigation scenarios.

4.2.1 Long-term emission reduction potential for methane

Methane emission reductions from coal mining

The key reduction option for methane emissions from coal production is methane recovery, which is only applicable to underground mining. In addition, the trend towards more surface mining is expected to continue, which has much lower methane emissions per ton of coal than underground mining, thereby substantially reducing emissions per tonne of coal mined. Emission reductions are based on maximising methane recovery (e.g. to 70% or 90% on average) from underground mining of hard coal (reduction options exist for other hard coal and/or brown coal). Potentially, about 90% reduction is technically possible, of which around 70% at relatively low costs (Hendriks and De Jager, 2001), for example, at costs of about 30 US$/tCeq (EPA, 1999). Based on this, we assume that overall, around 70% of the methane emissions from underground mining can be reduced in 2050 (notably hard coal) and 90% in 2100. Of this, 70% can be reduced at a cost of about 50 US$/tCeq and the remainder at a cost below 500 US$/tCeq. For surface mining virtually no reduction is possible.

Methane emission reductions from oil and gas production and distribution

The key abatement option to reduce methane emissions for oil and gas production is the reduction of venting by reducing leakage from valves etcetera, utilising the associated and process gases as fuel on-site or elsewhere, and/or by flaring of the remainder. The key reduction options for natural gas distribution are replacement of old leaky pipelines and more frequent leak search and repairs. In oil and gas production about 75% reduction of diminishing gas venting may be achieved (on average) by more reuse of the gas and better maintenance; further reduction to 95% is possible by flaring the remainder (EPA, 1999; Hendriks and de Jager, 2001). The costs are highly dependent on the location: offshore flaring instead of venting may cost about 50–300 US$/tCeq, whereas onshore flaring instead of venting would cost much less, for example, 5–15 US$/tCeq. As for gas distribution systems, it is estimated that replacing the leakiest parts will reduce the emissions at an additional cost of about 150–300 US$/tCeq by about 75% on average, while more frequent leak detection and repair will reduce remaining emissions by another 50%, for example, by doubling the inspection frequency at a cost of about 300 US$/tCeq. This results in an overall reduction of about 90% (Hendriks and de Jager, 2001). Practically all natural gas distribution networks will be replaced by 2100. Natural gas transportation has limited emissions and therefore limited reduction potentials.

Methane emission reductions from enteric fermentation

The main key reduction options for methane emissions from enteric fermentation are changing animal diets and the use of more productive animal types. However, the most important barrier is the lack of market incentives and the lack of knowledge. Graus et al. (2004) estimate a worldwide emission reduction potential of 5–10% in 2020 and 32% in 2050, most of which can be attained at relatively modest costs (less than 200 US$/tCeq). Based on their regional results, which show higher reduction rates in developed regions up to 50% in 2050, we assume that in the long run (2100) a global maximum of 60% can be attained at costs of less than 1000 US$/tCeq.

Methane emission reductions from animal waste

For methane emissions from animal waste the key reduction option is the capture and use of methane emissions through anaerobic digesters, which can be farm-scale digesters for the extensive agricultural zones and centralised digesters for the intensive agricultural zones (mainly OECD Europe). The implementation barriers are expected to be larger in developing countries than in the developed world (Graus et al., 2004). They estimate worldwide emission reduction potential of around 10% in 2020 and 44% in 2050, with costs mostly below 50 US$/tCeq. Given the fact that most developed world regions have an abatement potential of 50% in 2050 we assume a global maximum emission reduction of 60% in 2100 at costs of less than 1000 US$/tCeq.

Methane emission reductions from rice production

Most of the abatement options involve changing the water management regime to reduce the time over which anaerobic conditions in flooded fields occur, or altering the amendments to the soils to inhibit methanogenesis (Graus et al., 2004). The barriers for mitigation include the lack of financial incentives, no insurance facility, uncertainty regarding the potential and the lack of knowledge on the impacts on yields and alternative techniques (Lantin et al., 2003). For 2020, Graus et al. (2004) estimate the worldwide emission reduction potential to be limited to only 15% of emissions. However, for 2050, a worldwide emission reduction potential is estimated at 70% with costs between 50 and 350 US$/tCeq. As no information is available for the period after 2050, these same numbers are assumed up to 2100.

Methane emission reductions from landfills

Landfill gas recovery is a key reduction option for methane emissions from landfills. In addition, prevention of methane formation can be increased by incinerating municipal generated waste and by other low-emission waste-treatment technologies (e.g. aerobic treatment, anaerobic digestion) of organic waste. In most OECD countries about 20% is currently recovered (Olivier et al., 2002), while most other countries have no recovery techniques and almost no incineration. Emission reductions are based on maximising recovery of landfill gas and using bioreactors in industrialised countries and, later, also in the developing world (to 70 or 90% on average, for example), and/or reducing disposal of organic waste by increased incineration or composting (e.g. 50%). Potentially about 90%

reduction is technically possible (EPA, 1999), of which about 70% without extremely high costs. A recent estimate for various countries confirms that about 70% can be reduced at costs of less than 10 US$/tCeq (Bates and Haworth, 2001). Overall, a 90% reduction in 2100 could be achieved, of which 80% at costs of less than 20 US$/tCeq and the remainder at less than 500 US$/tCeq.

Methane emission reductions from sewage and waste water

Key reduction options for sewage and waste water methane emissions are more waste water treatment plants, less use of latrines and direct waste water disposal and higher recovery rates of methane. Most OECD countries have methane recovery systems in place in their waste water treatment plants, but the recovery rates can still be increased. Most developing countries have limited waste water treatment plants, mostly latrines and direct disposal of direct waste water through open sewers. Almost half of the global CH_4 emissions from waste water stems from latrines and another 30% originate from open sewers. Other sources are industrial and residential waste water treatment. Waste water treatment plants have lower methane emission factors than emissions from latrines and polluted surface water disposed of through open sewers; this is, in particular, due to recovery of the methane (more than 90%). Thus, the maximum technically feasible emission reduction is composed of implementing waste water treatment plants with high recovery in non-OECD regions, replacing the use of latrines and open sewers, and further improving the recovery rate in OECD countries. Overall, we assume that in the long term 95% reduction of waste water emissions could be achieved at additional costs for CH_4 recovery of less than 500 US$/tCeq.

Other methane emission sources

Other CH_4 emitting sources include biomass and savanna-burning, relating to land clearing for agricultural extension, and fuel wood and agricultural waste-burning, which mainly cover traditional biomass for energy production and cooking. Furthermore, some methane emissions occur in the iron and steel production, and the chemical industry. Where the first two sources are rather difficult to abate and the last four relatively small compared to total CH_4 emissions, no reduction potential has been assumed for these sources.

4.2.2 Long-term emission reduction potential for nitrous oxide

Nitrous oxide emission reductions from transport

Nitrous oxide emissions from road transport are mainly due to catalyst-equipped petrol-based cars, where the key reduction option is the application of low-N_2O catalytic converters. Current catalytic converters are only designed to reduce emissions of ozone precursors such as NMVOC, CO and NO_x, increasing N_2O emissions with respect to uncontrolled emissions: for example, from 0.6 to 4.2 g/GJ. However, improved catalysts that can at least prevent the increase of N_2O emissions limit N_2O emissions to very low levels. There is a substantial potential to reduce emissions, because without climate policies the large-scale use of conventional catalysts is likely to occur in all regions. The emission reduction for petrol cars would be about 85% (Olivier and Berdowski, 2001; Olivier et al., 2002). Total emission reduction potential depends on the share of petrol-based cars in transport energy use, with the 65% share (in 2000) leading to a global reduction potential of about 80–90%. Of this potential, we estimate that about 50% can be reduced at very limited extra costs. In the long term and at somewhat higher costs a reduction of 85% may be possible compared to present emission factors. Although a technological breakthrough such as the fuel cell can considerably change emission levels, this consideration is not taken into account.

Nitrous oxide emission reductions from industrial sources
Key reduction options for nitrous oxide emissions from industry are formed by the application of emission control technology (adipic acid production: N_2O destruction, for example, thermal, and nitric acid production: catalytic reduction of N_2O). Emissions from adipic and nitric acid production can be largely abated: 98% for adipic acid (Reimer et al., 1999; WBCSD/WRI, 2005) and 80–90% for nitric acid (WBCSD/WRI, 2005) and even up to 90–95% (Van den Brink et al., 2002). However, given the existing present-day implementation of measures, reduction potential for adipic acid production does not represent a 98% reduction, but a further reduction of about 65%. The additional costs of these options are quite low, 1 US$/tCeq for adipic acid and 1–5 US$/tCeq for nitrid acid (COHERENCE, 1999; De Beer et al., 2001). This in fact implies that the 2100 abatement potential is equal to the potential of the EMF-21 database.

Nitrous oxide emission reductions from fertiliser use
Several options exist to reduce N_2O emissions from fertiliser use. These include improving fertiliser use efficiency, restricting the use of fertilisers in time, using fertiliser-free zones and replacing current fertilisers by new types with lower emissions (Graus et al., 2004; Hendriks et al., 1998; Mosier et al., 1998). An important factor that determines the total reduction potential is the baseline application of some of these options and the implementation barriers. Graus et al. (2004) estimate the reduction potential to be about 35% in 2050 based on a limited set of measures. While this might be relatively optimistic with respect to implementation barriers for the measures they have looked at, the fact that other measures could achieve a similar reduction has convinced us to use this number. Furthermore, we assume that in the long term (2100), 40% can be reduced. These estimates are also used for indirect emissions from fertiliser use (as defined by the IPCC), as they are obviously directly linked to their direct emissions.

Nitrous oxide emission reductions from animal waste
Several options exist to reduce N_2O emissions from animal waste. Measures include dietary changes to reduce nitrogen excretion from animals (e.g. improving the protein quality of the diet and reducing nitrogen intake), reducing the number of animals (by increasing their productivity), optimising manure management and limiting grazing (Brink, 2003; Clemens and Ahlgrimm, 2001). While many studies mention these measures as a way to reduce N_2O

emissions, few actually quantify the potential, most probably reflecting the uncertainty in implementing several of these measures. Brink et al. (2003) based on Hendriks et al. (1998) and AEA-Technology (1998) estimates the potential to be about 35–45% for Western Europe for 2010. This potential is achieved mostly by measures with medium to relatively high costs. Given the reluctance of other studies to quantify potential for this sector and the difference in types of husbandry worldwide, we assume a possible 30% reduction in OECD countries in the short term and only 10% in low-income countries. For 2050 we assume that 40% can be reduced and, for 2100, 45%. In all cases, these are relatively low-cost measures, assumed to be fully attainable at 500 US$/tC. These estimates are also used for indirect emissions from animal waste (as defined by the IPCC), as they are obviously directly linked to their direct emissions.

Nitrous oxide emission reductions from domestic sewage

Reduction of N_2O emissions from wastewater is possible by controlled nitrogen removal at waste water treatment plants. Optimising the N-removal process to achieve a more complete reduction to N_2 emissions instead of N_2O emissions can reduce emissions of the latter by 50% (Hendriks et al., 1998). In addition, emissions can also be reduced by N-enriched wastewater as an alternative to fertilisers (thus reducing fertiliser emissions). The reduction potential is largely determined by the possibility of implementing technical measures, i.e. the existence of waste water treatment. On the basis of Graveland et al. (2002), we assume that in the short term (2010), 5% of emissions in OECD countries and 2% of emissions in non-OECD countries can be reduced. In the mid-term (2050), these numbers are 20% and in the long term (2100), increase to 35%. In all cases, these are medium-cost measures, assumed to be fully attainable at 500 US$/tCeq.

Indirect nitrous oxide emission reductions from non-agricultural sources

Apart from indirect N_2O formation from agricultural sources, NO_x (and some NH_3) emissions from combustion sources and industrial processes also give rise to these emissions. Using the IPCC methodologies, these indirect N_2O emissions are estimated for 2000 at about 0.6 Tg N_2O (Olivier et al., 2005), which is approximately 5% of the global total other anthropogenic N_2O emissions that are accounted for in this paper. The reduction potential for N_2O is the same as for reducing NO_x emissions as air pollutant. NO_x reduction options in road transport are the application of catalytic converters, and in power plants and large industrial combustion plants deNO_x technology such as Selective Catalytic Reduction (SCR) or Non-SCR can be applied. However, although reducing emissions of these air pollutants will result in a proportional reduction of related indirect N_2O emissions, we do not include them in our analysis, because their abatement would occur outside the framework of climate policy.

Other emissions of nitrous oxide

Other N_2O emitting land-use-related sources include biomass and savanna-burning activities, related to land clearing for agricultural extension, and fuel wood and agricultural waste burning, which cover mainly traditional biomass for energy production and cooking. Other

N_2O emitting sources are crop residues and biological N-fixation. No mitigation potential has been assumed for these sources, as most of them are rather difficult to abate and relatively small compared to the other sources.

4.2.3 Long-term abatement potential for fluorinated gases

Hydrofluorocarbon emission reductions

A key reduction option for HFCs is the thermal destruction of HFC-23, which is a by-product of HCFC-22 production. Of this production, 98% reduction is technically feasible (Klein Goldewijk et al., 2005), with 90% at costs of about 1 US$/tCeq, and up to 98% at less than 500 US$/tCeq (Harnisch and Gluckman, 2001). For the use of HFCs the key reduction options are substitution, less leaky applications (notably in commercial refrigeration but also for Mobile Air Conditioning (MAC)) and recovery when products are disposed of. Substitution of HFCs, for example, by hydrocarbons (such as for foam blowing) may reduce total HFC emissions by about 15% and less leaky applications (notably in commercial refrigeration: from 20% down to 0.5% and for MAC from about 10% to 0.5% (Schwarz and Leisewitz, 1999). Substitution by other compounds may also occur in commercial refrigeration (Heijnes et al., 1999) and recovery when products are disposed of (about 25%). Overall reduction may be about 95%, if only applied in closed applications and with maximum recovery during maintenance and when old equipment is disposed of (Harnisch and Gluckman, 2001). In practice, slightly less (e.g. 90%) may be achieved due to actual non-optimised handling of the appliances.

Perfluorocarbon emission reductions

The key reduction options are the use of modern process technology for aluminium production and minimising the use and emissions of fluorinated gases in semiconductor manufacturing, for example by replacing the use of PFCs as solvents and/or recovery of emissions and (thermal) destruction. The global emission reduction from aluminium production may be roughly 80% (85% within EU cf. Heijnes et al., 1999) if the baseline scenario assumes the same process mix and emission factor as in 2000. In fact, the global aluminium industry has committed itself to reducing the global average PFC emission factor in 2010 by 80% compared to 1990 (Marks et al., 2005). However, this does not capture all plants, for example, most of the old smelters in Russia and China are not included. Global aluminium production emissions may be reduced by about 80% in 2050 if all plants switched to PFPB and all old Søderberg plants are discontinued by 2050, and by about 90–95% in 2100 with fullly optimised process control. The additional cost refers to either switching from CWPB and SWPB to PFPB or to further optimisation of the process control, of which the costs for retrofitting are less than 20 USD/tCeq (EPA, 2001; Heijnes et al., 1999). The semiconductor industry is aiming at substantially reducing its global PFC emissions by 10% in 2010 compared to 1990, despite the strong expected growth in production (WSC, 2005). By capturing all F-gas emissions and using thermal destruction, virtually all emissions could be eliminated (Heijnes et al., 1999). PFCs are used as a solvent in some regions but not in others. This means that alternative compounds or alternative processes are technically feasible and actually used. Thus a complete phase-out in all countries should be possible.

Sulfur hexafluoride emission reductions

Key reduction options for SF_6 production and use are improved recovery, minimising leakage and optimising usage. Emissions from manufacture of Gas Insulated Switchgear (GIS) and other SF_6-containing circuit breakers and their use may be reduced by 80% by 2020 at costs of less than 100 US$/tCeq (Wartmann and Harnisch, 2005), and while emissions from primary magnesium production and magnesium die casting may be reduced by optimising the use of SF_6 as cover gas by about 90% at costs of less than 200 US$/tCeq, emissions from semiconductor manufacture and miscellaneous applications may be reduced by almost 100% (Heijnes et al., 1999).

4.3 Modelling non-CO_2 greenhouse gases

4.3.1 Construction of the time-dependent non-CO_2 MAC curves

Given the quality and current status of the EMF-21 data set on reduction options, we aim here to develop a set of long-term MAC curves that dynamically link the short-term potentials to the long-term potentials discussed in the previous section. This implies taking future technological developments and cost reductions into consideration. We assume that technological developments lead to improvements in reduction efficiency and a decrease in costs. To construct the MAC curves in time, several steps will need to be taken (see also Figure 4.2). First, we express the EMF-21 MAC curves (over the cost range of 0-200 US$/tCeq) in relative reductions against frozen efficiency (i.e. current, 2000 technology). As abatement technologies become slowly cheaper over time, we assume that the whole curve moves outward (point A in the left part of Figure 4.2).

The literature survey, as presented in section 4.2, is used to identify time-dependent maximum reduction potentials and costs, which change over time as a function of changing implementation barriers and technology development. For 2010, this maximum is equal to the potential per source included in the EMF-21 database, while the values summarised in Table 4.1 are used for 2050 and 2100. These time-dependent maximum reduction potentials and costs are used to extend the MAC curves, including technology developments above 200 US$/tCeq, and assuming a linear increase from reduction potential at this 200 US$/tCeq towards the tabulated maximum reduction potentials and costs (see point B on the left-hand side of Figure 4.2). Finally, to avoid double counting in abatement options, improvements in emission factors under the baseline scenario (representing abatement measures already implemented for reasons other than climate policy) are subtracted from the low-cost side of the MAC curve (see point C on the right-hand side of Figure 4.2). The resulting relative MAC curves can then be projected onto different baseline emission scenarios to determine the absolute MAC curves. By doing so we assume that there are no real differences between technologies used in the different baseline scenarios. We also assume that there are only volume differences in total sectoral emissions and, with this, abatement potential differences due to differences in population and economy size and efficiency levels.

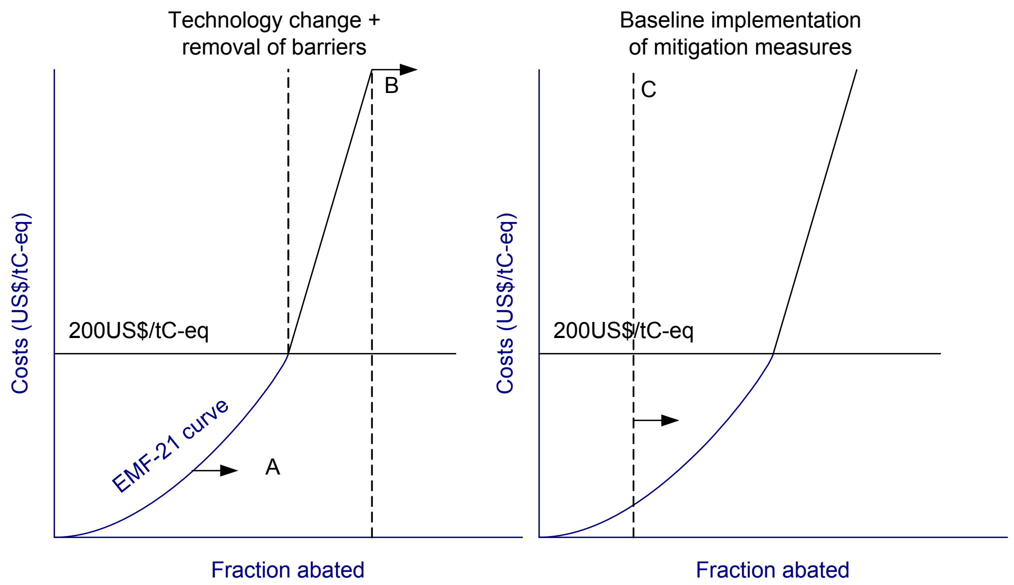


Figure 4-2 Construction of non-CO_2 MAC curves in time from the EMF-21 data set, including technological change (A), extension of curves above 200 US$/tC-eq. (B) and action already taken in the baseline (C). For detailed description see text.

4.3.2 The three sets of non-CO_2 MAC curves

Three sets of non-CO_2 MAC curves are constructed to assess the impacts of the different steps described above on the overall potential. Figure 4.3 shows the maximum abatement potentials in 2100 for these three sets, per source. The first bar presents the maximum reduction potential (reduction at 200 US$/tCeq) of the original EMF-21 data set, assuming no technological development whatsoever (further referred to as EMF-21). In the second bar, this set was extended using a conservative estimate of technological development, as per Van Vuuren et al. (2006b) (further referred to as Van Vuuren et al.). This set was included for reference purposes only. For the third bar, the Van Vuuren et al. set was further extended using the maximum reduction potentials and accompanying marginal costs, as presented in Table 4.1 (further referred to as this study). Furthermore, MAC curves for N_2O animal waste and N_2O domestic sewage, which are not present in the EMF-21 data set, were added to the set based on Brink et al. (2003) and Graveland et al. (2002). The differences between the 2010 reduction potentials (EMF-21) and estimated 2100 potentials, including technology change (this study) for several sources are very large (see CH_4 gas and oil production, sewage, enteric fermentation and animal waste, and N_2O transport and fertiliser use, and the fluorinated gases).

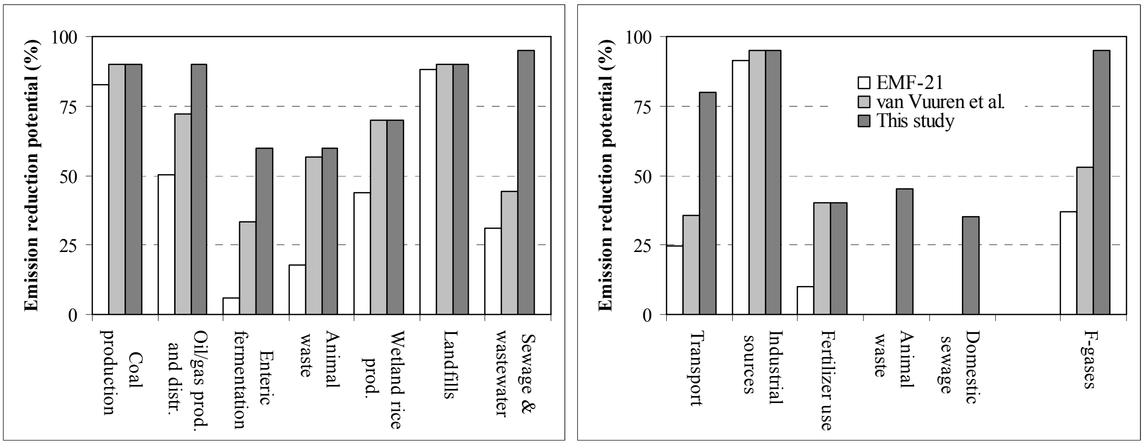


Figure 4-3 Maximum relative abatement potentials compared to baseline level, for methane emissions (left) and nitrous oxide and the fluorinated gases (right) for the three non-CO_2 MAC curve sets compared to 2100 emission levels.

4.3.3 Substitution among gases

To allow for substitution among the different GHGs we make use of Global Warming Potentials (GWPs) with a 100-year time horizon. Although 100-year GWPs are suggested by the IPCC, several researchers point out that the choice of time-horizon is arbitrary and the results can change significantly by switching to GWPs with a 20-year or 500-year time horizon (Reilly et al., 1999). Furthermore, the concept can only partly take into account the impacts of the different lifetimes of the various gases, or the economic efficiency of reducing them. Different metrics for comparison have been proposed. Fuglestvedt et al. (2003) provide a comprehensive overview of the different methods proposed, and the advantages and disadvantages of using them, while Van Vuuren et al. (2006c) provide a comparison of stabilisation scenarios studies that use GWPs or substitute on intertemporal optimisation. Despite this continuous scientific debate the concept is regarded as convenient, and to date no alternative measure has attained a comparable status.

4.4 Stabilisation scenarios under different assumptions for the development of reduction potential

In this section we analyse the role of the non-CO_2 GHGs in long-term stabilisation scenarios. We analyse the role of technology changes and reductions of implementation barriers on the marginal price of reduction and the overall global costs, as well as the contribution of the different emission sources to total abatement effort. For this purpose, we use the MAC curve sets as described in the previous section and combine them with MAC curves for energy and industry-related CO_2 emissions and curves describing the potential and costs of carbon plantations for CO_2 sequestration. For the applied methodology see Van Vuuren et al. (2006b).

The MAC curves of *energy- and industry-related CO_2 emissions* were determined with the energy model TIMER 2.0 (Van Vuuren et al., 2006a). This energy model calculates regional energy consumption, energy-efficiency improvements, fuel substitution, and the supply and trade of fossil fuels and the application of renewable energy technologies (including the use of biofuels), as well as of carbon capture and storage. The TIMER MAC curves were established by imposing a carbon tax and recording the induced reduction of CO_2 emissions, taking into account the technological developments, learning effects and system inertia. There are several responses to a carbon tax in TIMER. In energy supply, options with high carbon emissions (such as coal and oil) become relatively more expensive compared to options with low or zero emissions (such as natural gas, carbon capture and storage and renewables). The latter therefore gain market share. In energy demand, investments in efficiency become more attractive.

The MAC curves for *carbon plantations* were derived using the IMAGE 2.3 model (Strengers et al., in prep.). In this model, 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 where the sequestration by plantations exceeds sequestration by natural vegetation. On the basis of grid cells that are potentially attractive for carbon plantations, carbon sequestration supply curves are established and converted into MAC curves by adding land and establishment costs (for methodology, see Graveland et al., 2002; Strengers et al., in prep.).

Next to the constructed MAC curves, a baseline emission scenario and a multi-gas emission pathway (leading to stabilisation of the GHG concentration in the atmosphere) have been chosen. The difference between the total baseline emissions (CO_2 plus non-CO_2 emissions) and the emission pathway is the global emission-reduction objective, that is, total CO_2-equivalent emissions which need to be abated yearly to reach the global CO_2-equivalent concentration objective associated with the stabilisation profile. To determine abatement action and costs, we make use of the multi-gas cost module of the FAIR 2.1 model (Den Elzen and Lucas, 2005). This model uses aggregated permit demand and supply curves, derived from the MAC curves for the different regions, gases and sources. This is to determine the market equilibrium permit price (henceforth known simply as 'permit price') on the international trading market, the shares of the different abatement options in total abatement and the accompanying global abatement costs, by applying a least-cost approach.[33]

4.4.1 The global emission reduction objective

The baseline scenario used in this study is the updated IMAGE B2 scenario, which represents an implementation of the corresponding IPCC SRES scenario (Nakicenovic et al., 2000) (hereafter referred to simply as the 'B2 scenario'). This scenario is seen as a continuation of present-day trends – with medium assumptions for population growth, economic growth and more general trends such as globalisation and technology development. In terms of quantification, the scenario roughly follows the reference scenario of the World Energy Outlook 2004 (IEA, 2004) – and after 2030, economic assumptions converge to the B2 trajectory (Nakicenovic et al., 2000). The long-term UN medium population projection is

[33] See Den Elzen et al. (2005) for a discussion on the strengths and limitations of this cost methodology.

used for population (UN, 2004). Trends in agricultural production (production levels and yields) are based on the Adaptive Mosaic scenario of the Millennium Ecosystem Scenarios, which were elaborated for these parameters by the IMPACT model (Rosegrant et al., 2002). All other assumptions are based on the earlier implementation of the B2 scenarios (IMAGE-team, 2001).

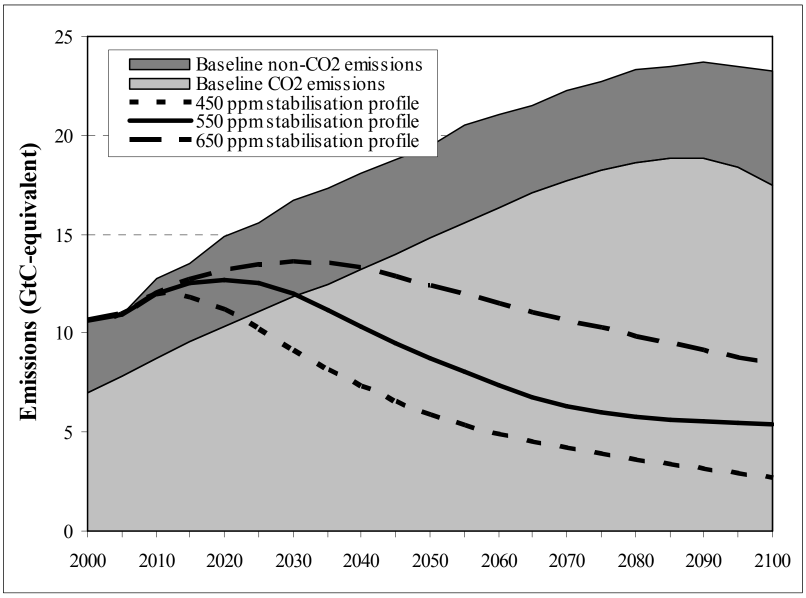


Figure 4-4 Baseline emissions and the 450, 550 and 650 ppm emission stabilisation pathways.

The aforementioned scenario, distinguishing between CO_2 and non-CO_2 emissions, is presented in Figure 4.4. The CO_2 emissions originate mainly from the combustion of fossil fuels. The energy- and industry-related carbon dioxide emissions increase sharply from 25 $GtCO_2$ in 2000 to 54 $GtCO_2$ in 2050, then level off to reach 64 $GtCO_2$ in 2100 and continue to be the major source of GHG emissions. For the non-CO_2 GHGs, total CH_4 and N_2O emissions increase up to 2050, then remain fairly constant. Over the century, their contribution to total greenhouse gases drops from 22% to 15%, as their growth rate is slower than that of CO_2. This is caused by the fact that most land-use-related drivers of these emissions have strong saturation tendencies. For CH_4, only emissions from animal husbandry, gas production and landfills are likely to grow rapidly in the absence of climate policies. For coal and oil production, changes in methane production levels and capture for economic or safety reasons already reduces some CH_4 emissions. Wetland rice emissions remain fairly constant, as not much expansion is assumed to occur and yields improve. For N_2O, only increases in fertiliser use and animal waste are expected to lead to increasing N_2O emissions. Fluorinated gases form by far the fastest growing category of emissions. The reasons for their increase include replacement of ozone-depleting substances by HFCs, rapid growth rates of major emitting industries (semi-conductors, electricity production) and replacement of ozone-depleting substances by HFCs. It should be noted that despite these rapid increases, in absolute terms F-gas emissions remain relatively small compared to the other sources.

The baseline emissions are compared to constrained multi-gas emission pathways, corresponding to a stabilisation of total GHG concentration at a level of 550 ppm CO_2-equivalent, as developed by Den Elzen et al. (2006) (see the solid line in Figure 4.4). These emission pathways take into account constraints on the rate of the emission reductions because technical and political inertia prevents the global GHG emission levels from changing dramatically from year to year or from decade to decade. Fast reduction rates would require the early retirement of existing fossil-fuel-based capital stock, which may be associated with high costs.

4.4.2 Results for the 550 ppm stabilisation profile

In the analysis of the mitigation cases, we first analyse the impacts of a CO_2-only versus a multi-gas approach on the overall costs of reaching the concentration stabilisation target. Furthermore, we use the different sets of non-CO_2 MAC curves to assess the change of non-CO_2 reduction potential over time. The marginal price of the reductions and total abatement costs as percentage of GDP is shown in Figure 4.5. Obviously, both the marginal price and the overall costs are much higher when taking only CO_2 emission reductions into account as this lowers the total abatement potential, i.e. the supply of emission reductions. For the three multi-gas cases we see an increase in the marginal price towards 2065 for this study and 2080 for EMF-21. Differences in the peak can be explained by the differences in technology developments, which are the largest for this study.

Technology development not only lowers the reduction costs but also increases the reduction potential. After 2065 and 2080 the respective increases in reduction potential (both CO_2 and non-CO_2) are larger than the increase in the reduction objective, resulting in a decrease of the marginal price. For the three multi-gas cases, the overall costs increase in all scenarios towards 2060, attaining abatement costs between 1.2% and 1.4% of worldwide GDP, after which it decreases towards 0.4% to 0.5% in 2100. The costs for the CO_2-only cases are much higher, reaching approximately 2% of world GDP in 2060 and still rising. The decrease in the overall costs after 2060 in the three multi-gas cases is partly the result of dropping marginal prices, while the large increase in world GDP also has a significant influence.

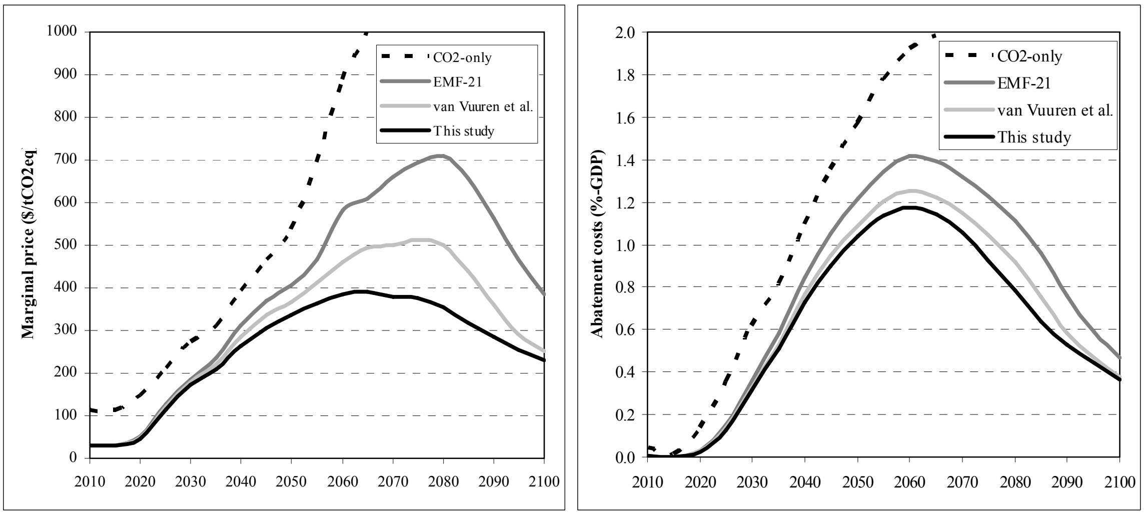


Figure 4-5 Marginal prices (left) and relative abatement costs as a percentage of GDP (right) for the four cases considered.

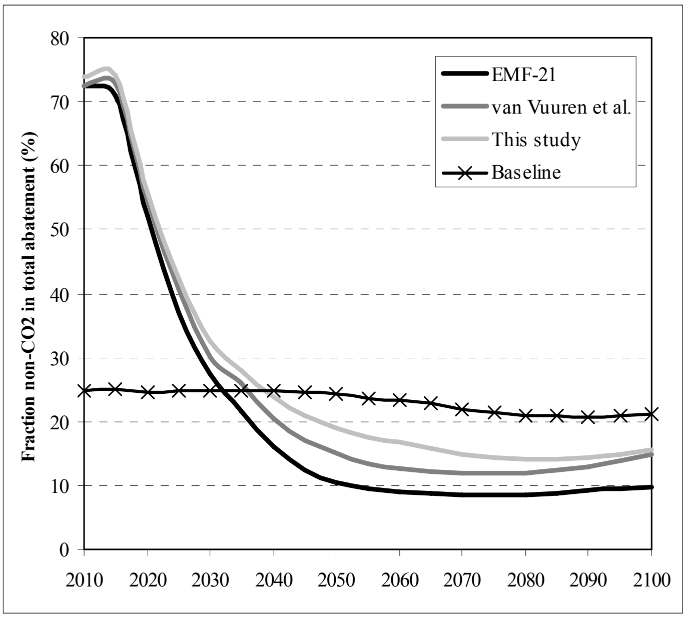


Figure 4-6 Non-CO_2 reduction share in total emission reductions (right) for the three multi-gas cases. The baseline represents the share of non-CO_2 GHGs in total baseline emissions

Figure 4.6 shows the shares of the non-CO_2 emission reductions for the three multi-gas cases in total reduction. In the short term (up to 2030–2035) the share of the non-CO_2 emission reduction is much larger than their baseline emission shares. This can be explained by the fact that most non-CO_2 emission-reduction options are relatively cheaper than reductions taken in the energy system, and are therefore taken first. The share of non-CO_2 reductions increases even slightly towards 2015, as the potential of non-CO_2 emission reductions increases more than the CO_2 reduction potential from the energy system. In the long term, the share of the non-CO_2 emission reductions drops below their baseline share. In part, the overall shift simply reflects the fact that non-CO_2 emissions represent approximately one-fifth of total GHG emissions, and that reduction becomes more proportional to the emission shares. However, it also reflects the underlying reduction potential estimates. There is obviously a large difference in the future non-CO_2 abatement shares between the three multi-gas cases. When no technological developments are assumed, the potential of non-CO_2 reductions only increases when the baseline increases (EMF-21). For the other two cases, technological developments are assumed to result in much larger future potentials and therefore also higher shares.

Table 4-2 Absolute sectoral non-CO_2 emission reductions and their shares in total non-CO_2 emission reductions for stabilising at 550 ppm CO_2-equivalents.

	2025		2050		2075		2100	
	Emission reductions (GtC-eq.)	Share in Emission reductions (%)	Emission reductions (GtC-eq.)	Share in Emission reductions (%)	Emission reductions (GtC-eq.)	Share in Emission reductions (%)	Emission reductions (GtC-eq.)	Share in Emission reductions (%)
CH_4								
Coal production	185	18	188	10	394	18	628	25
Oil/gas prod. and distr.	217	21	394	20	118	5	98	4
Enteric fermentation	76	7	247	13	294	13	325	13
Animal waste	7	1	21	1	23	1	23	1
Wetland rice prod.	51	5	117	6	116	5	116	5
Landfills	204	19	268	14	342	16	379	15
Sewage and waste water	72	7	97	5	110	5	119	5
Total	**811**	**77**	**1332**	**68**	**1397**	**63**	**1688**	**66**
N_2O								
Transport	1	0	5	0	6	0	5	0
Industrial sources	33	3	31	2	25	1	35	1
Fertiliser use	64	6	128	7	153	7	173	7
Animal waste	18	2	60	3	62	3	48	2
Domestic sewage	1	0	5	0	7	0	4	0
Total	**117**	**11**	**230**	**12**	**253**	**11**	**266**	**10**
F-gases								
HFCs	78	7	271	14	419	19	484	19
PFCs	25	2	68	3	89	4	80	3
SF6	21	2	54	3	47	2	43	2
Total	**124**	**12**	**393**	**20**	**556**	**25**	**606**	**24**
Total	**1052**	**100**	**1955**	**100**	**2206**	**100**	**2560**	**100**

Table 4.2 presents absolute non-CO_2 emission reductions and their shares in total non-CO_2 reductions using the MAC curve set from this study. Taken over the entire century, the largest share of abatement comes from CH_4. The share of the fluorinated gases is also significant, while the share of N_2O emission reductions remains rather small. The figure shows a declining increase in time of the overall reductions, where the largest increase comes from CH_4 landfills and enteric fermentation, N_2O fertiliser and HFC emissions. The increase

in emission reductions is both a baseline effect (increase in emissions due to increasing purchasing power and population) and a technological development effect (increase in abatement technology and thereby abatement potential). The dynamics in coal, oil and gas production can be explained from the baseline. Until approximately 2050 most of the increase in coal mining is surface mining, with much less CH_4 emitted, while after 2050 underground coal mining increases, raising total emissions and thereby also the abatement potential. For oil and gas, some mitigation already takes place in the baseline by flaring the CH_4 emissions. This is already done in most industrialised countries and is assumed to increase in most developing countries, resulting in a decrease of emissions, and thereby reduction potential, in the second half of the century.

4.5 Sensitivity analysis

This section analyses the extent to which the non-CO_2 share and the global abatement costs depend on key assumptions relating to the mitigation and policy options for the non-CO_2 emission sources. In addition to assumptions on technology developments, and maximum achievable reduction potentials and costs, this sensitivity analysis also includes the choice of baseline scenario and the concentration stabilisation target. The B2 baseline and the 550 ppm CO_2-equivalent concentration stabilisation target are used as the reference case, as already assessed in the previous section. The key assumptions and the levels on which they are based can be found in Table 4.3. A high emission growth scenario (A1b baseline) and a low emission growth scenario (B1 baseline) are used to assess the influence of the baseline scenario.[34] The multi-gas emission pathways aiming at the low 450 ppm and the high 650 ppm CO_2-equivalent concentration stabilisation targets, as developed by Den Elzen et al. (2006) are used to assess the influence of the concentration stabilisation targets (see dotted lines in Figure 4.4). To assess the sensitivity of the assumptions on maximum abatement potentials and accompanying costs, the maximum potentials, as presented in Table 4.1, are increased by 20% to represent a more optimistic estimate and decreased by 20% to represent a more pessimistic view. The accompanying costs are also increased or decreased by 20% to represent a pessimistic and an optimistic view, respectively. To assess the sensitivity of the technology development, this parameter is set to 0%/yr for the pessimistic case to 0.8%/yr for the optimistic case. Figure 4.7 shows the results of this sensitivity analysis for the year 2050 as a percentage change with respect to the reference case. With respect to the non-CO_2 share in total abatement, the methodology is most sensitive for assumptions on the concentration stabilisation target and the potential maximum reduction, where the range differs according to an increase or a decrease of approximately 15%. Looking at the effort rate, the greatest sensitivity is towards the baseline scenario and the concentration stabilisation target. Here, the range differs according to an increase or a decrease of almost 60%. The effects on the overall costs of assumptions for the marginal costs are relatively low (5%).

[34] The A1b scenario is characterised by very high economic growth and rapid technology transfer, and a leading consumer trend is towards a fast-food, high-meat, Western-style diet, whereas the B1 scenario is characterised by rapid economic growth, an emphasis on quality-of-life and a rapid decline in energy- and material-intensive economic activities.

Table 4-3 Key assumptions and the levels they are varied on as used in the sensitivity analysis

	Reference scenario	Optimistic scenario	Pessimistic scenario
Baseline scenario	B2	B1	A1b
Emission stabilisation target	550 ppm CO_2-eq.	450 ppm CO_2-eq.	650 ppm CO_2-eq.
Max price	See Table 4.1	Table 4.1 -20%	Table 4.1 +20%
Max reduction potential	See Table 4.1	Table 4.1 +20%	Table 4.1 -20%
Technology development	0.4%/yr	0.8%/yr	0.0%/yr

Thus, the non-CO_2 share seems rather robust over the different baseline scenarios. Nevertheless, as the costs are determined relative to the baseline scenario, scenarios with higher emission levels obviously result in higher costs. The concentration stabilisation targets have a much greater influence over the non-CO_2 share, while the overall costs are also in the same range. Both effects are the results of a lower (650 ppm) or higher (450 ppm) concentration stabilisation target and resulting reduction objective. A lower reduction objective results in a larger share of cheap non-CO_2 emission reductions, and obviously a lower price. A higher reduction objective works the other way around. Technology development influences, including maximum abatement potentials and accompanying costs, are partly outweighed by opposite changes in the non-CO_2 share.

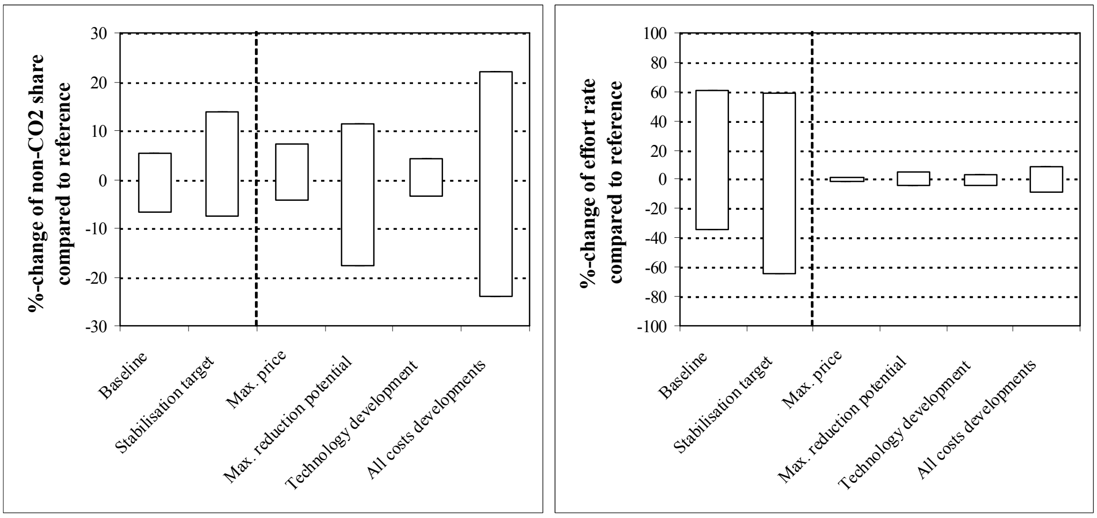


Figure 4-7 The impact of the key parameters on the non-CO_2 share in total abatement (left) and on the global effort rate (right) in 2050 (see also Table 4.3).

4.6 Discussion and conclusions

Various studies have found that reducing non-CO_2 emissions, alongside CO_2 emissions from the energy system, form the bare necessity for constructing emission stabilisation scenarios that can accommodate stringent climate targets. Including non-CO_2 abatement options not only lowers the overall abatement costs, but also brings the lower concentration stabilisation target more within reach. In this article, we extend the work done within EMF-21, by emphasising the importance of assessing the long-term reduction potential of non-CO_2 GHGs. The information on mitigation potential in the EMF-21 database only focuses on technologies that can be used in 2010 (for which fairly robust information is available). The database provides abatement potential for only 30% of the CH_4 emissions and less than 20% of the N_2O emissions. The reason for this is that the potential is limited by the focus on technologies that could be implemented around 2010.

In the long term, technology progress and removal of implementation barriers are likely to increase the reduction potential (similar to the reduction potential for CO_2 from energy consumption). This is why we looked into the existing literature to assess the long-term reduction potential of the different gases and present a methodology to extend the short-term MAC curves to 2100 for the most important non-CO_2 greenhouse gases and their emission sources. The methodology uses a technological development factor and further extends the curves using maximum potential reductions and accompanying costs. These factors, potentials and cost estimates are differentiated in time and over the various emission sources, but remain constant for the different world regions. In our analysis, we first assessed the impacts of including non-CO_2 mitigation in reaching long-term GHG concentration stabilisation targets, and then compared the impacts of assuming no progress in abatement potential against a situation in which potentials increase in time.

Taking into account technology progress, including non-CO_2 mitigation options can decrease the overall costs of climate policy by approximately 80% in the short term, up to 30–40% in the long term (depending on the technology development). Including non-CO_2 mitigation options not only increases the potential emission reductions by approximate 20%, but the costs of these abatement options are significantly lower than most options in the energy sector. Furthermore, technology developments are most important for the land-use-related source, since according to present-day technology their potentials are still small. Including technology developments can further decrease the overall costs. However, increasing these developments decreases the overall costs only slightly, as generated extra reductions enter the system at relatively high costs and now compete with emission reductions that can be taken in the energy system. Extra cost reductions due to this technology development increases, and can total up to 12%.

In addition to the diminishing role of non-CO_2 abatement in the overall costs in the long term, its share in total abatement also decreases in time. In the short term, the share of non-CO_2

abatement is relatively large, at around 75%. This relatively low share can be explained by the fact that most non-CO_2 abatement options are cheaper than the CO_2 reduction effort in the energy system; the global reduction objective is still relatively small. In the long term, CO_2 emission reductions from the energy system become more and more important, lowering the non-CO_2 to 10–15%. The latter is mainly due to the limited potential of non-CO_2 reductions and the rapidly increasing global reduction objective.

Methane emission reductions form the largest part in non-CO_2 abatements as their overall emissions are the largest and, for most emission sources (mainly from fossil fuel production and landfills), are relatively easy to abate. A high rate of reduction can also be achieved for fluorinated gases, but their share in total emissions is much smaller. Nitrous oxide is a less important gas, not only because the baseline emissions are relatively small, but also because the relative maximum potentials are much lower. This last point mainly applies to the land-use-related sources such as fertiliser use and animal husbandry, for which the maximum achievable reduction potential is assessed as around only 40%.

The set, as developed in this paper, has several attractive properties. First of all, it is completely consistent with the EMF-21 set, as it uses EMF-21 as its starting point in 2010. As such, it embodies the information that was developed in EMF-21 and discussed among a large group of experts. The rules used to make these curves dynamic are relatively simple and transparent, and the effects can be easily assessed. Finally, using maximum potential reductions from the literature for relatively high marginal prices includes technology advances that can already be foreseen, although the timing and effects are not yet fully known. Besides these advantages the methodology also has several disadvantages. The main disadvantage is that the maximum potentials are uniform for all regions and therefore assume that all regions have the same access to these new technologies and start from the same technology, which is certainly not the case. This can obviously be easily improved if regional information becomes available. Furthermore, one could argue that the maximum potentials could depend on the concentration stabilisation target as a higher reduction objective increases the need to invest in abatement potential, which means technology. The estimates are based on known and foreseeable technologies. However, a technological breakthrough, especially in the agricultural sector, could significantly increase this potential. This mainly applies to animal husbandry, as this is the main emitting source for both CH_4 and N_2O. Nevertheless, as the share of total non-CO_2 emissions remains small over the entire century, in spite of possible technological breakthroughs, their share in total reductions and therefore their share in extra overall costs reduction remain limited.

5 The potential role of hydrogen in energy systems with and without climate policy

B. van Ruijven, D.P. van Vuuren, H.J.M. de Vries

5.1 Introduction

For at least several decades, the idea of hydrogen-based energy systems has attracted the attention of engineers and environmental scientists. Interest first surged in the early 1970s in response to the first oil crisis and the growing concerns about environmental issues (Caprioglio, 1974;TNO, 1975; Lucas, 1976). The perceived advantages are its nearly zero emissions (improving air quality) and the possibility of local production on the basis of a variety of fuels (decreasing dependence on imported oil) (Dunn, 2001; Lovins, 2003). Interest subsided after the oil price decline in the mid-1980s but resurged in the early 2000s due to its potential role in reducing greenhouse gas emissions (see for instance initiatives from both public and private parties: (Arnason and Sigfuasson, 2000; Shell, 2001; GM, 2002; U.S. Department of Energy, 2002; European Commission, 2003)).

While the contribution of hydrogen in improving urban air quality and dependence on imported oil is obvious, its role in reducing climate change is less straightforward. On the one hand, the high end-use efficiency in fuel cells and the possibility to produce hydrogen from non-fossil sources or clean fossil fuels (fossil fuel combustion in combination with carbon capture and storage (CCS)) – could reduce greenhouse gas emissions from the energy system (Ogden, 1999a; Azar et al., 2003; Barreto et al., 2003). On the other hand, hydrogen can also be produced from relatively cheap coal without CCS technology, which leads across the whole chain to a considerably higher *carbon/energy* ratio than today's energy technologies (Edmonds et al., 2004). In addition, the question remains whether hydrogen-based technologies will ever be cheap enough to be an effective competitor to fossil-based and non-fossil-based technologies. These contradictory arguments contribute to uncertainty about the contribution of hydrogen to the mitigation of greenhouse gas emissions.

Model-based scenario studies have been designed to assess the role of hydrogen in future energy systems and the potential consequences for future carbon emissions and climate policy. For this purpose, global energy models have been extended to also cover hydrogen-based technologies. These include, for instance, the MESSAGE (Barreto et al., 2003), MiniCam (Edmonds et al., 2004) and GET (Azar et al., 2003) models. Such scenario studies, however, have not led to a single, consistent view on potential hydrogen-based energy systems. The GET and MESSAGE model runs indicate a very important role of hydrogen in reducing greenhouse gas emissions (Azar et al., 2003;Barreto et al., 2003). Other scenarios indicate a possible increase in such emissions as a result of increasing coal uses (Edmonds et al., 2004). These model results confirm the technical analysis indicating the existence of quite diverse technological pathways. Apparently, the future role of hydrogen depends on specific model assumptions – or even model structure – and the type of scenario considered (e.g., baseline or mitigation).

To explore the relationship between assumptions and outcomes for hydrogen-based energy systems in global energy models in more detail, we have performed a series of model experiments in the TIMER 2.0 model. In these experiments, we specifically look into the question of which uncertainties influence the potential role of hydrogen in future energy systems and to what extent, and how the potential role of hydrogen is related to climate policy.

This article describes the results of this analysis. We first summarise the results of a literature survey on assumptions for production technologies, infrastructure development and different end-use functions and related technologies. Values found in literature have been translated into pessimistic, intermediate and optimistic scenarios for hydrogen technology development. These three sets of assumptions are used as inputs for model experiments and scenario construction with the TIMER 2.0 model, using the TIMER B2 baseline scenario as reference (see section 5.3.2). Model runs are presented for six different cases: the baseline and a climate mitigation scenario, each in combination with the three hydrogen variants mentioned above. This set allows us to explore most of the potential H_2-scenarios which seem to matter on the basis of present-day insights.

5.2 The future of hydrogen: what does literature say?

5.2.1 Ranges of assumptions in literature as the basis for scenarios

There is a vast literature on the future possibilities of hydrogen energy. Some use full-fledged energy models, others are based on partial analyses or expert views. Focus, method and results show significant differences. Several scenario studies looking specifically into the role of hydrogen project a major role for this energy carrier in future energy systems – although timing and intensity of introduction differ significantly (see Table 5.1 for a subset of these scenarios). But other scenario studies, the short-term energy projections of the IEA among them, hardly pay attention to hydrogen (International Energy Agency, 2004). As with several other aspects of future energy systems, there is a lively debate on advantages and disadvantages of hydrogen-based energy systems (Clark II and Rifkin; Keith and Farrel, 2003;Lovins, 2003; Morris, 2003; Hammerschlag and Mazza, 2005).

As a basis for our model experiments and scenario construction, we have done a careful analysis of published long-term hydrogen studies (Van Ruijven, 2003a). In the brief overview in this paper, we focus on a sub-set, for which the main characteristics are shown in Table 5.1. We discuss the assumptions and results of these studies in relation to three important issues: 1) the type of technologies used to produce hydrogen, 2) the type of technologies and applications in end-use, and 3) the technical and economic aspects of infrastructure developments.

Table 5-1 Comparison of several hydrogen studies that use long-term global energy models.

	(Barreto et al., 2003)	(Azar et al., 2003)	(Edmonds et al., 2004)
Model	MESSAGE-MACRO	GET 1.0	MiniCAM
Scenario	IPCC/SRES B1-H_2	IIASA/WEC C1[a]	IPCC/SRES B2
Climate Target		400 ppm	550 ppm
Time	Initiated 2000 10% market 2030	Initiated between 2030 and 2050	Initiated 2010 30% market 2060
Production	Small-scale SMR and off peak electrolysis Large-scale SMR with CO_2-seq. Biomass and solar thermal	Small-scale SMR Large-scale SMR and Coal with CO_2-seq. Solar	Coal / Gas / Biomass CO_2-seq.
Applied in Sectors	Transport Residential/Service Industry	Transport	Transport
End-use Technology	Micropower (also from vehicles) CHP from FC plants	Fuel cells	Fuel cells and direct combustion
Infrastructure		Pipeline	Short pipelines, trucks, trunk lines

[a] This is an ‘ecologically driven’ scenario which assumes that technological development leads to efficiency improvements, so that per capita energy demand in developed countries is reduced.

5.2.2 Production

Currently, hydrogen is widely used in oil refineries, produced by steam methane reforming and coal gasification. However, most hydrogen production technologies for energy purposes (thus large-scale and low-cost) are currently still in the laboratory phase, or at best in the demonstration phase. In literature, some studies include only those in the demonstration phase (Ogden, 1999b; Barreto et al., 2003), while others also include anticipated future technologies such as bio-photocatalytics and photolysis (U.S. Department of Energy, 2002). While the latter category can be important in the long term, their assessment implies a quantification bordering on speculation.

Interestingly, there is convergence regarding the initial development of a hydrogen energy system. Natural gas plays an important role, almost all transition scenarios start with small-scale production of hydrogen from natural gas via steam methane reforming (SMR), possibly in combination with electrolysis during off-peak hours (Ogden, 1999b; Azar et al., 2003; Barreto et al., 2003). In the long term, literature shows three different possible configurations of the large-scale hydrogen energy system:

- large-scale production of hydrogen from fossil sources, mainly coal and natural gas (Turton and Barreto (in press); Ogden, 1999b; Barreto et al., 2003; Edmonds et al., 2004);

- a situation with climate constraints, when a fossil-based hydrogen system can be combined with CO_2 capture and sequestration (CCS) (Edmonds et al., 2004); and
- renewable hydrogen production, based on biomass gasification, direct solar thermal hydrogen production and electrolysis from solar or wind electricity (Barreto et al., 2003).

These configurations do not necessarily exclude each other, most studies find a succession of hydrogen production technologies, mainly first fossil-based and second towards a CCS or a renewable-based system.

Table 5-2 Ranges of hydrogen production technology characteristics from literature.

Technology	Current Capital Cost	Efficiency	Source
Coal Gasification (CG)	500–900 $/kW	60–65%	(IEA/AFIS, 1996b; Ogden, 1999b; Padro and Putsche, 1999)
Partial Oxidation of Oil (PO)	400–600 $/kW	50–60%	(Momirlan and Veziroglu, 2002)
Steam Methane Reforming (SMR)	100–350 $/kW	75–85%	(Thomas et al., 1998; Ogden, 1999b; National Research Council, 2004)
Biomass Gasification (BG)	800–1400 $/kW	50–70%	(IEA/AFIS, 1996b; Ogden, 1999b; Padro and Putsche, 1999; Hamelinck and Faay, 2001; National Research Council, 2004)
Electrolysis (E)	350–2000 $/kW	75–85%	(Thomas et al., 1998;Ogden, 1999b;Padro and Putsche, 1999)
Solar Thermal (ST)	3000–10000 $/kW	50%	(Bolton, 1996;Glatzmaier et al., 1998)
Small-scale Steam Methane Reforming (SSMR)	2000–4000 $/kW	75–85%	(Thomas et al., 1998;Ogden, 1999b;National Research Council, 2004)

The costs of producing hydrogen consist largely of feedstock and investment costs. Ranges for the specific investment cost and efficiency estimates for hydrogen production technologies reported in literature for the next few decades are given in Table 5.2. Future hydrogen production costs are generally assumed to be lower than current values as a result of technology development. For small-scale SMR, costs are generally significantly higher than that of large-scale SMR but some authors expect cost declines down to the level of large-scale SMR. We developed our scenarios, which we describe later, from these literature data (see Appendix C). We only used solar thermal hydrogen production as climate neutral backstop technology and excluded nuclear thermal.

5.2.3 End-use

The primary end-use technology associated with hydrogen is the fuel cell. Since fuel cells produce both heat and power, possible applications are almost infinite, and hence, literature on future hydrogen energy applications describes a wide range of possibilities. The main advantage of fuel cells is in vehicular applications, as they double the efficiency of transport compared to current internal combustion engines (ICE). Another advantage is that these fuel cells theoretically can also deliver electricity to the grid while the car is parked. This application of micropower influences the central power production and makes fuel cells more profitable (Dunn, 2001; Barreto et al., 2003). Most authors therefore project the most significant breakthrough of hydrogen (if any) in the future transport sector (even without electricity delivery).

A smaller number of authors expect the application of hydrogen energy in other economic sectors as well. The possibility of small-scale combined heat and power production is attractive for households and offices that can install their own fuel cells (Barreto et al., 2003; Lovins, 2003). Expectations for hydrogen in the industrial sector are more moderate. As many industrial applications can be served directly by electricity, hydrogen is expected only to fulfil niche functions (Barreto et al., 2003).

Table 5-3 Ranges of fuel cell characteristics from literature.

Technology	**Current Capital Cost** ($/kW)	**Future Capital Cost ($/kW)**	**Efficiency**	**Source**
Proton Exchange Membrane (PEM) Mobile	1200–1500	45–600	30–60%	(IEA/AFIS, 1996a;Thomas et al., 1998;Ogden, 1999b)
PEM Stationary	1400		60%e/40%th	(Tillemans and de Groot, 2002)
Solid Oxide Fuel Cell (SOFC) Stationary	1100		45%e/35%th	(Tillemans and de Groot, 2002)

So far, fuel cells are produced at a small-scale at high costs, but mass-production is expected to bring major cost reductions (Thomas et al., 1998; Tsuchiya and Kobayashi, 2004). The premature stage of fuel cell technology makes literature data somewhat speculative. As shown in Table 5.3, literature on current cost is relatively consistent, estimating fuel cell cost about 1100–1500 US$ kW^{-1}. However, estimations of future costs vary heavily, some studies project moderate cost reductions, while others foresee enormous breakthroughs with mass-production. An aspect of fuel cells that is currently under debate is the efficiency in vehicular applications. As current ICEs have a tank-to-wheel efficiency of 15–21%, and a future expected maximum of 25% (ICE-Hybrids excluded), the theoretical efficiency of fuel cells in mobile applications is definitely higher than current technology. However, as fuel cells in cars will seldom work at maximum power, estimates of the effective fuel cell efficiency are lower. Some authors project the real efficiency to be 30–36% (Van den Brink, 2003), 36–41% for an North-American driving cycle (GM, 2001) and 44–49% for an European driving cycle (GM, 2002). We used the whole range that we found in literature for the development of our scenarios (see Appendix C).

5.2.4 Infrastructure

The introduction of hydrogen in an energy system requires substantial changes in infrastructure. Although hydrogen is currently produced and transported on a small-scale for industrial purposes, large investments are needed to develop a complete infrastructure for energy applications. Most publications agree that this is the main barrier for the development of a hydrogen economy, and generally, transition studies and government route maps foresee a first period of small-scale hydrogen use in niche markets, without a need for distribution networks. From these small-scale experiments and pilot projects, the application and demand for hydrogen can increase, reaching a stage in which large-scale production becomes affordable (Ogden, 1999b; U.S. Department of Energy, 2002; Azar et al., 2003; European Commission, 2003). As shown in Table 5.1, the attention paid to infrastructure development varies widely between long-term studies. Some authors explicitly include several infrastructure options and their costs (Azar et al., 2003), while others only state that infrastructure is an important aspect of hydrogen energy systems (Barreto et al., 2003).

The main uncertainties in the literature on hydrogen infrastructure are costs and the form in which hydrogen is transported (gas, liquid or metal-hydrates). As hydrogen is a rather voluminous gas at normal temperature and pressure, it has to be either pressurised or liquefied. Currently, hydrogen for industrial applications is transported by trucks (liquid) or pipelines (pressurised gas). Future hydrogen energy systems can be based on both these technologies, depending on the cost development and the demand densities (Ogden, 1999b; Azar et al., 2003). In any case, the transport infrastructure costs will contribute considerably to the hydrogen price (see Table 5.4). Pipelines are the cheapest way of hydrogen transport, but are only affordable in case of a high hydrogen demand density. Distribution as a liquid by truck is also relatively cheap, but then storage is more expensive and compressors and dispensers are capital intensive. To deal with these uncertainties, we simulated two steps in infrastructure development in our model (see Section 5.3.4) and varied the costs of transport and distribution in the scenarios (see Appendix C).

Table 5-4 Hydrogen infrastructure costs.

Technology	**Cost**	**Source**
Storage (3 days)		
Liquid	6–18 $/GJ	(Ogden, 1999b; Dutton, 2002)
Compressed Gas	2–4.5 $/GJ	(Ogden, 1999b; Dutton, 2002)
Metal Hydrides	3–7 $/GJ	(Dutton, 2002)
Transport		
Pipeline	0.1–0.5 $/GJ/100 km	(Ogden, 1999b)
Liquid Truck	0.2–1.5 $/GJ/100 km	(Padro and Putsche, 1999)
Gas Truck	4.9–29.4 $/GJ/100 km	(Padro and Putsche, 1999)
Metal Hydrides Truck	2.6–16.4 $/GJ/100 km	(Padro and Putsche, 1999)
Distribution		
Refuelling Station	4–6 $/GJ	(Ogden, 1999b)

5.3 Modelling hydrogen in TIMER 2.0

5.3.1 The TIMER 2.0 Model

We used the TIMER 2.0 model to explore the possibilities of hydrogen in future energy systems. The TIMER 2.0 model is the energy sub-model of the Integrated Model to Assess the Global Environment, IMAGE 2.2 (IMAGE-team, 2001) that describes the main aspects of global environmental change. TIMER is a system-dynamics energy model that simulates year-to-year investment decisions based on a combination of bottom-up engineering information and specific rules on investment behaviour, fuel substitution and technology. TIMER 2.0 (Van Vuuren et al., 2005) is a revised version of the TIMER 1.0 model (De Vries et al., 2001), with main differences being extension of renewable energy modelling (Hoogwijk, 2004), carbon capture and storage and hydrogen (Van Ruijven, 2003b).

In the TIMER 2.0 model the demand for end-use energy is related to the economic activity in five sectors: industry, transport, residential, services and other. The demand formulation includes autonomous and price-induced changes in energy-intensity. Energy supply is based on fossil fuels (coal, oil, natural gas), biomass, solar and wind power, hydropower and nuclear power. Fossil- and biofuels can be traded among 17 world regions. The production of each primary energy carrier includes the dynamics of depletion and learning-by-doing. To this framework of sub-models we added a hydrogen model, which is connected to all primary energy supply models, the electricity model and the energy demand model.

5.3.2 The TIMER 2.0 B2 Scenario

The baseline scenario used here is the TIMER 2.0 B2 scenario. This scenario, based on the IPCC SRES B2 scenario, assumes a continuation of present day trends, with medium values for population and economic growth. In the implementation of the scenario, for the period 2000–2030, we have used the assumptions and results of the IEA reference scenario to roughly calibrate our scenario (thus the same population and economic growth, and roughly similar energy use and emission trends). From 2030 onwards, population follows the UN medium scenario, while economic growth rates are based on the original B2 scenario. The global population stabilises around 2100, at 10 billion people. The global growth rate of Gross Domestic Product (GDP) per capita starts at 2% yr^{-1} and declines slowly to 1.5% after 2050. Most currently low-income regions have relatively fast GDP per capita and energy use growth rates already early in the century. The African regions form an exception – here economic growth rates above global average only occur after 2040. Primary energy use, globally, increases from 400 EJ today to 1200 EJ in 2100. In the first half of the century, natural gas use rises rapidly. However, in the second half of the century, oil and natural gas prices are relatively high (as a result of depletion of low-cost resources). As a result, trends reverse: coal starts to gain market share in the electricity and industrial sector and represents 40% of all energy consumed by the end of the century. Carbon emissions increase from 6 GtC yr^{-1} today to 18 GtC yr^{-1} around 2100. Compared to most scenarios published today, these should be regarded as values slightly above the medium. In the default implementation of this scenario no penetration of H_2 as a major energy carrier is assumed.

5.3.3 The TIMER-H_2 model

The TIMER-H_2 model involves the production, demand, infrastructure and technology dynamics of hydrogen-related technologies, as described below (see Figure 5.1). In brief, hydrogen production costs are determined from capital costs, fuel costs and (if relevant) CO_2 sequestration costs. The costs of energy services from hydrogen for the end-user are the sum of these hydrogen production costs (also regarding end-use efficiency) and the end-use capital cost and infrastructure costs. The market-share of hydrogen is determined by the relative differences of the energy service costs on the basis of hydrogen and the same costs based on other energy carriers. The demand of hydrogen equals the market share times sectoral energy demand. Subsequently, hydrogen demand is met through investments into hydrogen production capital. Finally, there is a feedback loop from technological learning, as hydrogen production capital costs decline with increasing cumulative installed capacity.

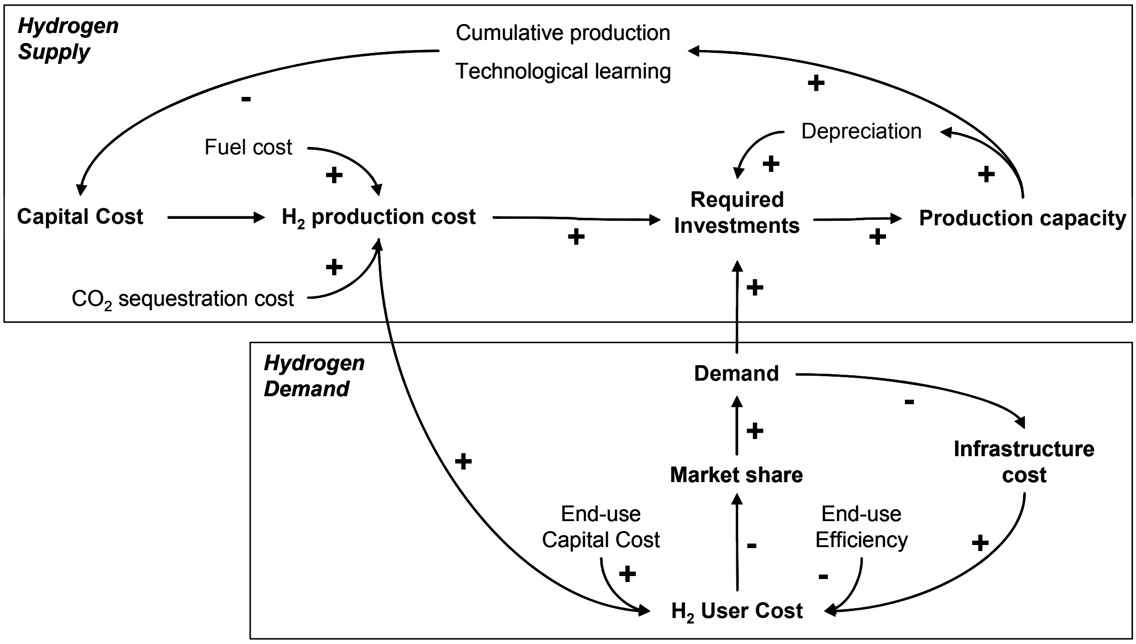


Figure 5-1 Overview of the TIMER-hydrogen model. Arrows indicate influence factors or inputs for calculation.

Hydrogen production

In TIMER 2.0, hydrogen can be produced from coal gasification, partial oxidation of oil, steam reforming of natural gas, gasification of biomass, electrolysis and direct solar thermal production of hydrogen. For the production of hydrogen from natural gas, the model distinguishes between both large-scale and small-scale steam methane reforming (SMR). This is in order to simulate a transition period in which there is no infrastructure and (more expensive) small-scale SMR is the only available technology for stationary applications of hydrogen energy. The capacity, investments and depreciation of hydrogen production technologies are simulated by a vintage stock model, assuming a lifetime of 30 years. The investment shares of hydrogen production technologies are based on the mutual cost differences, weighted in a multinomial logit formula (see Appendix B). The costs of feedstock for hydrogen production (coal, oil, natural gas, biomass electricity and solar) and the dynamics of carbon sequestration resources and capacity are modelled elsewhere in TIMER.

For each of the technologies, technological progress is simulated by learning-by-doing curves, describing the dynamics of decreasing cost as a function of increasing cumulative production capacity (Argote and Epple, 1990; Rogner, 1998). The concept is applied to the capital cost of hydrogen production technologies. We assumed technological learning to be based on global cumulative production capacity, with variations in specific cost reduction based on openness between regions and relative contribution of a region to the global cumulative production capacity. Parameterisation of technological learning is derived from Barreto et al. (2003), with variations in scenarios. We were not able to find literature estimates of learning parameters for solar thermal and small-scale SMR. For these technologies we used a hybrid learning method: initially the costs of solar thermal and small-scale SMR decrease with a constant rate, between 0.4–1.5% yr^{-1}, simulating R&D developments in the pre-introduction period. When these technologies become competitive and production capacity is installed, endogenous technological learning takes over. Technology for carbon capture and sequestration is modelled as an add-on to the base technology, using extra capital and operation and maintenance costs and decreasing the hydrogen production efficiency. We assumed that with SMR CO_2 is only captured from the pure CO_2 outflow (88% of total CO_2 captured), and with coal gasification and POX (oil) the CO_2 is captured from a mix of exhaust gases (95% of total CO_2 captured). Our assumptions, based on Hendriks et al. (2002) are slightly more positive than the recently published overview by Damen et al. (2006), but must be seen as 'future values'. The scenario assumptions on hydrogen production technologies are based on literature data as shown in Table 5.2 and elaborated per scenario in Appendix C.

Hydrogen end-use

The total energy demand in TIMER 2.0 is based on assumptions on changes in population, economic activity and energy efficiency improvement. Based on mutual differences in useful energy costs, the market share of secondary energy carriers is allocated based on a multinomial logit formula (see Appendix B). We defined useful energy as the energy that is available to fulfil a demanded energy service, corrected for differences in end-use efficiency between different energy carriers. Thus, hydrogen can penetrate into five end-use markets. Another option is mixing hydrogen into the natural gas grid. Without creating difficulties for the end-user (both safety and equipment adjustment), this is only possible up to a maximum level of 5% on an energy basis (Hendriks et al., 2002). It can reasonably be assumed that this option is only attractive for end-use in the residential and service sectors. Similar to other end-use market allocation, the share of hydrogen in natural gas is based on relative costs via a multinomial logit with an upper constraint.

The most important assumptions on end-use are those on the cost and efficiency of fuel cells. We assume exogenous cost decline series for fuel cells. For the industry sector we assumed that Solid Oxide Fuel Cells (SOFC) will be applied (Wurster and Zittel, 1994; Reijnders et al., 2001). For other, both stationary and mobile applications we assumed Proton Exchange Membrane (PEM) fuel cells (Thomas et al., 1998;Ogden, 1999b;Tillemans and De Groot, 2002). In the transport sector we consider also variations in efficiency of PEM fuel cells, as discussed in Section 5.2.3. We only assumed differences in technology, without taking into account the non-energy cost and differences in service characteristics (e.g., a revolutionary new vehicle design with fuel cells). The assumptions for end-use parameters are based on the ranges presented in Table 5.3 and can be found in Appendix C.

Although clean fuels are sometimes exempted from energy taxes, it is assumed that on the longer run taxes on energy are needed to maintain the necessary infrastructure. Therefore, in the pessimistic and intermediate scenarios we assume an energy tax to be applied to hydrogen. For the transport sector we used the regional taxes on oil, in the other sectors we used the average value of taxes on other energy carriers. These taxes, based on IEA statistics, are exogenous and depend on region, time and scenario. Depending on the region, they amount to 1–15 US$ GJ^{-1} in the transport sector and 0.2–1.5 US$ GJ^{-1} in the other sectors. A similar approach is applied to biofuel, often a direct alternative to hydrogen. In the optimistic scenario we assumed no taxes on hydrogen, to create an optimistic case for both technology development and policy.

Hydrogen distribution: The transition storyline

Transport and distribution of hydrogen is a major issue in the transition to a hydrogen energy system. In our model we distinguish two steps in the hydrogen chain: transport and distribution. We defined the transport step as the distance from large-scale plants to residential areas or refuelling stations. Therefore, transport only applies to hydrogen produced on a large scale and includes the costs for a hydrogen transport network (e.g., pipelines or trucks). The distribution step includes the final distribution of hydrogen, for example the small-scale network in residential areas or the refuelling station itself. The costs of distribution are added to both large-scale and small-scale produced hydrogen (see Figure 5.2).

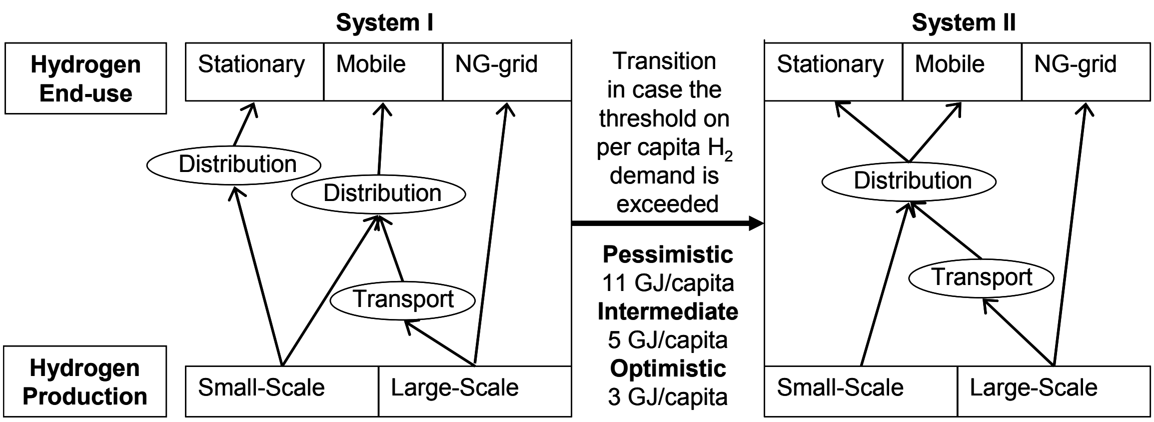


Figure 5-2 Transition in transport and distribution of hydrogen.

Because the development of a hydrogen transport infrastructure is expensive, hydrogen for stationary applications will initially only be produced from small-scale steam methane reforming plants near end-use locations. It is only when hydrogen demand density rises above a certain threshold that investments in large-scale infrastructure (pipelines) will be made and stationary applications can be served by both small-scale and large-scale hydrogen plants. We assume that hydrogen demand per capita is a proxy for demand density and use, based on data from Ogden (1999b) and Thomas (1998), a threshold of three (optimistic) to eleven (pessimistic) GJ per capita. For the transport sector we assume that hydrogen can initially be produced at all scales, since demand is dispersed and can be provided by truck. Hydrogen mixed into the natural gas grid is assumed to be produced only from large-scale production facilities. This transition at above a certain threshold value is shown in Figure 5.2.

The transport and distribution costs for hydrogen are likely to change in time. We have linked these costs to the hydrogen demand per capita as well, since a higher hydrogen demand density leads to shorter transport distances and the transport technology will become cheaper when it is widely applied. Several options for transport of hydrogen were analysed. Based on a spatial analysis by Mintz et al. (2002) and the ranges presented in Table 5.4, transport costs in the pessimistic scenario decline from 12 US$ GJ^{-1} to 6 US$ GJ^{-1}, in the intermediate scenario from 10 US$ GJ^{-1} to 3 US$ GJ^{-1} and in the optimistic scenario from 10 US$ GJ^{-1} to 2 US$ GJ^{-1}.

5.3.4 The TIMER-H_2 Scenario Set

We have translated the values found in literature into pessimistic, intermediate and optimistic scenarios for hydrogen technology development. In the pessimistic set of assumptions, we describe a world in which no major hydrogen-related breakthroughs are established and transitional dilemmas, like the chicken-egg problem with demand, supply and infrastructure development, are not solved. Technologies and costs continue to improve slowly between now and 2100 towards the lower range of technology parameters found in literature (see Table 5.2; 5.3; 5.4 and Appendix C). In the intermediate scenario, some promising improvements in technology are made, but after a while new boundaries are encountered. In particular, in the first decades of the scenario fuel cells rapidly become cheaper. However, after this initial breakthrough, further progress slows down. In the production phase, no major new cost reductions are achieved – and partly because the major development of fuel cell markets does not occur – production capacity stays limited and hydrogen production technology does not learn as much as was hoped for. Some hydrogen distribution infrastructure is developed for the transport sector, but apart from few niche markets transition is costly. In this scenario, technologies improve to the lower range of technology estimates by 2050 but improve more slowly in the second half of the century towards more intermediate values. Finally, in the third optimistic scenario, breakthroughs in hydrogen technology are realised and transitional issues are vigorously solved. Fuel cells are mass-produced at low cost, hydrogen production technology becomes cheaper and better through learning and distribution infrastructure is developed rapidly at low costs. In this scenario, technologies are assumed to improve rapidly to reach an intermediate range by 2030 and the most optimistic values in literature in 2100. We assumed these technology improvements as an exogenous process, and did not take into account any related costs, for instance R&D investments. It should be noted that we vary assumptions on the hydrogen technology itself and that developments in other technologies (e.g., batteries, hybrid vehicles) are assumed similar in all scenarios.

These three sets of assumptions are combined with the TIMER 2.0 B2 scenario, as described in section 5.3.2. One additional dimension is added: the existence of climate policy. All scenarios were run in a default case without climate policy and under the constraint that greenhouse gas concentrations will be stabilised at 450 ppm CO_2-eq. While different emission profiles exists to go to 450 ppm CO_2-eq, we have used an emission path from the FAIR model, as described in (Den Elzen and Lucas, 2003;Van Vuuren et al., in prep.). This profile can be interpreted as a median scenario in timing, without major overshoot. Recently published studies on the probability distribution of climate sensitivity suggest that such low stabilisation levels are required in order to have a reasonable chance of reducing global mean temperature change to 2°C above pre-industrial levels (Den Elzen and Meinshausen, 2005). For this study, this ambitious stabilisation target (compared to most literature published on mitigation scenarios) is chosen to have a clear signal from climate policy on the development of the energy system. One additional scenario is run with climate policy to explore specifically the role of excluding CCS in the optimistic hydrogen scenario (as CCS technology costs and acceptance are also uncertain). This implies that the model is run for nine different cases. First is the B2 baseline and then the three hydrogen variants without climate policy: the H_2 Pessimistic case (NoCP Pes), intermediate case (NoCP Int) and optimistic case (NoCP Opt). As we found that under the NoCP Pes scenario no penetration of hydrogen occurs, this scenario is actually equal to the baseline (and is thus used for this purpose throughout the paper). The second scenario set is identical but now with a climate policy constraining the CO_2-equivalent concentration to 450 ppm by 2100: Cp Pes, CP Int and CP Opt. The last case is the one without the possibility of carbon capture and sequestration (CP Opt NoCCS).

5.4 Results

5.4.1 Scenarios without climate policy (NoCP)

Hydrogen Production

Figure 5.3 shows the costs of the various options to produce hydrogen in OECD Europe in the three scenarios without climate policy. In principle, for all options there is a downward pressure on costs as a result of learning-by-doing. In terms of the differences between the intermediate and optimistic scenario, a higher progress ratio and lower starting values for investment costs under the optimistic scenario contribute to making hydrogen production more competitive than under the intermediate scenario. This in turn leads to more investments, driving technologies further down the learning curve. By the end of the century the observed cost differences are largely caused by the differences in cumulative capacity; the cost differences as a result of different progress ratios play a smaller role. In addition to the decrease of capital costs from learning effects, total production costs may increase as feedstock costs (in particular oil and natural gas) are expected to increase over the century.

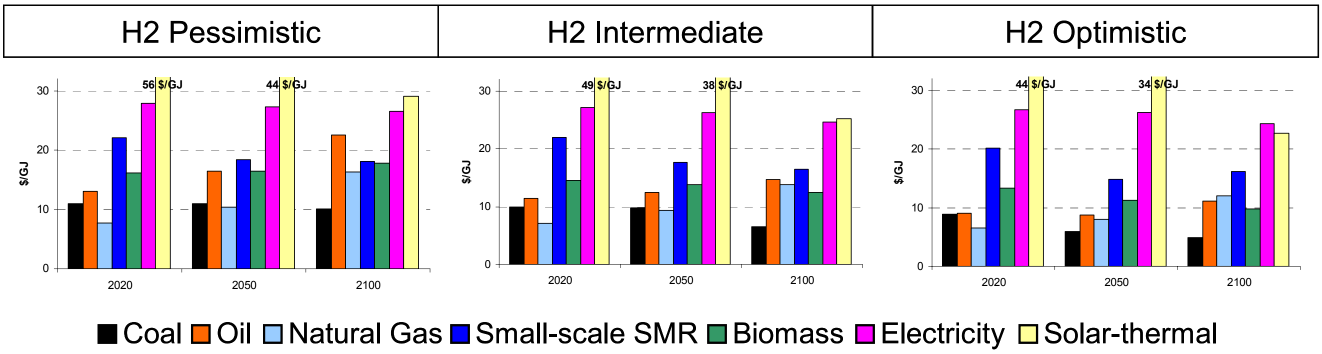


Figure 5-3 Hydrogen production cost before transport and distribution and before tax, for several technologies in OECD Europe and without climate policy.

Figure 5.3 shows that hydrogen production from coal and natural gas is for most of the century the cheapest option. Initially hydrogen can be produced from large-scale SMR at about 5–10 US$ GJ^{-1}. These costs remain more or less constant in the first 50 years, as a result of decreasing investment costs on the one hand and increasing natural gas prices on the other. The latter effect dominates by the end of the century, raising production costs to over 10 US$ GJ^{-1} in all scenarios. This means that in the second half of the century, hydrogen production from coal is the cheapest technology, at costs declining to about 5 US$ GJ^{-1} in the optimistic scenario. The small-scale methane reform option has relatively high production costs as a result of unfavourable economies of scale and lower efficiency. Nevertheless, this option may well be cost-effective in the residential/services sector where the hydrogen can be produced at the demand site without additional transport costs. The options to produce hydrogen from oil, electricity and solar-thermal are hardly competitive in any to the scenarios without climate policy. Hydrogen produced from biomass is among the low cost options in the second half of the century in the intermediate and optimistic cases.

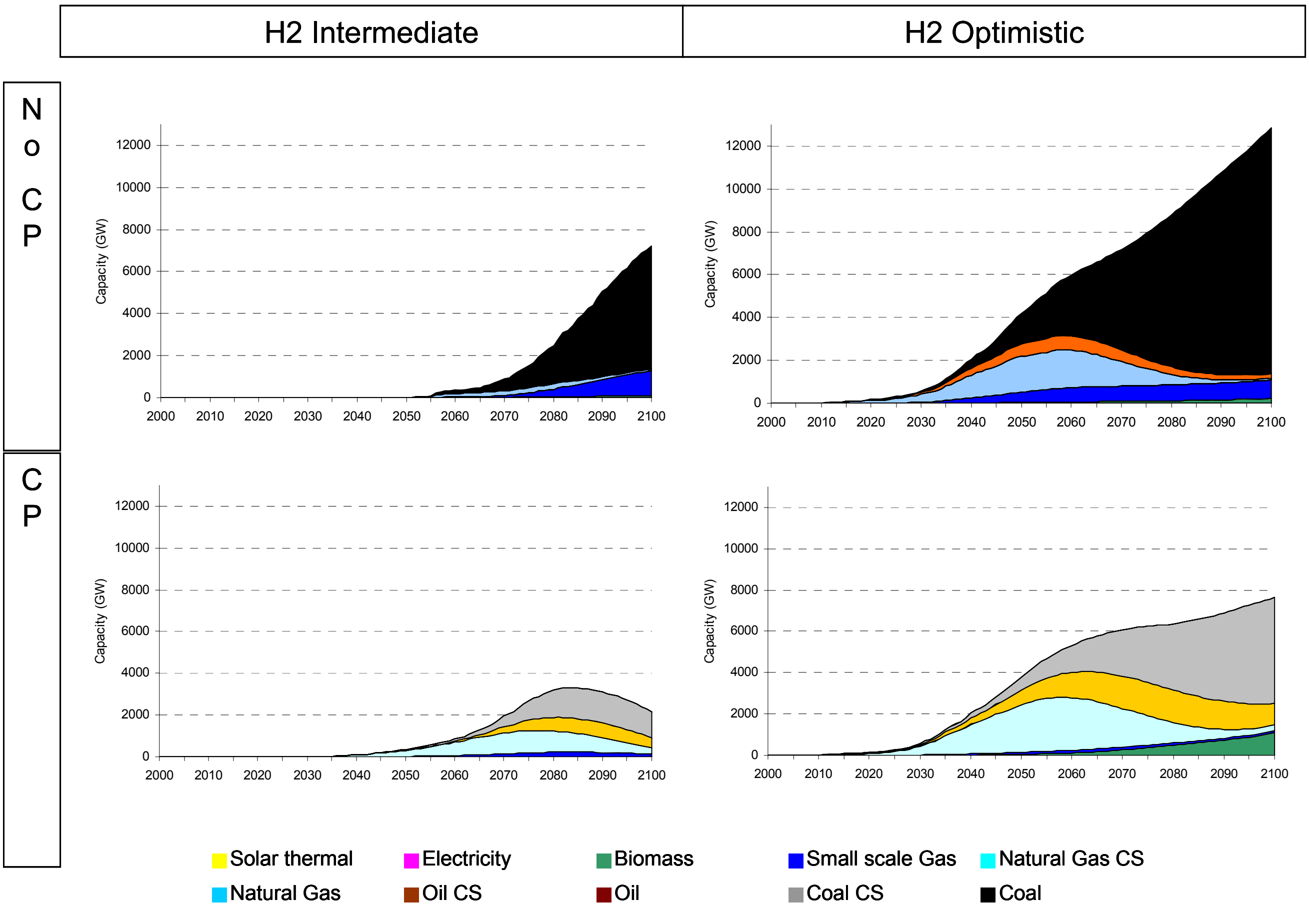


Figure 5-4 World hydrogen production capacity for the intermediate and optimistic hydrogen scenarios with and without climate policy (CP). With pessimistic assumptions on hydrogen technology and cost, no penetration occurs.

Hydrogen production is shown in Figure 5.4 (upper graphs). Hydrogen starts to be produced in the second half of the century – where under some of the scenarios hydrogen becomes competitive (see further in this section). In the pessimistic case, hydrogen remains too expensive – and thus there is no consumption. The production shares shown in Figure 5.4 obviously directly reflect the costs shown in Figure 5.4. The hydrogen production in the scenarios is almost exclusively based on coal and natural gas.

Of course, hydrogen production costs and hence market prices differ across regions due to differences in coal and gas production costs, technology level and trade opportunities. In the Middle East and the former Soviet Union (FSU), abundant natural gas resources lead to relatively low costs for natural gas-based routes even in the longer term. Regions with large coal resources and less natural gas, in particular East Asia, South Asia and Southern Africa, have the coal-based route as the cheapest hydrogen production technology already at the beginning of the century.

Inter-regional fuel trade is possible in the TIMER model if there is a large enough price differential (Van Vuuren et al., 2005). Yet, in none of our scenarios are significant amounts of hydrogen traded between regions. This result is also found by Baretto et al. (2003) and is due to the high costs of hydrogen transport over long distances – in our model simulations 80% higher than natural gas transport (Ogden, 1999b). Besides, a region needs a large-scale hydrogen infrastructure before it can start importing or exporting. However, hydrogen trade causes a significant increase in international coal trade compared to the baseline scenario, in particular towards OECD Europe, Southeast Asia and South America.

Hydrogen end-use

The price of hydrogen for end-users varies per region and sector, due to differences in production technologies, transport and distribution costs and different energy taxes. Figure 5.5 shows a breakdown of the hydrogen price in the transport sector of OECD Europe. In our results, transport is the first sector where hydrogen penetrates the market. The figure shows that production costs represent about 50% of all end-use costs (excluding taxes). The other half is formed by transport and distribution cost (again excluding taxes). The figure also shows that end-use taxes could represent a major share of end-use prices. Globally compared, energy taxes are highest in the transport sector of OECD Europe, which causes a significant difference between the intermediate (tax equal to oil) and optimistic (no tax) scenarios. In all other regions and sectors these differences are much smaller. We found that, although the energy tax has a significant impact on the hydrogen cost, it does not influence the penetration of hydrogen in the pessimistic scenario.

The direct alternative of hydrogen in the transport sector, oil, has an end-use price of about 15 US$ GJ^{-1} in the OECD European transport sector. However, because hydrogen is more efficiently applied in fuel cells, the useful energy price of hydrogen in the NoCP Int scenario is 30% higher than oil in 2020, about equal in 2050 and 30% lower in 2100. In the NoCP Opt scenario, useful energy costs of hydrogen in the transport sector of OECD Europe are 30% lower than oil in 2020 and 80% in 2100.

Thus, with our assumptions, hydrogen is in the NoCP Int scenario only competitive in the transport sector, although some hydrogen is also mixed into the natural gas grid and thus indirectly delivered to the residential and service sector (Figure 5.6, upper left). In the residential and service sector, hydrogen cannot compete in the combined heat-and-power (CHP)/fuel cell application with natural gas and electricity. In the NoCP Opt scenario, hydrogen technology improves so much that it penetrates not only the transport but also the residential and service sector markets (Figure 5.6, upper right). Large-scale use for transport takes off around 2015 and is completed at the end of the century. In the built environment hydrogen becomes globally a major final end-use carrier by the end of the century, providing

45% of the residential and 35% of the services sector – although electricity (24% and 57%, respectively) and natural gas (7% and 4% respectively) keep a significant market share as well. Even now, however, there is no large-scale penetration of hydrogen in the industry sector as it still cannot compete with coal, biomass and to some degree oil in this market.

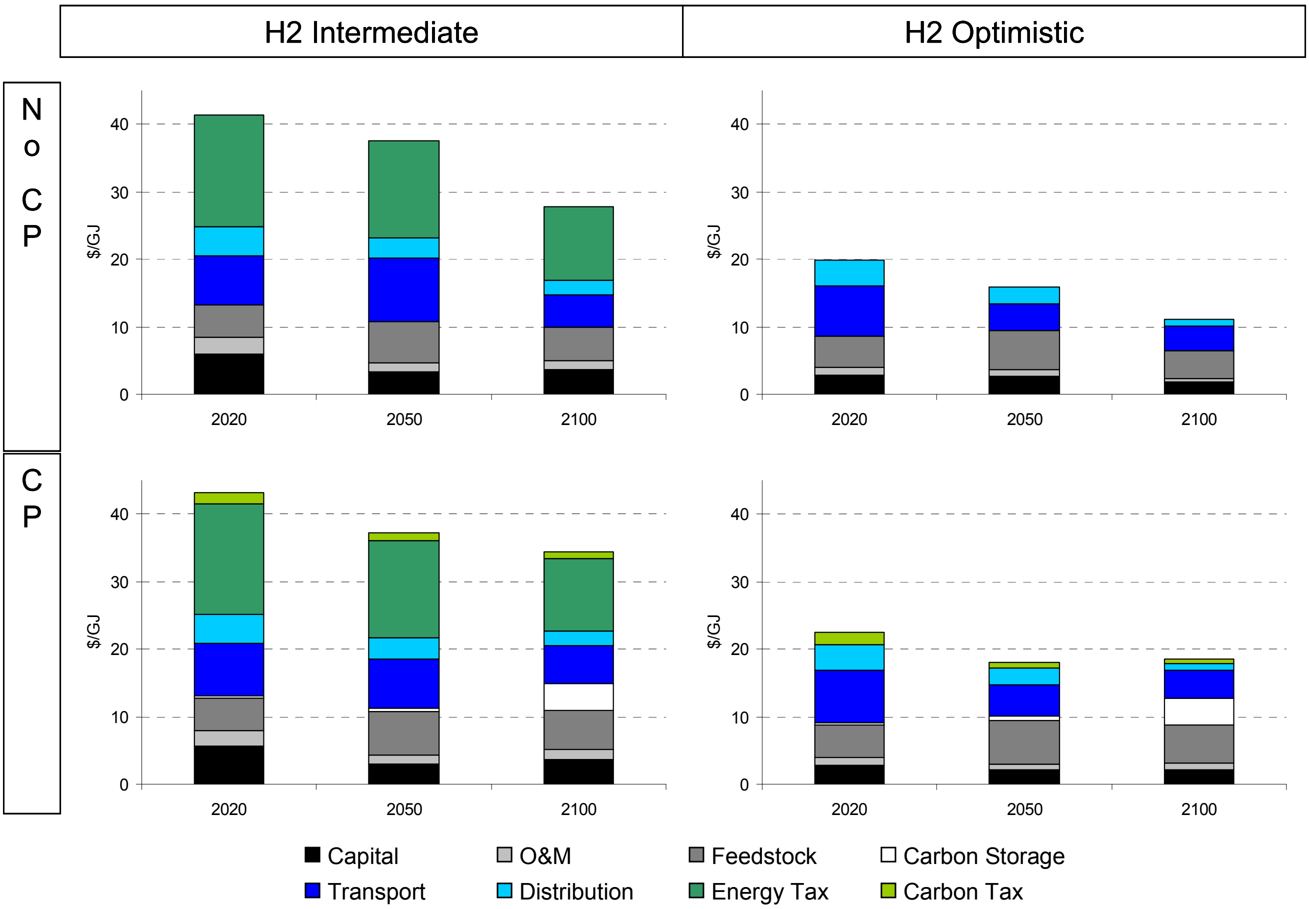


Figure 5-5 Breakdown of hydrogen cost for end-use in the transport sector of OECD Europe in the intermediate and optimistic hydrogen scenarios with (upper) and without (lower) climate policy (CP). With pessimistic assumptions on hydrogen technology and cost, no penetration occurs.

A closer look at the results indicates that OECD Europe, Eastern Europe and Japan are the first regions where hydrogen is introduced in all scenarios with hydrogen penetration. This early introduction of hydrogen can be explained from higher energy prices and taxes in these regions, which are not levied on hydrogen in the NoCP Opt scenario and are thus an implicit subsidy for hydrogen. At the end of the 21st century the worldwide penetration of hydrogen into final energy consumption is about 40% in the optimistic scenario, with 50–60% in Canada, OECD Europe and Japan and less than 35% in Africa and South Asia. Because hydrogen has in the intermediate scenario a higher price and thus is less competitive vis-à-vis other options which are introduced in response to rising oil and gas prices, penetration is significantly less: worldwide 20% in 2100, with 25–30% in Canada, the USA, OECD Europe and Oceania and less than 15% in Africa.

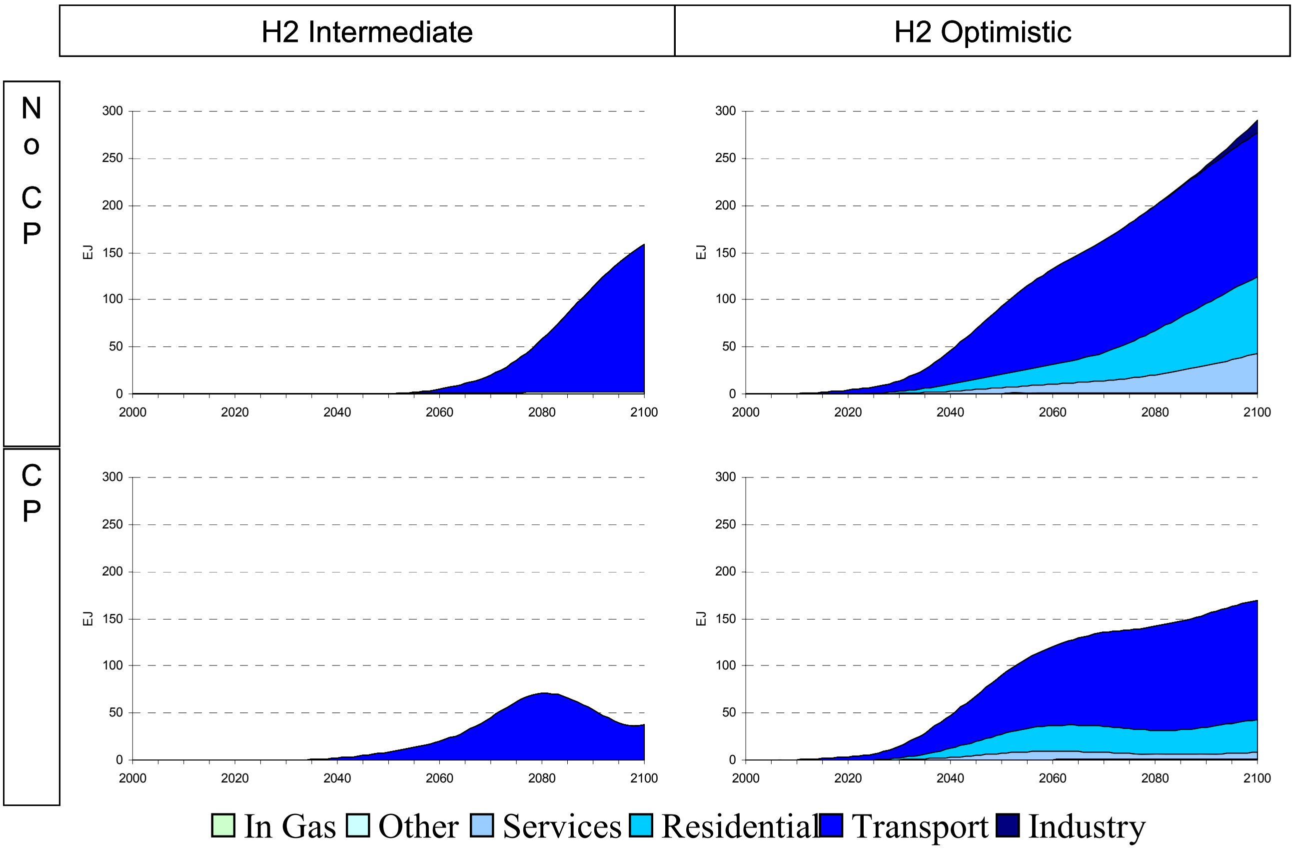


Figure 5-6 World hydrogen end-use for the five sectors in the intermediate and optimistic hydrogen scenarios with (upper) and without (lower) climate policy (CP). With pessimistic assumptions on hydrogen technology and cost, no penetration occurs.

Primary Energy Use

The simulation experiments suggest that the introduction of hydrogen can have important strategic and environmental consequences for the world energy system. It can reduce local emissions as it is a clean fuel, in particular urban pollution from transport. It may also shift energy trade patterns as it can substitute for oil while being produced from coal or natural gas. However, the resulting primary energy use may for this very reason worsen the problem of climate change. As Figure 5.7 shows, in the NoCP scenarios with hydrogen coal use is significantly higher than in the baseline scenario (upper middle and right compared with upper left graph). It also accelerates the use of natural gas, causing a more rapid depletion and subsequent decline in use of this relatively low-carbon fuel. Hydrogen thus brings a new golden era for coal: by 2100 coal satisfies 60% of world energy demand.

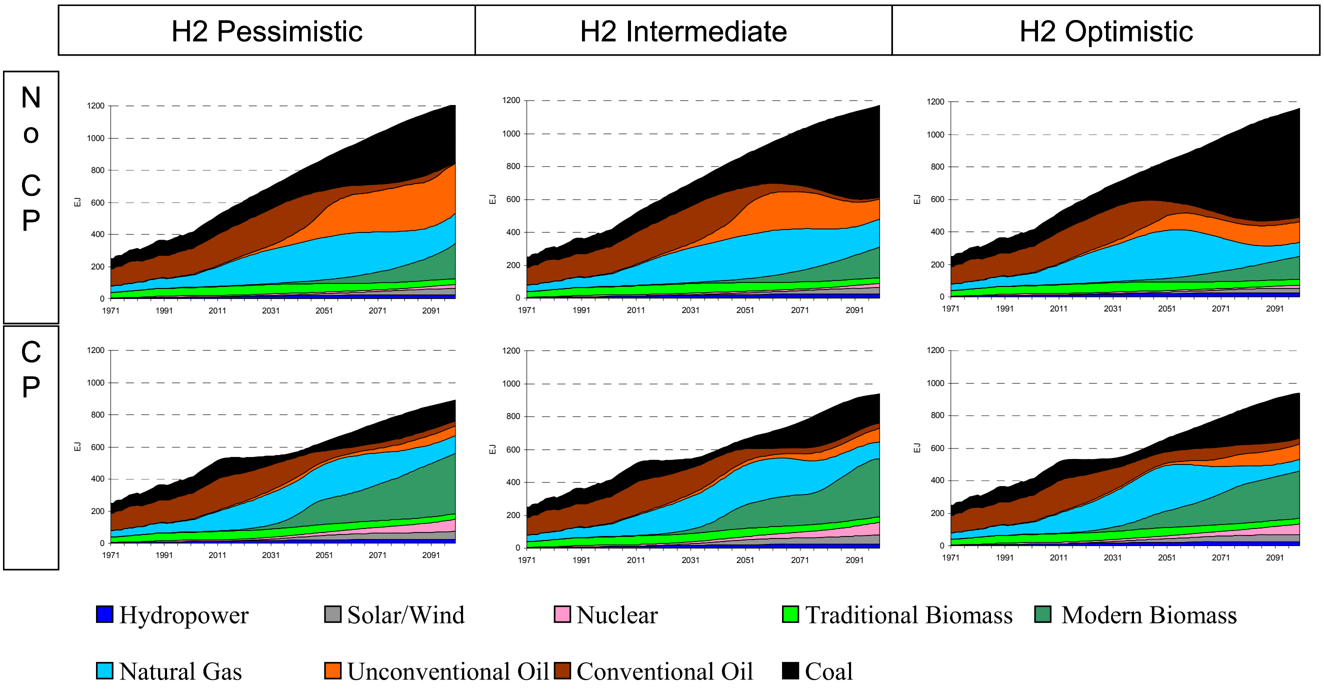


Figure 5-7 World primary energy use in all hydrogen scenarios with (upper) and without (lower) climate policy (CP). With pessimistic assumptions on hydrogen technology and cost, no penetration occurs.

What are the consequences of such a scenario? Firstly, it presumes that such vast amounts of coal – in the order of 28 billion tonnes per year, half of which for hydrogen – can be produced and processed. In the model, this production mainly occurs in the USA and East Asia. Obviously, coal mining and transport at this scale will cause huge mass flows with environmental consequences. Secondly, it has consequences for CO_2 emissions. In fact, until 2080 the differences in carbon emission between the pessimistic (no H_2), intermediate and optimistic case are small because both coal and natural gas use increase at the expense of oil (see Figure 5.8, coal with a higher carbon content and gas with a lower carbon content). However, in the scenario without hydrogen penetration emissions start to decline after 2080 as a result of the growth of non-carbon options such as nuclear, wind/solar, and biomass. Interestingly, a successful hydrogen penetration implies, without climate policy, that as a result of increased coal use, carbon emissions keep growing in the last part of the 21st century. Thus CO_2 emissions of the intermediate and optimistic scenarios are respectively 6% and 15% higher than the baseline scenario.

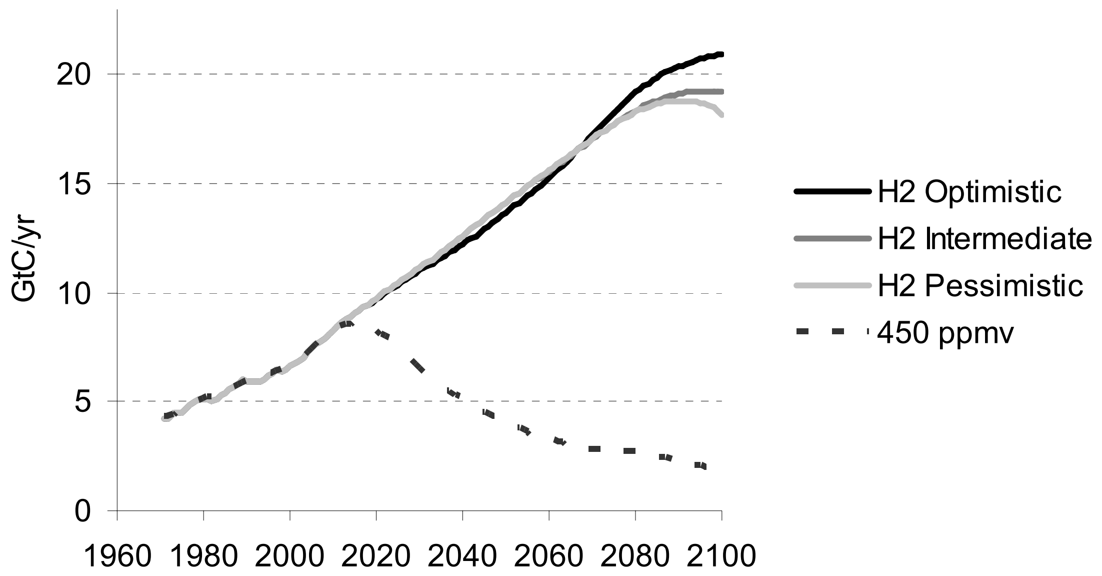


Figure 5-8 Global CO_2 emissions from all hydrogen scenarios without climate policy. With pessimistic assumptions on hydrogen technology and cost, no penetration occurs.

5.4.2 Scenarios with climate policy (CP)

To explore the relationship between hydrogen-based energy systems and climate policy in more detail, we have simulated three additional scenarios in which the CO_2-equivalent concentration is stabilised at 450 ppm by the end of the century. This is an ambitious goal and it requires the introduction of a rapidly increasing carbon tax. The carbon tax serves in the TIMER model simulations as a generic way to stimulate all kinds of measures to reduce carbon emissions – all elements of more detailed climate policy formulations, such as increasing energy efficiency, stimulating renewable and nuclear energy options and the introduction of carbon capture and sequestration (CCS) (Van Vuuren and De Vries, 2001).

One of the most striking results is that less hydrogen is used in the scenarios with climate policy. This can be explained by two dynamics: firstly, due to energy savings the total demand for energy is lower with climate policy (see e.g., Figure 5.7) and secondly, hydrogen now competes directly with biofuels. As the costs of hydrogen rise with climate policy, because of CCS technology and rest-emissions, the costs of biofuel stay the same. In the CP Int scenario, the share of biofuel in the transport sector decreases at the expense of hydrogen. In the CP Opt scenario hydrogen is pushed aside by biofuels in the built environment, as it stays the main energy carrier in the transport sector.

Figure 5.9 shows the carbon tax (or carbon price) profiles which are required to force the carbon emissions along a 450 CO_2-equivalent concentration profile. Our results show that hydrogen introduction can actually play an important role in climate policy (as suggested by the large differences between scenarios). The reason is that once the energy system (and in particular the transport sector) has hydrogen penetration, the additional costs to produce hydrogen from fossil fuels with CCS are limited compared to hydrogen production without CCS. Without hydrogen, reducing CO_2 emissions to very low levels is complicated by the high-cost reductions in the transport sector.

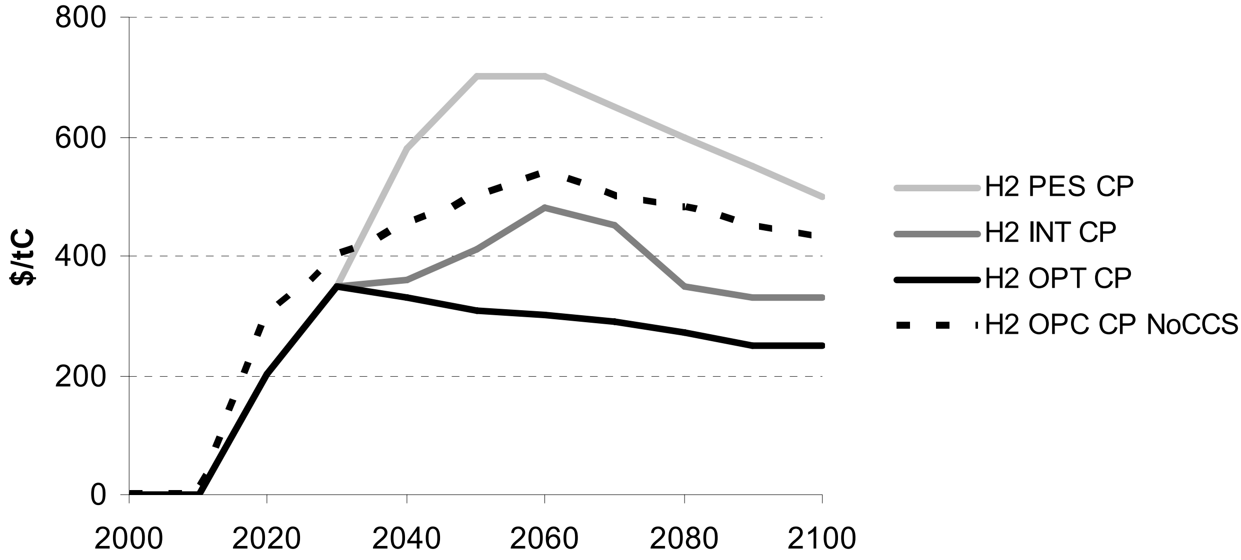


Figure 5-9 Global carbon price in the hydrogen scenarios with climate policy. With pessimistic assumptions on hydrogen technology and cost, no penetration occurs.

In the CP Int scenario, hydrogen is produced from fossil fuel CCS technologies. Hydrogen costs in end-use remain competitive and by the end of the century the world can use twice as much coal as at present despite the climate constraint (Figure 5.7 lower middle graph). This leads to the significantly lower carbon tax (Figure 5.9) which is also reflected in the low additional costs of climate policy in hydrogen end-use prices (Figure 5.5 lower graphs). The favourite hydrogen-based carbon emission reduction options are first gas-conversion and then coal-conversion with CCS (Figure 5.4, lower left graph). In the CP Opt scenario the hydrogen-coal-CCS chain is being introduced at an exceedingly large scale. Primary energy use is for some 30% based on coal (Figure 5.7, lower right graph) which is converted to hydrogen while capturing and storing in the order of 4.5 billion tonnes of carbon per year. Over 75% of the hydrogen use occurs in the transport sector (Figure 5.6, lower right graph). This can be induced by a rather modest carbon tax, as is seen from Figure 5.9. The way to use hydrogen while at the same time reducing carbon emissions is the large-scale conversion of natural gas into hydrogen with CCS, starting already around 2020, and gradually switching feedstock from gas to oil and from 2050 onwards to coal (Figure 5.4, lower right graph).

Evidently, this expansion of the hydrogen economy hinges on the availability of carbon capture and sequestration (CCS) options at the presumed declining cost levels used in this simulation. It also presumes that the associated risks are acceptable in those regions where it will occur at the largest scale: the USA, East Asia, OECD Europe and South Asia. As CCS plays such a dominant role in our results, while the technology itself still needs to be tested on a large scale, we have also simulated a scenario in which CCS is assumed not to be available. As one would expect, there is now rapid growth in the use of non-carbon options for electric power generation such as nuclear and wind/solar (Figure 5.10, right graph*)*. At the same time the use of hydrogen from biomass in the transport sector increases rapidly because the cost-effective option of hydrogen from fossil fuels with CCS is no longer available (Figure 5.10, left graph). Hydrogen production from fossil energy carriers becomes much less attractive. Only hydrogen from natural gas is competitive in some markets and now starts much earlier, around 2020, than in the other scenarios. Later, the SMR option also becomes interesting because its disadvantage with regard to CCS, namely that a costly CO_2 distribution network is required, does not matter anymore. As a result, world hydrogen demand is lower than in the other optimistic scenario variants and world coal use nearly vanishes.

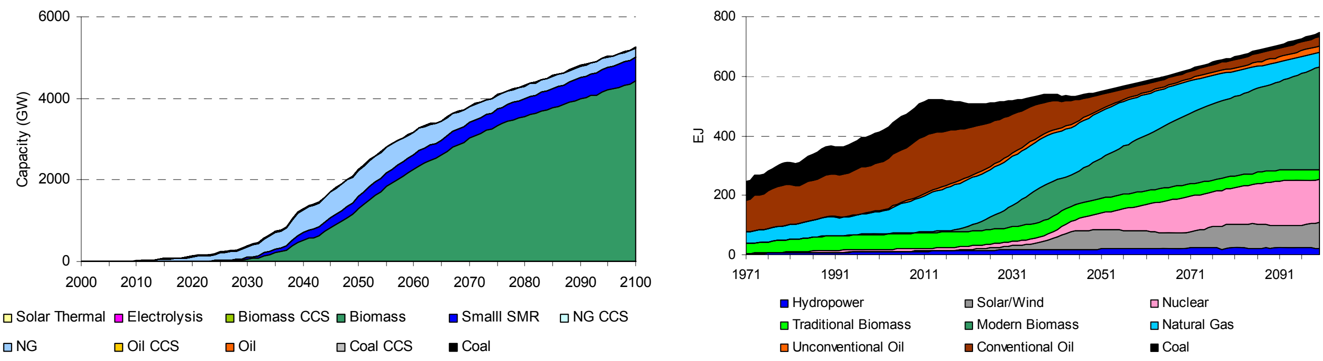


Figure 5-10 Overview of the optimistic hydrogen scenario with climate policy and without CCS: global hydrogen production capacity (left) and global primary energy use (right).

5.4.3 Impact of hydrogen on future energy systems

Carbon Intensity

The results in the previous section show that the environmental consequences of hydrogen use for carbon emissions are ambivalent. Without climate policy, carbon emissions are likely to increase with hydrogen use but at the same time it creates relatively cheap carbon mitigation options. Figure 5.11 compares the influence of hydrogen on carbon intensity of primary and secondary energy flows. Without climate policy, the primary carbon intensity increases with hydrogen use, as coal is substituted for oil and natural gas. Secondary energy carbon intensity decreases with hydrogen use as hydrogen, with zero carbon content, substitutes for oil. With climate policy, primary energy intensity is similar for all scenarios, because carbon emissions are constrained to a 450 ppm stabilisation scenario. Secondary energy carbon intensity still decreases with the use of hydrogen.

This finding is in contrast with Barreto et al. (2003), who developed a sustainable hydrogen scenario with a strongly decreasing primary carbon intensity, due to production of hydrogen from solar thermal and natural gas. However, it is in agreement with the scenarios described in Edmonds et al. (2004), who also found that coal is an attractive hydrogen feedstock without climate policy.

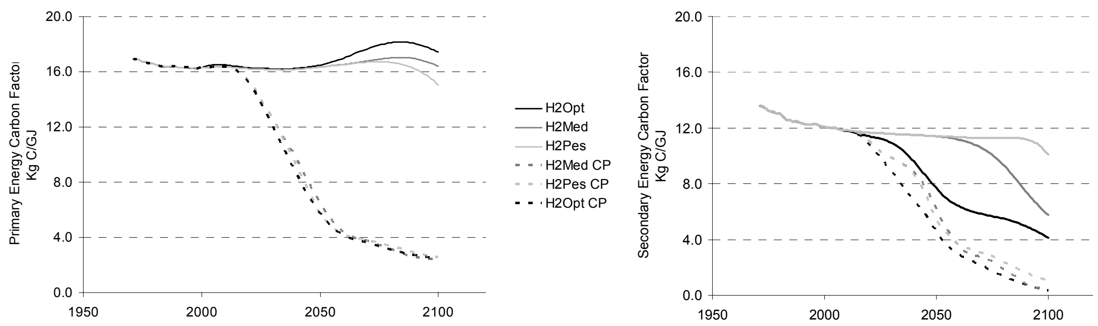


Figure 5-11 Global primary (left) and secondary (right) carbon intensity for all hydrogen scenarios with and without climate policy.

Configuration of the future hydrogen energy system

In section 5.2.2 we described three main configurations with respect to future hydrogen production that can be identified from the literature: large-scale production of hydrogen from fossil sources, mainly coal and natural gas; a fossil-based hydrogen system with CCS; and renewable hydrogen production, based on biomass gasification, direct solar-thermal hydrogen production and electrolysis from solar or wind electricity. Using the optimistic scenario, we were able to simulate three variants of these configurations. The variant without climate policy produces hydrogen from coal; the variant with climate policy produces hydrogen from coal with CCS or, if CCS is not available, from biomass and natural gas. We then analysed the total system costs, defined as the annuitised total capital costs in the energy system relative to the baseline scenario. The results are plotted against the penetration of non-carbon options in primary energy (Figure 5.12, left part) and hydrogen in secondary energy (Figure 5.12, right part*)*.

Without climate policy, the line coincident with the x-axis represents the baseline scenario, which has about 30% contribution from non-fossil sources (wind, solar, nuclear, modern biomass) by 2100 and no hydrogen penetration. With optimistic assumptions (NoCP OPT), hydrogen could penetrate the global secondary energy market by up to 40% by 2100, at 17% lower over-all energy system costs and almost halving the contribution of non-fossil sources. With a climate constraint, the baseline scenario (Baseline CP CCS) shows an increased contribution from non-fossil sources, to almost 60% by 2100 and an increase of costs compared to the baseline without climate policy. In this case, the introduction of hydrogen again decreases the share of non-fossil energy sources and lowers the over-all energy system costs with 8% by 2100. Evidently, if the carbon capture and sequestration (CCS) option is not available for whatever reason, the market penetration of non-fossil sources increases further and energy system costs increase significantly for the baseline scenario (Baseline CP NoCCS). However, combined with optimistic hydrogen assumptions (OPT CP NoCCS), the share of non-fossil energy sources is not influenced and costs decrease below the no-climate policy baseline scenario by 2100.

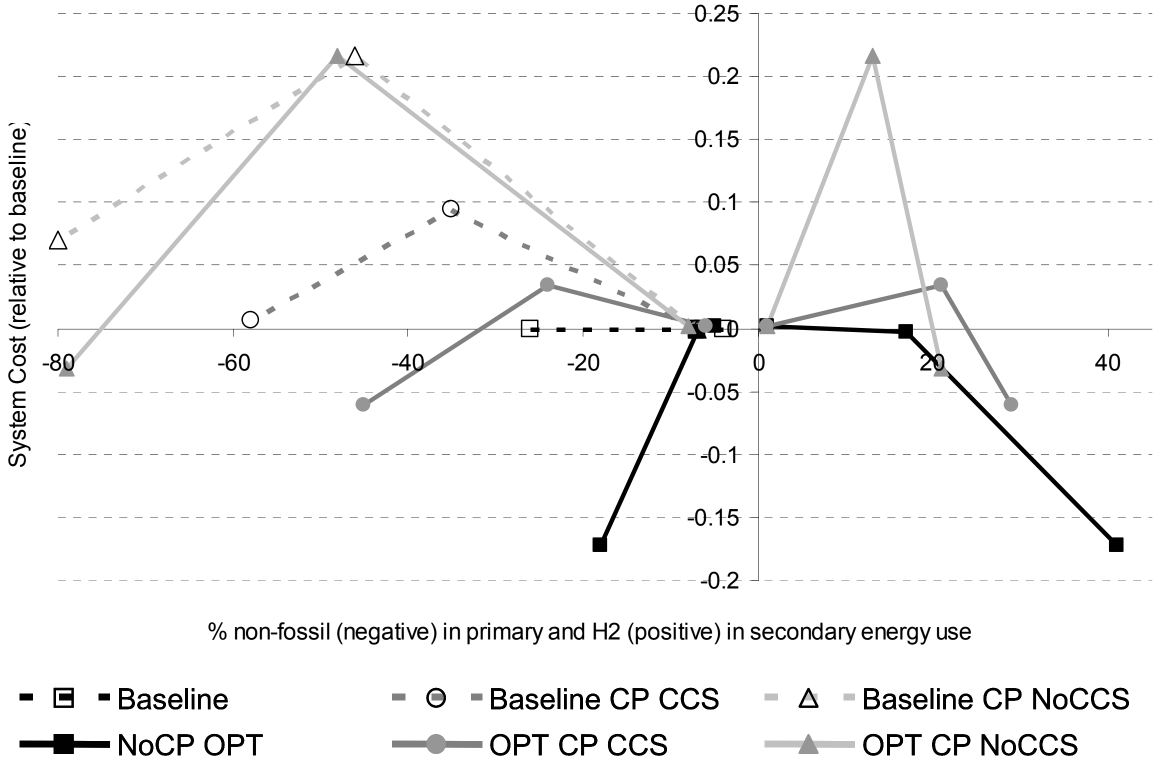


Figure 5-12 Comparison of different hydrogen energy system configurations (world) on costs, hydrogen penetration of secondary energy and contribution of non-fossil energy sources in primary energy, for 2020, 2050 and 2100.

5.5 Comparison with other studies

As has been emphasised throughout this paper, there are many uncertainties in any assessment of the prospects of hydrogen as an energy carrier. Some of these have been addressed by using a range (optimistic-intermediate-pessimistic); others are dealt with in the form of scenarios. A third way is to compare our results with studies done by others – although one cannot exclude collective bias. We chose the fraction of hydrogen in secondary energy markets over time and worldwide as the indicator for comparison (Figure 5.13). Included are only scenarios which expect any role at all for hydrogen, which in itself is a biased representation. Nevertheless, some lessons can be drawn.

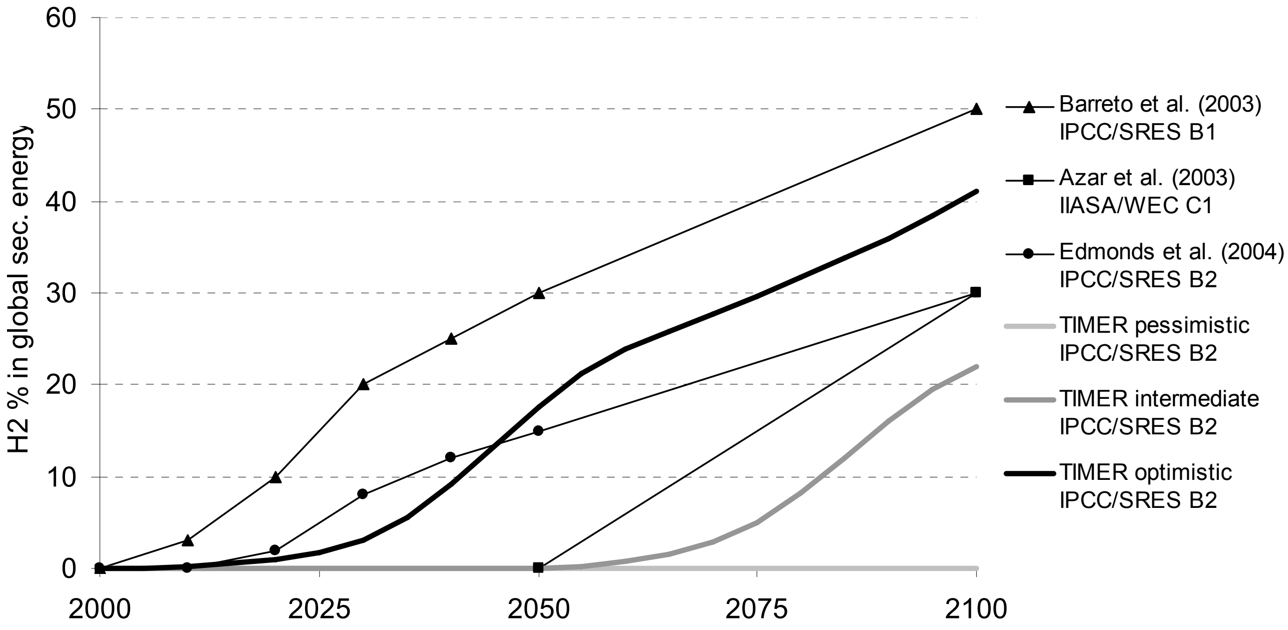


Figure 5-13 Comparison of hydrogen use in several long-term studies[35].

The fraction of secondary energy used in the form of hydrogen is in our optimistic scenario higher than in the scenarios by Edmonds et al. (2004) and Azar et al. (2003), but still lower than in the one by Barreto et al. (2003). If we relax the optimistic assumptions on hydrogen costs, our simulated pathway drops even below the scenarios of Edmonds et al. (2004) and Azar et al.(2003).

A more detailed comparison with the study by Edmonds et al. (2004) suggests several similarities. Although in TIMER the hydrogen energy system initially develops more slowly than in the MiniCAM model, both indicate coal gasification as the main hydrogen production technology – and both therefore calculate an increase in CO_2 emissions and point at the enhanced potential role of CCS as the main consequence of hydrogen in mitigation scenarios. The study by Barreto et al. (2003) is much more optimistic on the future role of hydrogen in the global energy system. This may be a consequence of the assumed high environmental awareness in the B1-H_2 scenario that they developed. Another difference is the application of micropower CHP systems from mobile fuel cells, an option not included in our simulations. A comparison with Azar et al. (2000) is more difficult, as their model simulates the transport sector only. Yet, their results for the transport sector are similar to those in our optimistic scenario and project a major shift from oil to hydrogen in the second half of the century.

[35] We assumed that the transport sector uses 30% of total secondary energy. Studies that assume hydrogen to ben fully applied in the transport sector are shown with a fraction of 30%.

5.6 Conclusion

In this analysis we present results of model-based explorations of the role of hydrogen in future energy systems under various assumptions about technology development and climate policy. Contrary to existing literature, we included a wide range of uncertainties in our scenarios, resulting in a broader overall context that explains existing studies from a different perspective. The results lead us to the following conclusions.

Hydrogen will probably not play an important role before mid-21st century in the world energy system, neither with nor without a climate policy. Thereafter it can become a major secondary energy carrier but only under optimistic assumptions. The transport sector is the key market; even under less optimistic assumptions hydrogen might play a role here. Air pollution from combustion of fossil fuels might be an additional motivation to use hydrogen in the transport sector. The best prospects are in OECD Europe and Japan, where energy prices are relatively high due to high taxes and low indigenous resources. The build-up of a large-scale hydrogen infrastructure, in particular for transport, plays a crucial role.

Coal and natural gas-based technologies seem to be economically most attractive for hydrogen production, with and without climate policy. In particular coal gasification and steam methane reforming are cost-competitive. Partial oxidation of oil, biomass gasification, electrolysis and solar thermal hydrogen production are more expensive and play consequently a minor role. Under carbon constraints, the fossil-fuel-based hydrogen production technologies are still the most attractive combined with carbon capture and sequestration (CCS); if CCS is not available, the preferred hydrogen path shifts towards biomass and natural gas.

Three typical configurations in future hydrogen production can be distinguished in different scenarios. We reproduced the three typical configurations also found in the literature and found them related to assumptions on climate policy and technology availability. Without climate policy, we found large-scale hydrogen production from fossil sources (like Edmonds et al.(2004); with climate policy, we found large-scale hydrogen production from fossil sources with CCS (like Edmonds et al. (2004)); in case of climate policy but with CCS not available, we found the development of a renewable energy-based hydrogen production system (like Barreto et al. (2003)).

Without climate policy, CO_2 emissions from energy systems with hydrogen are likely to be higher than those of systems without hydrogen. The reason for this result is that hydrogen is produced at the lowest cost from coal – hence, coal will be a substitute for oil in the primary energy supply and deliver hydrogen as a secondary energy carrier, particularly for the transport sector.

Energy systems with hydrogen respond more flexibly and at lower marginal abatement cost to climate policy. The reason for this is related to the previous conclusion: the use of hydrogen provides new and presumably cheap carbon emission reduction options in the form of centralised CCS.

6 Multi-gas emission envelopes to meet greenhouse gas concentration targets: costs versus certainty of limiting temperature increase

M.G.J. den Elzen, M. Meinshausen, D.P. van Vuuren

6.1 Introduction

The aim of this study is to develop multi-gas emission envelopes (consistent sets of emission pathways) for the six greenhouse gases (GHGs) covered under the Kyoto Protocol (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6) that are compatible with stabilising GHG concentrations. The ultimate aim is to avoid dangerous climate change. To determine allowable levels of GHG emissions, we will have to back-calculate from acceptable levels of climate change to emissions. This is not simple. Apart from the question of what an acceptable level of climate change constitutes – a political issue – there are major scientific uncertainties in the cause-effect chain. Many of these uncertainties also influence the shape of the emission envelope that results in a certain GHG concentration target, such as the baseline emissions and the potential to mitigate the different GHGs.

Several authors have earlier published emission pathways or envelopes leading to different concentration targets, i.e. (a) Eickhout et al. (2003); (b) Enting et al. (1994); (c) O'Neil and Oppenheimer (2004); (d) Wigley (2003b); (e) Wigley et al. (1996); and (f) Van Vuuren et al. (2005). Unfortunately, these studies suffer from one or more of the following four limitations. First of all, most studies focus mainly on CO_2 only (b, c, d and e). As non-CO_2 emissions contribute to the human-induced climate changes, the reduction of these non-CO_2 emissions will of course have advantages in terms of either avoiding climate impacts for a given CO_2 emission path (Hansen et al., 2000; Meinshausen et al., 2006) or reducing mitigation costs for avoiding certain levels of climate change (e.g., Manne and Richels, 2001; van Vuuren et al., 2003; 2006a). Secondly, some of these studies have developed only pathways leading to GHG concentration targets of 550 ppm CO_2-eq. and higher (a, c and f).[36] Studies that use recently published probability density functions for climate sensitivity show that for achieving low temperature increase targets, such as the 2^{o}C target which has been adopted as the long-term target of EU policy, these concentration levels have only a low degree of certainty of limiting global mean temperature increase to 2°C above pre-industrial levels, which is the current long-term target of EU policy (Hare and Meinshausen, 2004; Meinshausen, 2006). Thirdly, most of these studies present emission pathways rather than

[36] 'CO_2 equivalents' expresses the increased radiative forcing of other GHGs in terms of the equivalent CO_2 concentration that would result in the same level of forcing. In this paper, the definition of CO_2-eq. concentrations includes the Kyoto gases, tropospheric ozone and sulphur aerosols.

emission envelopes, thus they do not account for important uncertainties such as baseline emissions and timing of climate policies (a, b). And finally, this study attempts to take into account the actual mitigation potential, and the possible rates of emission reductions – rather than setting a constraint to following a smooth concentration profile (a, b, c, d and e). Alternative approaches have attempted to define possible pathways on the basis of a larger set of criteria, such as long-term temperature targets and maximum reduction rates, mapping out corridors of emissions consistent with these criteria, like in the Tolerable Windows Approach (Toth et al., 1997; Bruckner et al., 2003 or the Safe Landing Approach (Kreileman and Berk, 1997; Swart et al. 1998). These methodologies suffer less from the limitations discussed above but were still only focussing on CO_2, and had problems dealing with high levels of uncertainty.

The emission envelopes developed in this paper are designed to overcome these four categories of limitations, while still using a relatively simple, well-defined methodology. This methodology uses the FAIR-SiMCaP model that is able to relate long-term concentration targets to different multi-gas emission pathways (section 6.2). This model is fed with information from several specialised models on baseline emissions, mitigation potential and costs (time- and baseline-dependent marginal abatement costs curves). This allows us to develop pathways that can be technically achievable. It should be noted that developing multi-gas emission pathways is less straightforward than developing emission pathways for CO_2 only, as the reduction needs to be somehow distributed among the different gases, which all have specific radiative properties, lifetimes and mitigation costs and potential.[37] In the literature, two major approaches for determining 'economically optimal' shares are used: a) 100-year Global Warming Potentials (GWPs) as exchange rates between the gases to find 'optimal' split-ups of aggregated (CO_2-eq.) GHG emission paths and b) substitution instead of GWPs determined on the basis of cost-effectiveness in realising a long-term target within the model (e.g., Manne and Richels, 2001). Given the fact that this approach (a) reflects the current political framework (e.g., the Kyoto Protocol) and that policies develop incrementally rather than based on perfect foresight, we used the GWP approach for the development of the multi-gas pathways.

An important issue related to the different emission pathways forming the emission envelopes is the timing of abatement effort. This issue of the timing was initiated, in particular, by Hammitt et al. (1992) and Wigley et al. (1996). Wigley et al. argued that postponing abatement actions could be more cost-effective than early action strategies because of the benefits of technology development, more CO_2 absorption by the biosphere and ocean, and by discounting future costs. Other authors, however, responded that this conclusion would depend on the many (controversial) assumptions about the impact of declining costs for new technologies, discount factors applied to future climate change mitigation (and adaptation) costs (Azar and Dowlatabadi, 1999), and the role of inertia in the economic and energy system (limited capital turn-over) and uncertainty (Ha-Duong et al., 1997). Assuming

[37] Meinshausen et al. (2005) provides an overview of different methods that can be used for this purpose.

induced technology changes due to policy implementation and learning-by-doing (instead of changes being simply a function of time), explicit capital turnover rates could lead to a preference for early action, or at least a distribution of the reduction effort over the century as a whole. The debate about optimal timing is still ongoing. Yohe et al. (2004) recently showed that applying hedging strategies (i.e., cost-optimal reduction pathways incorporating the risk of more, or less, stringent action later in the century if new knowledge appears) to deal with uncertainties may lead to relatively early reduction pathways leaving as many options open as possible. Here, we address the issue of timing by developing a different set of emission pathways[38] (from early action to delayed response).

As such, the analysis presented here focuses on three questions for climate policy making:

- What are multi-gas emission envelopes that are technically feasible, and compatible with stabilising GHG concentrations at 450, 550 and 650 ppm CO_2-eq, and their resulting emission reductions?
- What are the effects of timing of abatement action on the emission pathways, and the resulting abatement costs?
- And finally, what is the likelihood that these emission envelopes will meet a range of temperature-change targets, including the EU 2°C target?

The analysis builds on earlier work of Den Elzen and Meinshausen (2005; 2006), which presented multi-gas emission pathways meeting the GHG concentration stabilisation targets of 400, 450, 500 and 550 ppm CO_2-eq. The analysis updates the earlier one with: (i) updated baseline scenarios; (ii) improved reduction potentials and abatement costs of GHG sources; (iii) more detailed analyses of emission envelopes (multiple sets of emission pathways) and (iv) feasible pathways for the 450 ppm concentration target.[39] Van Vuuren et al. (2005a) (at the global level) and Den Elzen et al. (2005) (at the regional level) elaborated the pathways developed here in terms of the technical and economic implications.

In section 6.2 we describe the overall modelling framework, and in section 6.3 the emission envelopes and their global emission reductions and abatement cost implications. Section 6.4 analyses probabilistic temperature implications, using the impact of the key uncertainty in the long-term climate projections, that is, climate sensitivity. Conclusions are drawn up in section 6.5.

[38] It is possible to draw a formal distinction between *scenarios* and emission *pathways*. While the emission pathway focus solely on emissions, a *scenario* represents a more complete description of possible future states of the world, including their socio-economic characteristics and energy and transport infrastructures. The emission envelopes described in this paper focus on the emission trajectory, and are therefore called pathways; however, as they are constructed on the basis of reduction potential of expert models, the difference between scenarios and pathways is less obvious than for emission pathways constructed in other studies.

[39] In our earlier study we had to assume additional, exogenous developments of the marginal abatement cost curves in order to meet the lower concentration levels.

6.2 Overall methodology

6.2.1 The FAIR-SiMCaP model

In order to assess the emission implications of different stabilisation levels, this study presents new multi-gas emission pathways (emissions of all six Kyoto GHGs, sulphur aerosols (SO_2) and ozone precursors) for the scenario period of 2000-2400, based on the reduction potential as estimated by specialised models (thus attempting to ensure technical feasibility). The timing of emission reduction within these pathways is determined iteratively to match a combination of criteria based on the prescribed climate targets, technically feasible rates of reduction and cost considerations (see section 6.3.1). At any moment in time, the emission reductions are distributed among the different reduction options by cost-optimisation. It should be kept in mind though that this approach does not calculate cost-effective pathways over the whole scenario period per se, but focuses on a cost-effective split among different GHG reductions for given emission limitations on global GWP-aggregated emissions.

For our method we used the FAIR-SiMCaP 1.1 model (Den Elzen and Meinshausen, 2005; 2006)[40], which is a combination of the abatement costs model, FAIR 2.1 model (Framework to Assess International Regimes for the differentiation of commitments (Den Elzen and Lucas, 2005; den Elzen et al., 2005) and the SiMCaP module (‘Simple Model for Climate Policy Assessment’), pathfinder 1.0 model (Meinshausen et al., 2006). The SiMCaP pathfinder module makes use of an iterative procedure to find multi-gas emission paths that correspond to a predefined climate target. Global climate calculations make use of the simple climate model, MAGICC 4.1 (Wigley, 2003a; Wigley and Raper, 2001; 2002). In turn, the FAIR cost model distributes the difference between the global baseline and mitigation pathway following a least-cost approach using regional marginal abatement costs curves (MAC)[41] for the different emission sources (Den Elzen et al., 2005). Furthermore, the costs model calculates the regional emission reductions (after emissions trading), international permit price and the global abatement costs. In this way, the FAIR-SiMCaP model combines the strengths of both models to: (i) calculate the cost-optimal mixes of GHG reductions for a global GWP-aggregated mitigation pathway (FAIR) and to (ii) find the global emissions pathway that is compatible with any arbitrary climate target (SiMCaP). The calculations consist of four steps:

1. Using the SiMCaP model to construct a parameterised global CO_2-eq. emission pathway, defined by sections of linear decreasing or increasing emission reduction rates (see for further details Den Elzen and Meinshausen, 2005). The pathway includes the anthropogenic emissions of six Kyoto GHGs. One exception is formed

[40] FAIR-SiMCaP 1.1 is an updated version of FAIR-SiMCaP 1.0, differences being the marginal abatement costs curves and baseline emissions.

[41] MAC curves are used here that reflect the costs of abating the last tonne of CO_2-eq. emissions and, in this way, describe the potential and costs of the different abatement options considered.

by the LULUCF (land use, land-use change and forestry) CO_2 emissions. While we consider the use of carbon plantations as a mitigation option, we currently lack information on the potential to reduce emissions from deforestation. For that reason LULUCF CO_2 emissions cannot be abated in the model (but are in fact already reduced in the baseline). Up to 2012, the pathway incorporates the implementation of the Annex I Kyoto Protocol targets for the Annex I regions excluding Australia and the USA. The USA follows the proposed greenhouse-gas intensity target (White-House, 2002), which is close to a number of businesses-as-usual projections.

2. The FAIR abatement cost model distributes the global emission reduction from baseline over the different regions[42], gases and sources following a least-cost approach for five-year intervals over 2000–2100[43], simulating a situation where states take full advantage of the flexible Kyoto Protocol Mechanisms (emissions trading) (see Den Elzen et al., 2005). For this purpose, FAIR makes use of (time-dependent) MAC curves (see Appendix D), and baseline scenarios, that is, potential GHG emissions in the absence of climate policies, from the integrated climate assessment model IMAGE[44] and the energy model, TIMER 2.0.[45] In the calculations we assume full participation of all regions after 2012, including the USA.[46] Note that the costs are only for abatement; climate damage is avoided and ancillary benefits are not included in such cost estimates. These abatement costs constitute one measure of the costs of climate policy, capturing direct costs based on MAC curves but not taking into account the costs related to a change in fuel trade or macro-economic impacts (including sectoral changes or trade impacts). The cost figures are obviously strongly dependent on our assumptions about abatement potentials and reduction costs for all GHGs, as analysed by Van Vuuren et al. (2005a) (see section 6.2.3).

3. The GHG concentrations and global mean temperatures are calculated using the simple climate model MAGICC 4.1. In this study, we applied default settings as used

---

[42] Calculations were done for 17 regions, i.e. Canada, the USA, Central America, South America, Northern Africa, Western Africa, Eastern Africa, Southern Africa, OECD Europe, Eastern Europe, the former Soviet Union, Middle East and Turkey, South Asia (incl. India), East Asia (incl. China) and Southeast Asia, Oceania (incl. Australia) and Japan (IMAGE-team, 2001).

[43] After 2100, there are no MAC curves, and here the CO_2-eq. emission reductions rates are assumed to apply to each individual gas, except where non-reducible fractions 0.9 and 0.3 have been defined for N_2O and CH_4, respectively.

[44] The IMAGE 2.2 model is an integrated assessment model consisting of a set of linked and integrated models that together describe important elements of the long-term dynamics of global environmental change, such as agriculture and energy use, atmospheric emissions of GHGs and air pollutants, climate change, land-use change and environmental impacts (IMAGE-team, 2001). IMAGE 2.3 is an updated version of IMAGE 2.2, differences being the possibility to explore impacts of biofuels and carbon plantations.

[45] The global energy model TIMER, as part of IMAGE, describes the primary and secondary demand and production of energy and the related emissions of GHGs on a regional scale (17 world regions). TIMER 2.0 is an updated version of TIMER 1.0 (De Vries et al., 2002). The main differences are additions with respect to hydrogen, biofuels and modelling of the electric power sector (Van Vuuren et al., 2005a).

[46] Whether the USA will take any stronger action after the first commitment period (2008–2012) is of course highly uncertain. There are, however, a number of reasons to assume that the USA could join a post-2012 regime aiming at emission reductions. Several states and cities are already implementing climate policies. Moreover, several proposals have been discussed in the US Congress that involve climate policies, and they may still reflect increasing support for climate policy. Drivers for such increasing support may include an awareness of climate change impacts (e.g., the discussion on whether Hurricane Katrina was caused by climate change) but also energy security policies.

for the IPCC Third Assessment Report (TAR), for example, with regard to aerosol-forcing assumptions and temperature-related feedbacks on the carbon cycle. One exception is the estimation of probabilistic transient temperature implications, where the climate sensitivity varies according to published probability density functions (PDFs). This estimation takes into account the dependency between climate sensitivity, ocean diffusivity and aerosol forcing in order to match the historical temperature evolution (with a method according to Meinshausen, 2006).

4. The parameterisations of the CO_2-eq. emission pathway (step 1) are optimised within the iterative procedure of the SiMCaP model (repeat step 1, 2 and 3) until the climate output and the prescribed target show sufficient matches.

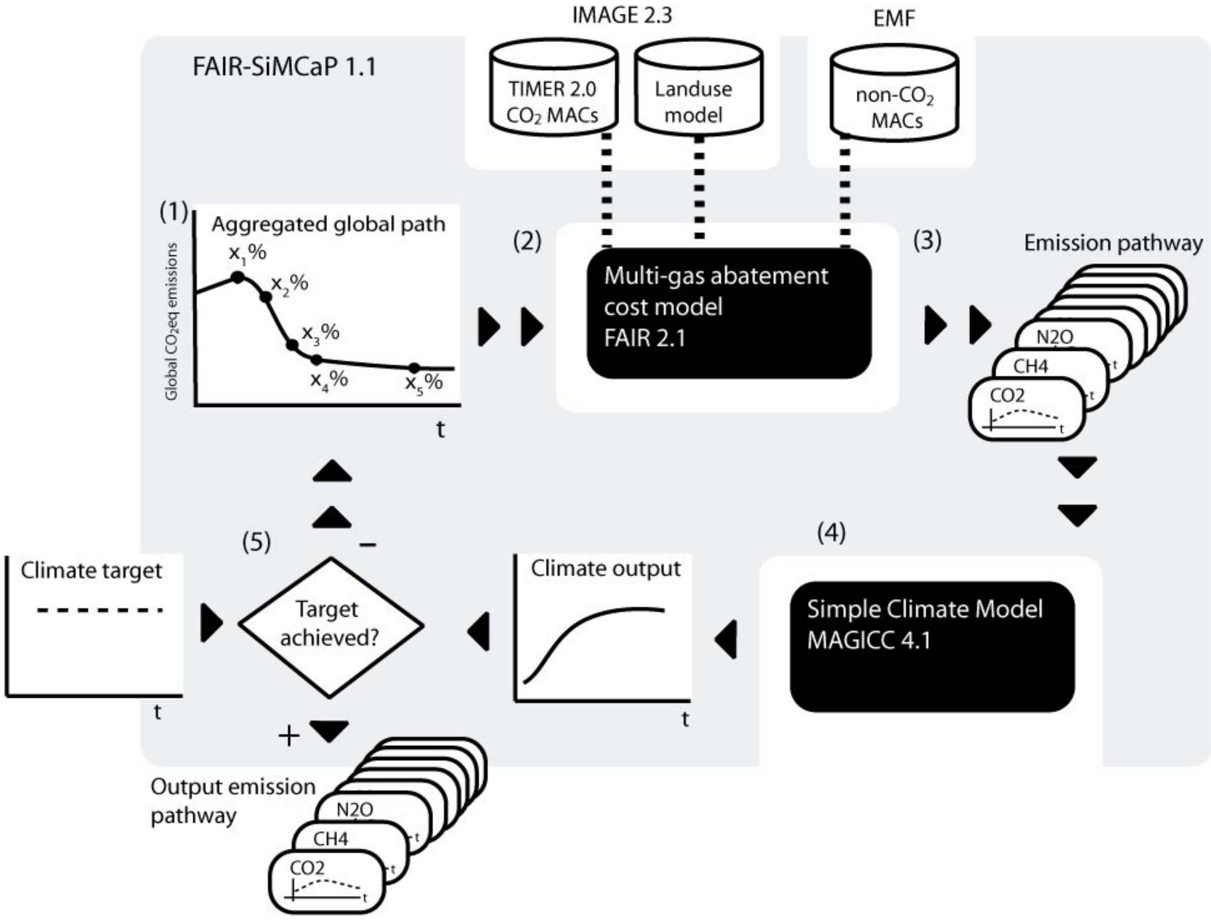


Figure 6-1 The FAIR-SiMCaP 1.1 model. The calculated global emission pathways were developed by using an iterative procedure as implemented in the SiMCaP pathfinder module. MAGICC was applied to calculate the global climate indicators, the multi-gas abatement costs and the FAIR 2.1 model to allocate the emissions of the individual greenhouse gases and the IMAGE 2.3 and TIMER 2.0 model for the baseline emissions scenarios along with the MAC curves. Note: the numbers refer to the four steps as explained in the text. Source: adapted figure from Den Elzen and Meinshausen (2005).

6.2.2 Baseline scenarios

The baseline scenarios used in this study are based on the set of SRES scenarios (Nakicenovic et al., 2000). This set explores different possible pathways for GHG emissions on the basis of two major uncertainties: 1) the degree of globalisation versus regionalisation and 2) the degree of orientation on economic objectives versus an orientation on social and environmental objectives. Recently, the storylines of the SRES scenarios have been re-implemented into the IMAGE 2.3 model. Here we use the IMAGE/TIMER SRES B2 scenario (Van Vuuren et al., 2005a) (hereafter known simply as the B2 scenario) as the central baseline scenario, while the IMAGE/TIMER SRES A1b and IMAGE/TIMER SRES B1 scenarios are used to show the impacts of different baseline assumptions. The B2 scenario represents a medium emissions scenario. The A1b scenario, in contrast, represents a world with fast economic growth, and correspondingly higher emissions early in the scenario. The B1 scenario describes a world characterised by strong globalisation in combination with environmental protection and correspondingly lower emissions. For the central B2 baseline scenario, energy sector CO_2 emissions continue to rise for most of the century due to increasing coal and gas use, peaking at 18 GtC in 2080 (making the scenario a medium-high baseline compared to existing literature) (Van Vuuren et al., 2005a). Total Kyoto GHG emissions also increase, from 10 GtC-eq. at present to 23 GtC-eq. in 2100 (Figure 6.2). As a result, the baseline reaches a CO_2 concentration of about 730 ppm CO_2 and a GHG concentration of 850 ppm CO_2-eq. by 2100. Figure 6.2 also shows the results for the A1b and B1 baseline.

6.2.3 Abatement costs

Costs are calculated here on the basis of marginal abatement curves which indicate the costs of reducing an additional emission unit. These costs constitute one measure of the costs of climate policy, capturing direct costs but not taking into account the costs related to a change in fuel trade or macro-economic impacts (including sectoral changes or trade impacts). In the literature, different costs metrics are used to describe the costs of climate policy: next to abatement costs (used by both partial and full equilibrium models) also GDP or consumption losses are reported (full equilibrium models). Abatement costs depend less on uncertainties in the macro-economic system while still representing a reasonable proxy of overall costs. On the other hand, macro-economic measures (GDP or consumption losses) represent a more comprehensive costs metric but results are also more uncertain (as a result, for instance, of distribution effects and impacts on investments), see IPCC Third Assessment Report (TAR) (Hourcade and Shukla, 2001; Morita and Robinson, 2001), or Repetto and Austin (1997) for the macro-economic impacts of recycling revenues. Differences between macro-economic costs measures and abatement costs may become in particular important if not all parties participate in climate policy (see for instance, Lasky, 2003). An overview of GDP impacts at a global scale in different models is available from Edenhofer et al. (2006) and the IPCC TAR (2001). The latter study also used abatement costs metrics.

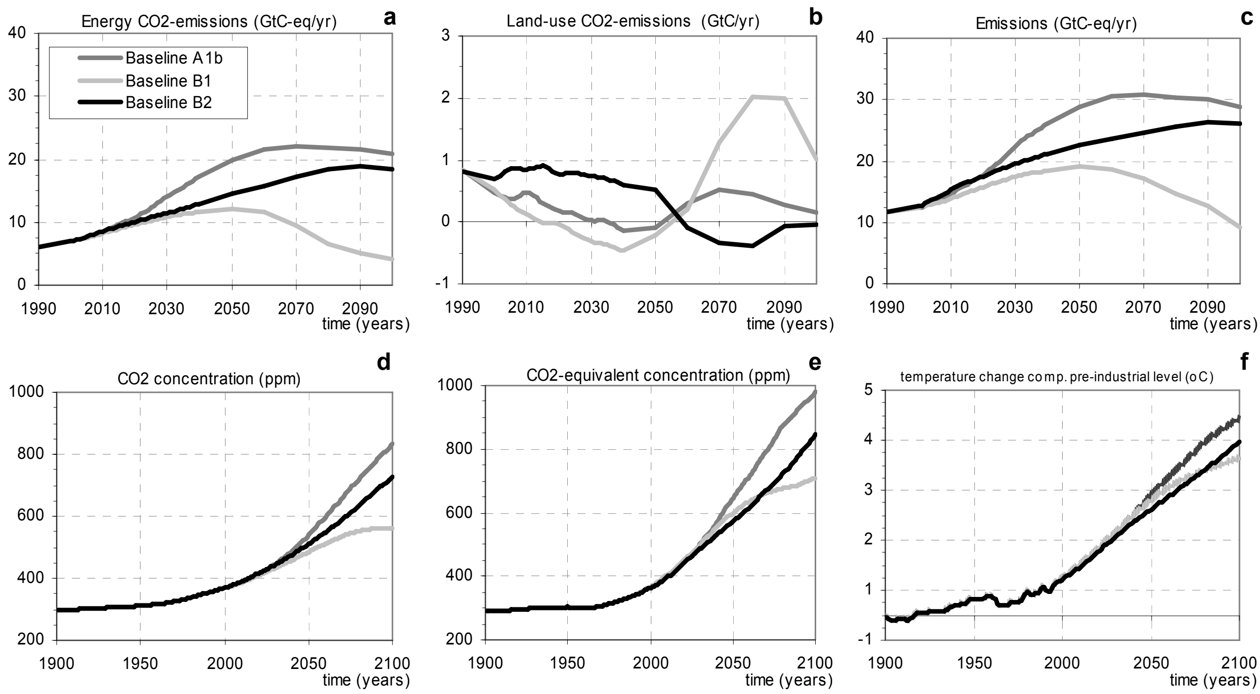


Figure 6-2 Comparison of the emission, concentration and temperature increases for the A1b, B1 and B2 baseline scenario. The upper panel shows the annual global energy-related CO_2 emissions (a), land-use CO_2 emissions (b) and total CO_2-eq. emissions (c).The lower panel shows the CO_2 (d) and CO_2-eq. (e) concentration, and the temperature increase compared to pre-industrial level (f) (assuming a climate sensitivity of 3°C).

The MAC curves as used for this study are described in detail in Appendix A. In brief, costs estimates for non-CO_2 gasses are based on the EMF-21 study (Weyant et al., 2005). Their curves have been made consistent with the baselines used here and adopted to account for technology change (the original curves were developed for 2010). The curves for carbon plantations were developed from the IMAGE model (see Strengers et al., 2006). Finally, for CO_2 emissions from the energy system MAC curves were derived from the TIMER model. Here, it has to be noted that costs strongly depend on the pathway based on 1) technology change and 2) limited rates of change. In FAIR this captured by not using not only one set of TIMER curves but several that differ in timing of climate policy. In the calculations, these are scaled on the basis of the actual reduction path. By using one common baseline and three coupled models (TIMER, FAIR and IMAGE), a consistent set of information on baseline emissions and costs are generated. Van Vuuren et al. (2006a) show that this leads to a outcomes that are consistent across the three models; moreover, they also compare the outcomes with other studies showing that the costs estimates compare well to those of other studies, i.e. Azar et al. (2006), Rao and Riahi (2006), our earlier work of FAIR and IMAGE/TIMER (Van Vuuren et al., 2005) and EMF-16/IPCC-TAR (Hourcade and Shukla, 2001). Obviously, costs estimates do strongly depend on the assumptions about abatement potentials and reduction costs. Van Vuuren et al. (2005) therefore also discuss the implication of uncertainties for overall costs – showing that the uncertainty range may well be 50% or more.

In addition to annual abatement costs (as % of GDP), in this study we also use the net present value (NPV) of abatement costs over the 2000-2100 period. This represents the cumulated costs over that period – but discounted over time.

6.3 Multi-gas emission pathways and envelopes and their resulting abatement costs

6.3.1 Methodology

A set of criteria has been defined for the development of the emission pathways:

1. *CO_2-eq. concentration stabilisation target* – The emission pathways need to meet long-term CO_2-eq. concentration (radiative forcing) stabilisation targets of 450 ppm (2.58 W m^{-2}), 550 ppm (3.65W m^{-2}) and 650 ppm CO_2-eq. (4.5W/m^2) at around 2200, 2100 and 2150, respectively. For the stabilisation level at 450 ppm, we allow an initial peaking (or overshooting) up to 510 ppm (about 3.2 W m^{-2}).[47]
2. *Criteria for the level of emission reduction* – For each moment in time, the required level of emission reductions (by GHG) needs to be met by a corresponding level of emission reduction potential (derived from the expert models).
3. *Criteria for the rate of emission reduction* – The emission pathways take into account the constraints on the rate of the emission reductions reflecting technical and political inertia that prevent the global GHG emission levels from changing dramatically from year to year or from decade to decade. Fast reduction rates would require the early retirement of existing fossil-fuel-based capital stock, which involves high costs. In a certain way the current energy production system is 'locked' into fossil fuels, and changing this infrastructure takes time (e.g., Gritsevskyi and Nakicenovic, 2000). But changing society and making political decisions is also a time-consuming process. Criteria on the rate of reduction are not included in the MAC curves. Therefore, following Kreileman and Berk (1997) and Swart et al. (1998) in their analysis of the 'safe landing' approach of emission corridors, we account for this inertia by simply assuming the following two constraints on the emission pathways (excluding LULUCF CO_2 emissions)[48]:
    - the global emission reduction rates should not exceed an annual reduction rate of x% yr^{-1} (default) for all default pathways;

[47] As the resulting SO_2 emissions are lower in this study compared to earlier emissions, the peak in concentrations is (temporarily) about 10 ppm higher around the peaking date, here we assume a 10 ppm higher peaking. For the emission envelopes we allow a variation of –2% to +1% in the final concentration stabilisation target. For 450 ppm the peaking may not exceed 515 ppm.

[48] Höhne (2005) used the same two constraints in his analysis of CO_2-only emission envelopes. In our earlier analysis, we only used the first constraint.

- the annual trend change (change from one year to the next) cannot change by more than *y* percentage points per year (default values). For example, if emissions have risen 2% from year *t* to year *t* + 1, emissions can only rise by 2 – *y* to 2 + *y* from year *t* + 1 to year *t* + 2.

We analysed 40 SRES non-climate policy and 18 available post-SRES mitigation scenarios (Swart et al., 2002) to identify the maximum rate of reduction in these scenarios – and to explore whether these rates are dependent on the stabilisation target. The results are shown in Figure 6.3, which indicates that with only a few exceptions are maximum rates of reduction in emission scenarios usually less than 3%, and that the maximum rate is indeed somewhat dependent on the stabilisation target. Based on this, we chose the values ranging from 2–3%, depending on the final concentration stabilisation target. In addition, the change in reduction rate (i.e., the second derivative of emissions) of all runs is constrained to below 0.25 percentage points per year.[49] This is consistent with the assumption that too rapid changes over time are costly. Although most scenarios are only reported on a decadal basis, their relatively smooth trajectories more or less support the quantitative assumption made here, implying that a decade will be needed to go from constant emission level to the maximum reduction rates. These three criteria do not define unique pathways, as there are still many pathways that may lead to the same concentration stabilisation target, and may also meet the criteria for the rate of emission reductions. Mainly due to the long residence time of CO_2 in the atmosphere, it is rather the aggregated emissions that define the concentration stabilisation level than the time of emitting. Significant differences in the timing of required emission reductions allow many alternative pathways. This is shown by the emission envelopes, which we calculate here, by systematically varying the parameters of the parameterised global CO_2-eq. emission pathway (see Appendix E). Within these envelopes, we define three types of emission pathways:

Default pathways – The timing of the mitigation of these pathways is characterised as medium (not early; not delayed response), and the reduction effort is spread as much as possible over the century, thereby leading to as low as possible maximum global abatement costs (as a percentage of Gross Domestic Product (GDP)). The default pathways are chosen (more or less) on the basis of the lowest maximum *z* costs, as illustrated for the 550 ppm target in Figure 6.4.

Delayed response pathways – Here, the timing of mitigation is based on delayed response, with emissions being reduced less in the short term. The advantage is evidently buying time to prepare societies for strong mitigation policies – and also reducing short-term costs as shown in Figure 6.4. However, costs are going to be higher in the long run compared to the default and early action pathways, as the latter pathways profit from induced technology development and an earlier signal of change to the energy system (and thus a more gradual response). Here, the central delayed response pathway is chosen as the one with the highest emissions and lowest relative costs in 2020.

---

[49] More specifically, for 550 ppm 2% and 0.25 percentage point, and for 450 ppm 3% and 0.4 percentage point.

Early action pathways – Here, the response is as fast as possible, with either the rate of emission reductions restricted by the maximum annual trend change, or the emission reduction itself restricted by the maximum reduction rate. Both cases lead to pathways with an early peak of global emissions. We have two central pathways for this group: (i) the *early action/rapid change pathway* (RC), with the highest maximum relative costs (above default) before 2050 as a result of the fast and high reductions in the first half of the century, and (ii) the *early action/average change pathway* (AC), with the lowest maximum costs (below default), but with fast increasing costs in the coming two decades (Figure 6.4).

The four pathways (*default, delayed response* and two *early action* pathways) lead to approximately the same concentration stabilisation target (long-term), but their CO_2-eq. concentrations in 2100 may differ, with the lowest concentrations for the early action RC pathways (see Figure 6.7a-c). As we want to compare the abatement costs and reductions of these four pathways, we oblige the delayed pathways to lead to the same temperature increase in 2100 as the default pathway (see Figure 6.7d-f).[50] For reporting reasons we show only the different representatives of the group (see Figure 6.4); furthermore, the emission pathways of the three groups are simply represented as grey lines, which together form the emission envelope.

[50] This holds for all pathways, except for the early response RC pathways, as this pathway leads to lower concentrations and temperature increase projections over the time horizon considered up to 2400.

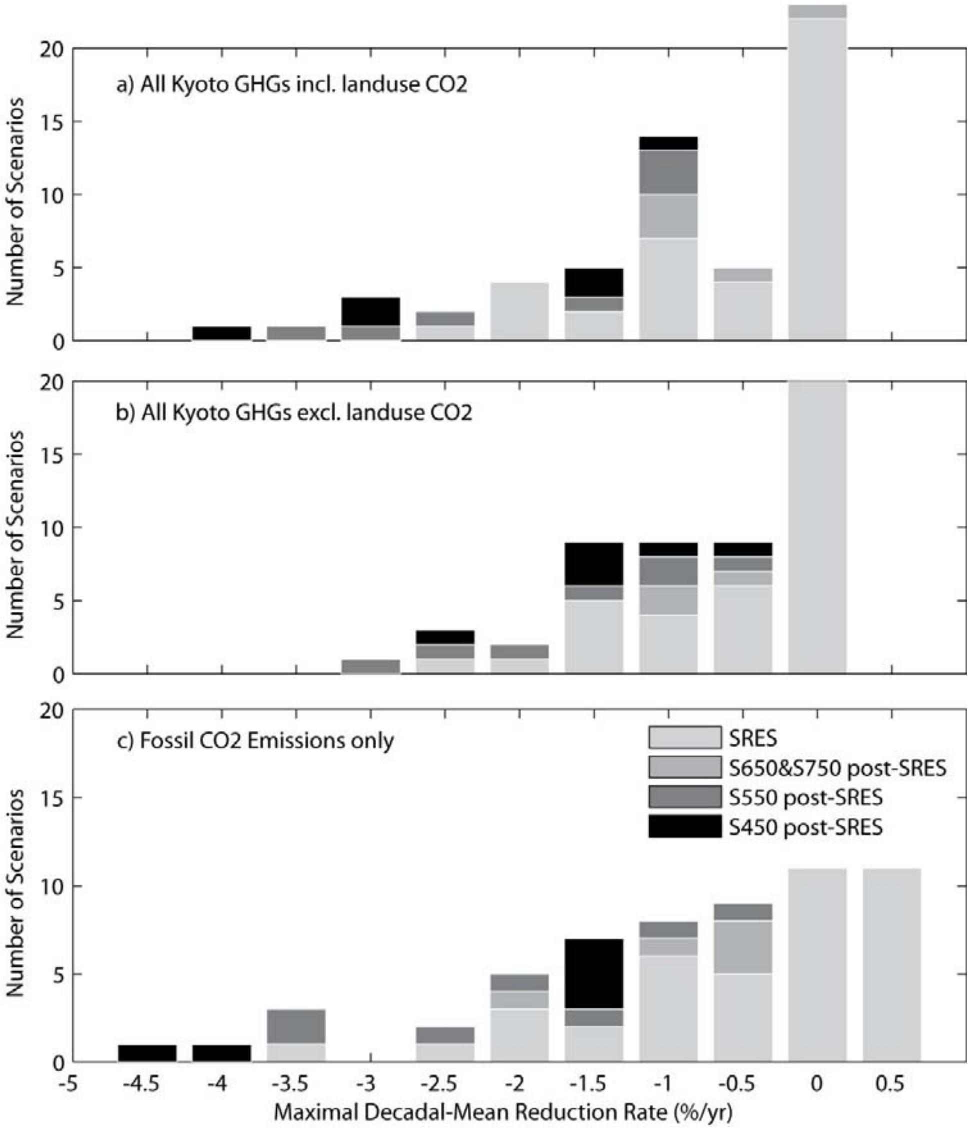


*Figure 6-3 Maximum decadal mean reduction rates in percentage per year for global emissions of (a) all Kyoto GHGs including land-use CO_2, (b) excluding land-use CO_2 and (c) energy-related CO_2 emissions for 40 SRES scenarios (Nakicenovic et al., 2000; Swart et al., 2002) and 18 post-SRES scenarios (Swart et al., 2002). Note: The maximum reduction rates for each scenario are here estimated as follows: the decadal emission changes (Ed/Ed+1) for each SRES and post-SRES scenario are calculated from 1990 to 2100 and the average annual emission change (in % yr–1) for each decade 'd' is then derived as Rannual = (exp(log(Ed/Ed+1)/10)-1)*100. The maximal reduction rate is then the minimal value for Rannual for each scenario. The post-SRES scenarios were designed to stabilise at different CO_2 concentration levels, namely 450 ppm CO_2 (S450), 550 ppm CO_2 (S550), 650 and 750 ppm CO_2 (S650 and 750).*

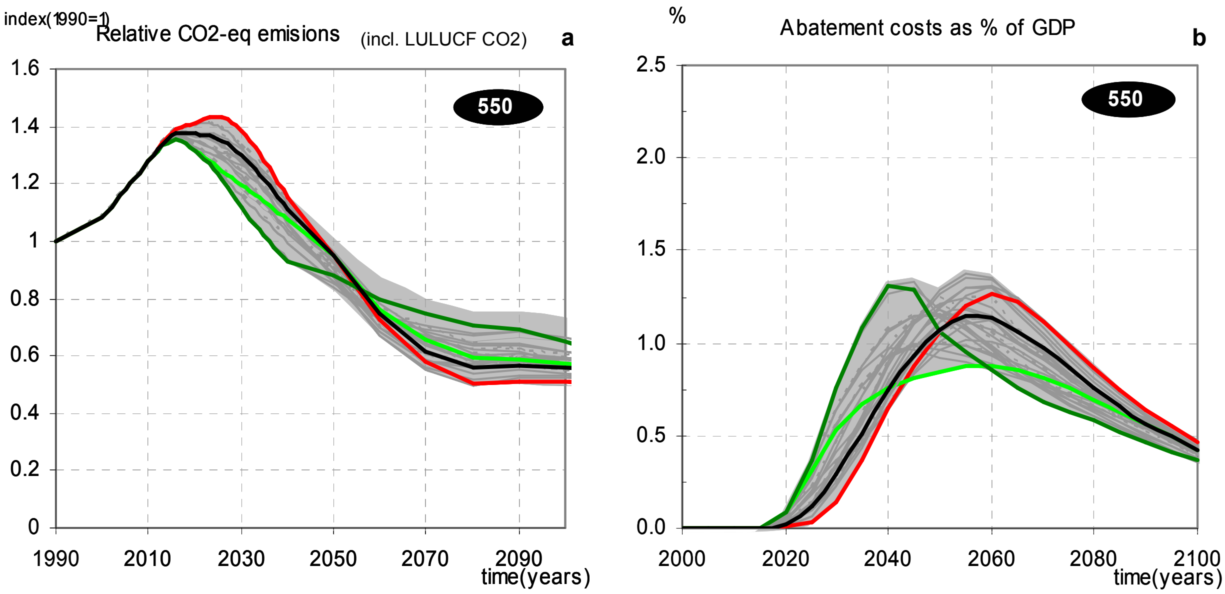


Figure 6-4 Global emissions relative to 1990 levels including LULUCF CO_2 emissions (left, a) versus the global abatement costs (b) for the default (bold), early action/rapid change RC (dark green), early action/average change AC (light green), delayed response (dark green) emission pathways and all pathways (grey) (forming the envelope) at 550 ppm CO_2-eq. concentrations for the B2 baseline scenario.

6.3.2 Emissions

Figure 6.5 shows the central default, delayed and early action emission pathways and their envelopes for the three baseline scenarios for the three concentration stabilisation levels.

Default pathways – The global GHG emissions (including LULUCF CO_2) for the default emission pathways at 650, 550 and 450 ppm CO_2-eq. need to be reduced in 2100 by 55%, 70% and 85%, respectively, from their B2 baseline levels (see , left panel). Under the 650 ppm CO_2-eq. pathway emissions can still slightly increase and stabilise at a level 40% above current emissions in the next three to four decades – followed by a slow decrease. For the 550 ppm CO_2-eq. pathway, however, emissions need to peak around 2020, directly followed by steep reductions in order to avoid overshoot of the 550 ppm CO_2-eq. concentration level. The emissions are approximately 5% below 1990 levels in 2020. For stabilisation at 450 ppm CO_2-eq., short-term reductions become even more stringent, with global emissions peaking around 2015 at 30% above 1990 levels. Global GHG emission reductions increase up to 35% below 1990 levels in 2050.

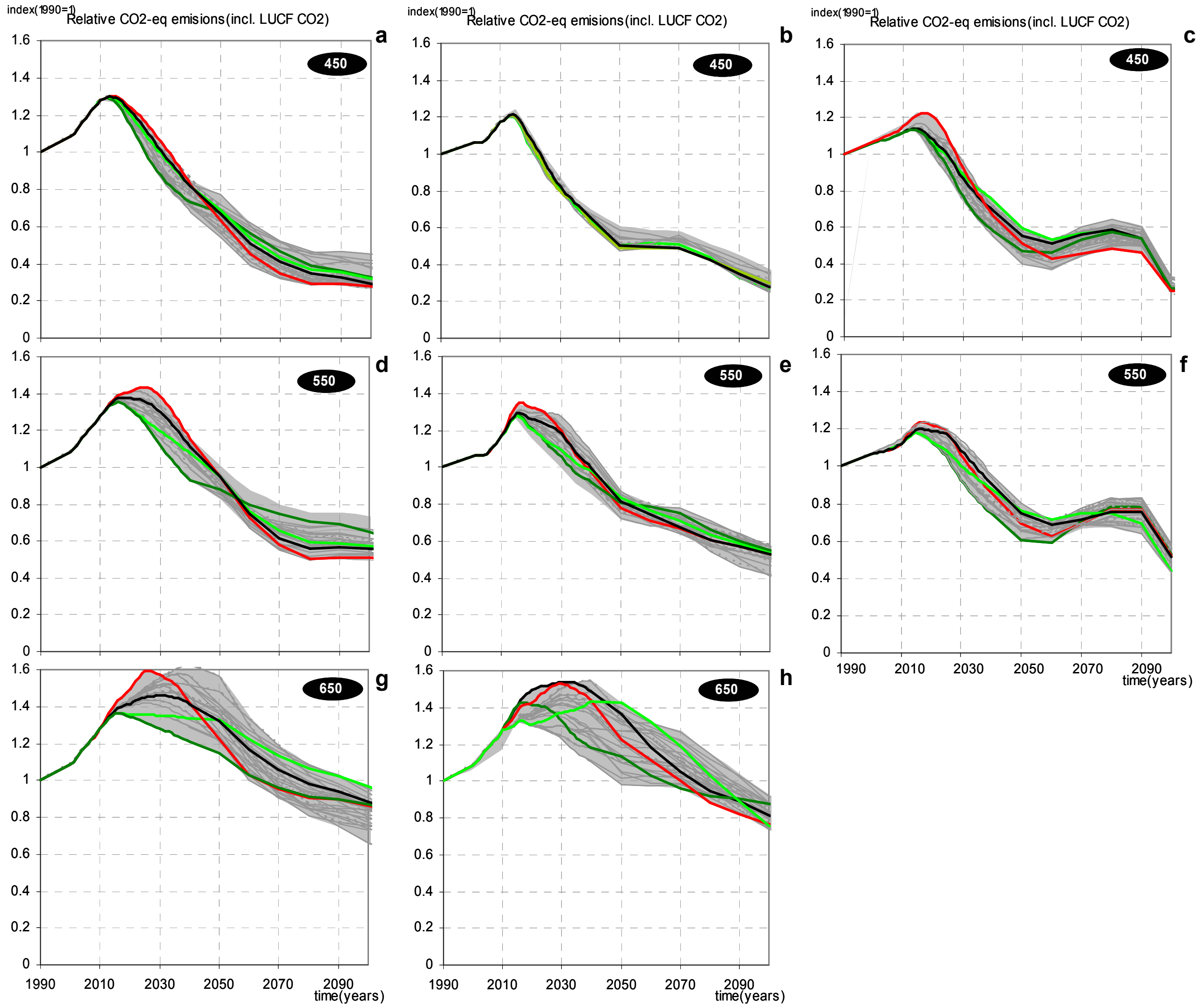


Figure 6-5 Comparison of the global emissions relative to 1990 levels for the global emission pathways: default (black), delayed (red) and early action (green) pathways and envelopes (set of grey lines) at 450 (upper, a-c), 550 (middle, d-f) and 650 (lower, g-h) ppm CO_2-eq. concentration for the B2 (left panel, a,d,g), A1b (middle panel, b,e,h) and B1 baseline (right panel, c,f) scenario. Note, for the A1b baseline scenario there was no delayed pathway possible, and for the B1 baseline scenario, there were no feasible pathways towards 650 ppm.

Table 6-1 The uncertainty range and the default change of global GHG emissions (including LULUCF CO_2 emissions) compared to 1990 levels for the different multi-gas pathways for stabilising at 450, 550 and 650 ppm CO_2-eq. concentration for the three baseline scenarios (in %).[a]

2020	B2		A1b		B1	
Baseline	Range	Default	Range	Default	Range	Default
450 ppm	[14;24]	22	[3;9]	8	[0;20]	7
550 ppm	[32;41]	37	[32;18]	26	[13;23]	19
650 ppm	[35;50]	41	[30;43]	35		
2050	B2			A1b		B1
Baseline	Range	Default	Range	Default	Range	Default
450 ppm	[–45;–23]	–33	[–52;–42]	–50	[–60;–40]	–45
550 ppm	[–7; 0]	–5	[–28;–13]	–18	[–40;–20]	–25
650 ppm	[21;57]	32	[5;42]	24		
2100	B2			A1b		B1
Baseline	Range	Default	Range	Default	Range	Default
450 ppm	[–74;–55]	–71	[–75;–65]	–72	[–77;–67]	–73
550 ppm	[–49;–26]	–44	[–59;–42]	–47	[–57;–41]	–49
650 ppm	[–25;–3]	–12	[–18;–8]	–21		

[a] The uncertainty range presented here needs to be considered carefully in the context of the envelope, choosing lower reductions in the beginning needs to be compensated by higher reductions later on and vice versa.

Delayed response versus early action pathways – The delayed pathways make it clear that running along the upper boundary of an envelope does not bring you to the concentration stabilisation target (see also Figure 6.4 and, 6.5 left panel). The early high emissions of these pathways, forming the short-term upper boundary of the envelope, will have to be offset by low emissions later on, forming the long-term lower boundary of the envelope. An opposite pattern can be seen for the early action pathways. The early low emissions of the early action RC pathways, forming the short-term lower boundary of the envelope, can be compensated by higher emissions in the long term, forming the long-term upper boundary of the envelope.

The transient evolution of CO_2-eq. and the CO_2 concentrations for the four pathways do not differ much. Thus, even if there is a net increase in terrestrial and ocean carbon in a scenario with temporarily elevated CO_2 concentrations and temperatures (e.g., Wigley et al., 1996), the effect in case of our pathways will be very limited. In other words, the cumulative emissions for the four different pathways for each stabilisation level do not vary much. For example, the cumulative emissions of the pathways within the envelope for the B2 baseline scenario and the 550 ppm target differ by –2% and +1% of the cumulative emissions of the default pathway. If we were to allow a higher overshoot, the effect could become more prominent, but would also lead to a higher rate of temperature increase, which in turn is likely to reduce the carbon uptake of the biosphere and the oceans.

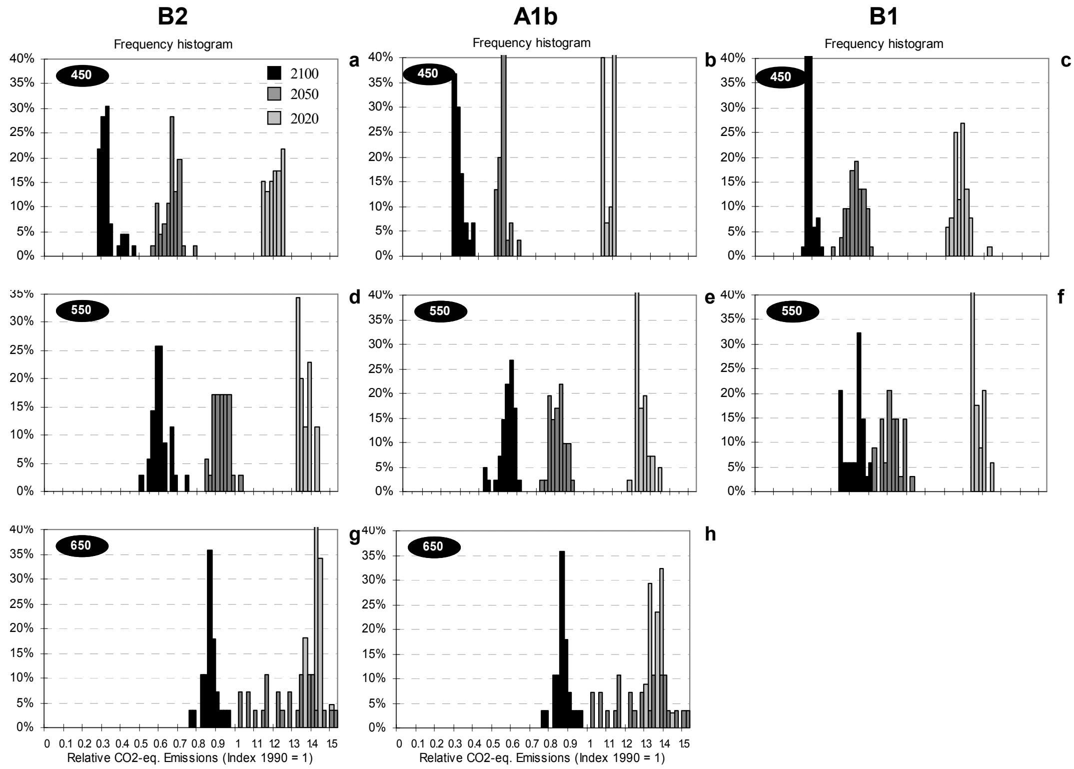


Figure 6-6 The frequency histograms of the global emissions relative to 1990 levels for the emission pathways as presented in Figure 6.5.

Emission envelopes – The envelopes show that there is indeed a large spread of emission paths leading to the same concentration levels, but the spread of emission pathways decreases for the lower concentration targets (see also Figure 6.5 and Figure 6.6, left panel). More specifically, for the lower concentration targets there is a limited space for emissions, going from early action to our default assumptions and finally delayed response. The envelopes for both 450 and 550 ppm CO_2-eq. show that emissions are required to peak before 2015 and 2025, respectively, with strong emission reduction following. Our calculations show this phase (striving to reach these concentration levels) to be the most difficult in climate change policy, even when assuming full participation of all countries under a climate regime. Without participation (in some form) of the major GHG emitters, the 450 ppm and 550 ppm target is outside our reach, as was shown by Den Elzen and Meinshausen (2005). Figure 6.6 (left panel) also shows that the envelopes of 450 and 550 ppm CO_2-eq. do not overlap (after 2015), which suggests that there are no emission pathways initially following 550 ppm (early action) and then turning to a 450 ppm pathway. For 650 ppm, the emissions may peak at 2030–2040 at the latest, although for a delayed response strategy (with higher short-term emissions) this peak also occurs before 2025. Here, we see quite some overlap between the emission envelopes of 550 and 650 ppm.

These conclusions have to be qualified of course for cases in which the limits applied here are relaxed; this affects the maximum emission reductions and changes in reduction rates from year to year. Furthermore, we want to emphasise again that these envelopes are not necessarily what they are considered to be as what they are, that is, envelopes around a set of pathways. Following the upper or lower boundary of the envelope for the whole time period does not lead to the concentration target. The envelope better reflects the idea that following the lower boundary in the beginning can be compensated by following the upper boundary later. Early reductions can be compensated with more relaxed reductions later, and vice versa.

Baseline – The emission pathways and resulting emission envelopes are baseline-dependent. For example, compare the columns in Figure 6.5 and Figure 6.6. This is a direct result of the differences in: (i) initial (starting point of the pathways in 2010) emissions and their growth and (ii) MAC curves and (iii) LULUCF CO_2 emissions. For example, in (i) the pathways under the B2 scenario have higher short-term (2020) emissions, and medium-term (2050) emissions, although their emissions are lower in the second half of the 21st century (see Figure 6.5). For example, in (ii) there are no feasible delayed pathways for the 450 ppm target for the high-growth emission scenario A1b, resulting in a small emission envelope compared to the other two envelopes for 450 ppm. For the B2 scenario, these LULUCF CO_2 emissions (iii) show a temporary increase at the end of the century due to a rapid introduction of biofuel in the transport sector. Therefore, these emissions form a large part of the total emissions from the pathways at the end of century, which needs to be compensated by lower emissions in the medium term.

Comparison with earlier study (Den Elzen and Meinshausen, 2005; 2006) – In general, the reductions for the Kyoto GHG emissions including or excluding LULUCF CO_2 emissions are very similar. However, our earlier study showed that the reductions excluding LULUCF CO_2 were about 10–15% higher than the reductions in the Kyoto GHG emissions including LULUCF CO_2. This is because of the much higher LULUCF CO_2 emissions for the updated baseline scenario due to the additional deforestation emissions from the biofuel plantations. Other differences with the earlier study, such as the updated baseline emissions and MAC curves, have only a minor effect on the emission pathways. Another difference is that in our earlier study the initial (2010) growth of about 1–1.5% yr^{-1} (depending on the baseline) was assumed to decline relatively rapidly after 2010 to 0.5% yr^{-1} for all concentration stabilisation targets. This is different for the 550 ppm and 650 ppm CO_2-eq. pathways in this study, since here we apply a boundary of how fast emission reduction rates can change from year to year. However, the boundaries for the 450 ppm stabilisation pathway are more or less in line with the assumptions of our earlier study.

Abatement across different gases – Initially, a substantial share of the reduction is, for all emission pathways, achieved by reducing non-CO_2 gases, while only 10% of the reductions comes from reducing energy-related CO_2 emissions (not shown here) (see also Van Vuuren et al., 2005a).The disproportional 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 methane emissions from energy production and N_2O emissions from adipic and acidic acid industries, and halocarbons). After 2015 ever more reductions need to come from CO_2 in the energy system – up to 80% in 2100. This shift simply reflects that non-CO_2 gases represent about 20% of total GHG baseline emissions. In addition, some non-CO_2 GHGs (including several sources for land-use related CH_4 but in particular N_2O emissions sources) cannot be reduced fully due to limited reduction potential. The share of non-CO_2 abatement declines somewhat further in the 450 ppm stabilisation – compared to the 650 ppm stabilisation. The use of carbon plantations shows an increasing contribution to about 1 GtC annually in 2100 for all targets due to increasing land availability.

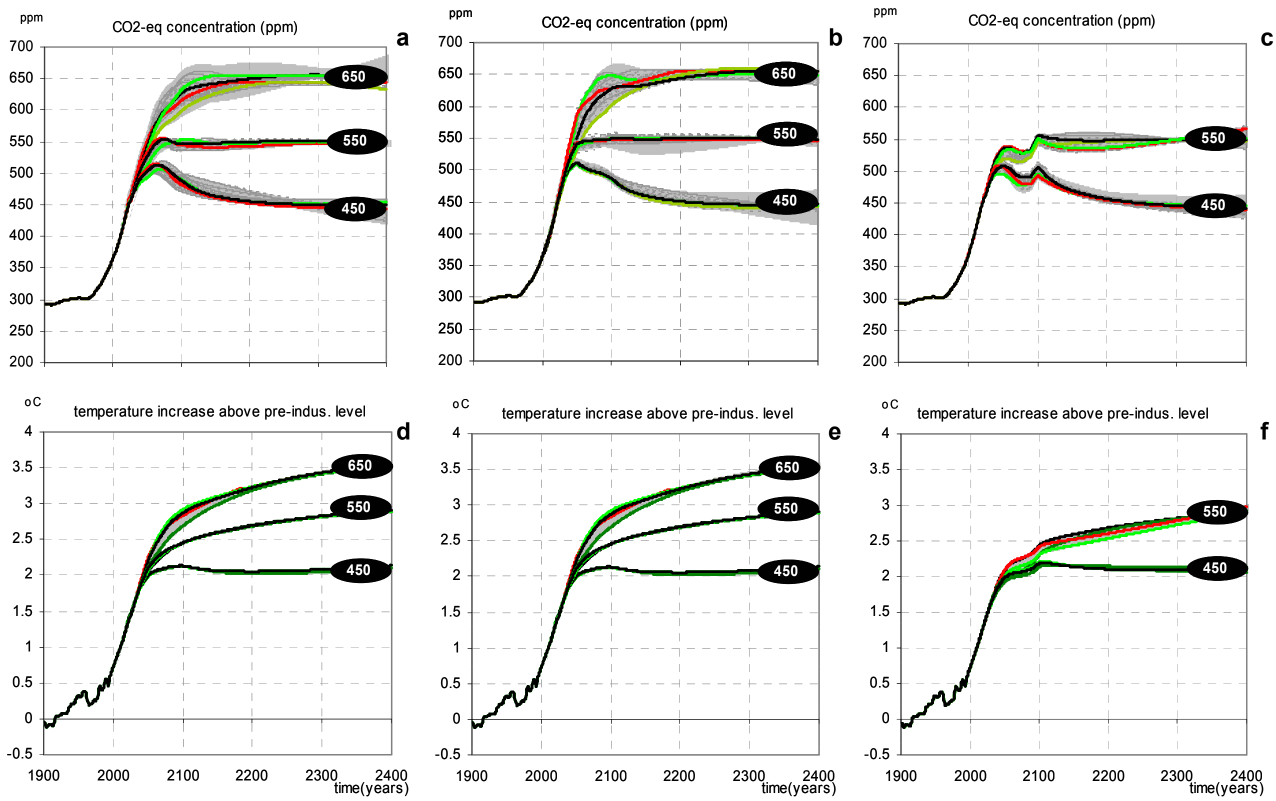


Figure 6-7 The CO_2-eq. concentration and temperature increase above pre-industrial levels for the global emission pathways(assuming a climate sensitivity of 3°C); default (black), delayed(red) and early action (green) pathways and envelopes (set of grey lines) for the three stabilisation levels for the B2 baseline (a), A1b baseline (b) and B1 baseline (c) scenario.

6.3.3 Global costs

Figure 6.8 shows the resulting abatement costs of the pathways as a percentage of world GDP. Although our relatively simple cost calculations are meant to be explorative (see the methods section) the following findings have emerged.

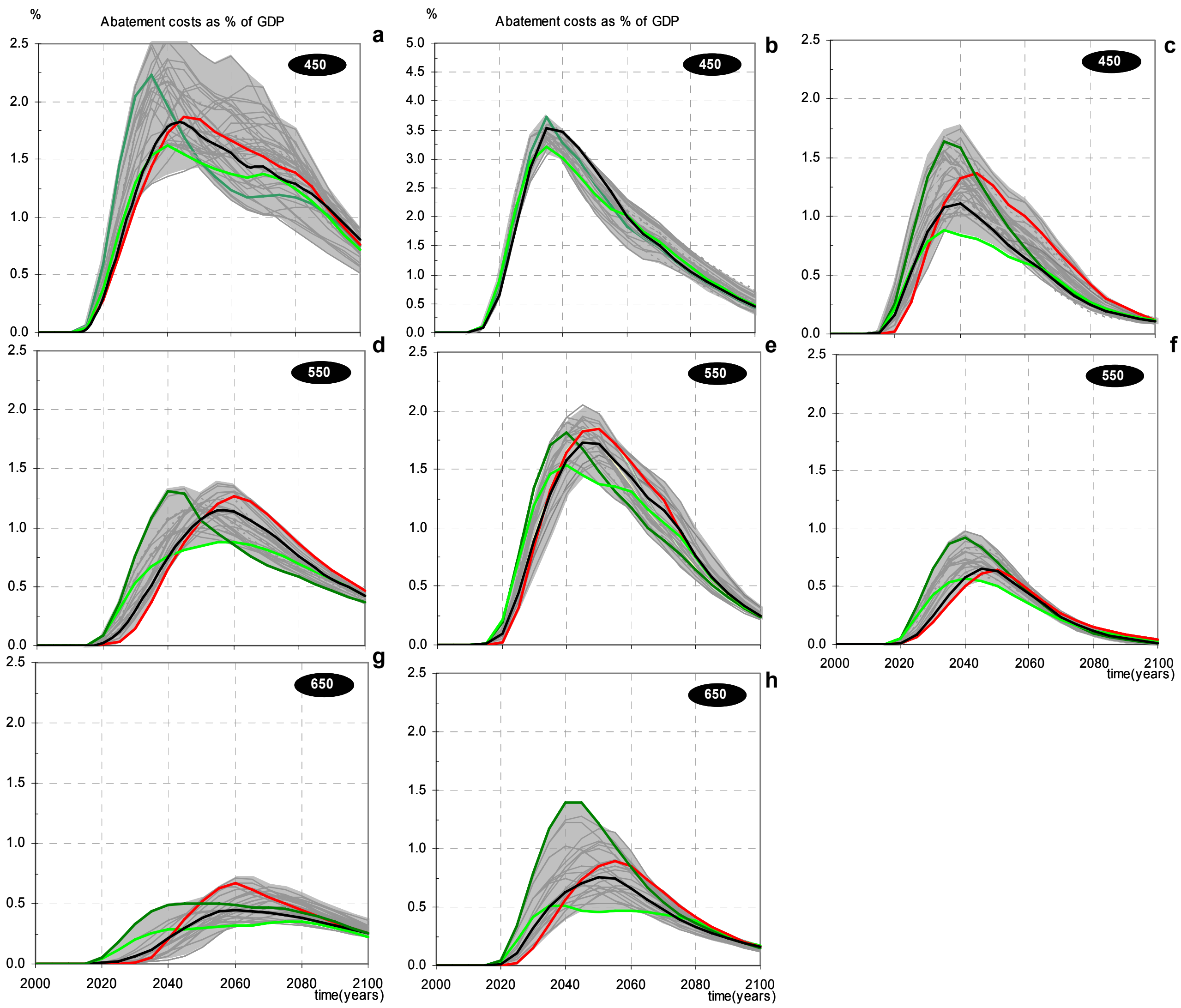


Figure 6-8 Comparison of the global abatement costs as % of GDP for the global emission pathways; default (black), delayed (red) and early action (green) pathways and envelopes (set of grey lines) at 450 (upper, a-c), 550 (middle, d-f) and 650 (lower, g-h) ppm CO_2-eq. concentration for the B2 baseline (left panel, a,d,g), A1b baseline (middle panel, b,e,h) B1 baseline (right panel, c,f) scenario. Note that a different scale is used for the A1b-450 ppm case.

Default pathways – The costs as a percentage of GDP increase for lower concentration stabilisation targets; however, it can also be seen that these costs increase much more rapidly in time. For the 450 and 550 ppm pathways, costs such as percentage of GDP reach a maximum level between 2020 and 2040 (1.2% of GDP for 550 ppm and 2% for 450 ppm).[51]

---

[51] Van Vuuren et al. (2006a) have showed that these costs estimates compare well to those of other studies. More specifically, 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. The costs of this study are similar to our earlier work of FAIR and IMAGE/TIMER (Van Vuuren et al., 2005), and in between the lowest and the highest estimate of EMF-16/IPCC-TAR (Hourcade and Shukla, 2001).

This re-emphasises our earlier conclusion that this time period (2020–2040) is evidently one of the most crucial periods for emission reductions. In fact, given the lags between climate policy drafting, implementation and actual emission reductions, the period before 2020 is politically equally important – certainly if one attempts to reach the lower concentration stabilisation targets. The costs very much depend on the participation of countries in emissions trading. Here, full participation is assumed. This implies that only if the participation of countries adopting absolute targets and taking part in the emission trading can be broadened, will our cost calculations be correct. The costs will be higher (or concentration targets will not be reached) when major emitting countries delay their participation. In the default pathways (but also alternative pathways) the relative cost (as a percentage of GDP) actually declines again after 2040, as GDP growth outstrips the growth in calculated abatement costs for most of the pathways (see Figure 6.8). [52]

Delayed response versus early action pathways – The cost pathways over time are shown after an initial rapid increase in costs, with the early action pathways resulting in the lowest average maximum (relative) costs benefiting from lower reduction rates, an earlier signal of change to the energy system and technology development. The delayed pathways, in contrast, avoid the early rise in costs, but see higher maximum costs during the 2020–2040 period. The default pathways result in maximum costs somewhere in between those two (see Figure 6.8). More specifically, the peak of the global costs for the B2 scenario is the lowest for early action AC (0.8% and 1.6% of GDP for 550 and 450 ppm, respectively), followed by the default pathway (1.1% and 1.8%), the delayed response (1.3% and 1.9%) and, finally, the early action RC pathway (1.3% and 2.2%). The NPV of abatement costs as a percentage of the NPV of GDP for the B2 baseline scenario varies between 0.2% of GDP for stabilisation at 650 ppm and 1.0% of GDP in the 450 ppm case (with a discount rate of 5%, Figure 6.9a). For the A1b scenario, the NPV of abatement costs are somewhat higher and for B1, lower. We can now compare the NPV of abatement costs for the early, default and delayed pathways under different discount rates (Figure 6.9b). No discounting shows that for the 450 and 550 ppm stabilisation targets early action (both variants) leads to the lowest NPV of costs, followed by the default case; the delayed pathway leads to the highest NPV of abatement costs (Figure 6.9b). The 650 ppm target gives a similar pattern, except that the early action RC pathway now gives similar costs as the delayed pathway. This result is, again, caused by technology development and the longer time needed for the energy system to respond. Under the discount rate of 5%, the differences between the early action AC, default and delayed pathways are small. The early action RC pathway leads to the highest costs.

More specifically, discount rates less than 2% would favour early action RC pathways for the 450 ppm target, discount rates less than 8% would favour early action AC pathways and to a

---

[52] The trajectory of the carbon tax also depends on the fact that we constrain our emissions not to exceed the final target earlier in the century (or if they do, by a margin as small as possible). Given population and GDP trajectories, targets may be just as binding early in the century as latter in the century.

lesser extent the default pathway. Finally, discount rates more than 8% would favour delayed response – on the basis of economic arguments alone. For the 550 ppm target, this will depend on the scenario. For the B2 scenario, the discount rates of less than 1% would favour early action RC, 1–3% early action AC, 3–4% default pathways and more than 5% delayed pathways. However, for the A1b scenario there are higher discount rate thresholds, less than 2% early action RC, 1–3% early action AC, 3–9% default pathways and more than 9% delayed pathways. For the 650 ppm target, the discount rates of less than 2% would favour early action RC, 2–5% default pathways and more than 5% delayed pathways.

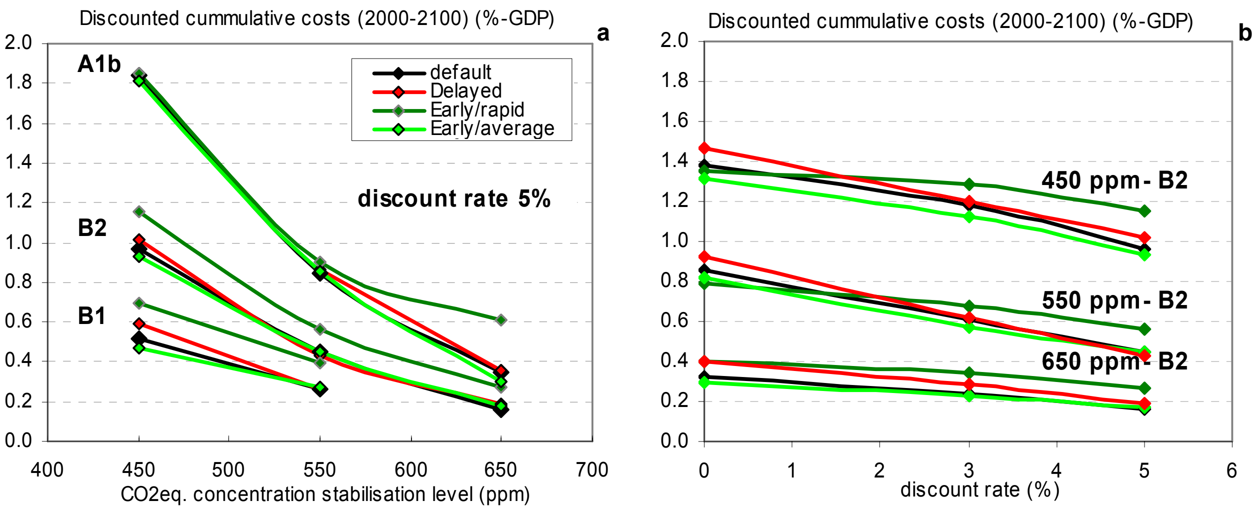


Figure 6-9 Net Present Value of abatement costs for different stabilisation levels, starting from different baseline scenarios for the discount rate of 5% (a), and as a function of the discount rate of 3% (b).

Cost of the envelopes – The costs of the complete set of emission pathways show an even wider range than the range already seen for the early action, default and delayed pathways, especially for the 450 ppm target. In general, the costs peak later for the higher concentration targets, but the date of the peak shows a wide range. For example, this can be before 2030 (early action RC) for the B2 baseline and the 550 ppm target, but may also be as late as 2070 (early action AC), although a maximum around 2050 is more likely. For the 450 ppm target, the latest date is much sooner (2050). The maximum level itself can also vary considerably: for the B2 baseline and the 550 ppm target, this range is between 1–1.7%, whereas for the 450 ppm target it can vary between 1.5 and almost 3%.

Baseline – Figure 6.8 also shows the global abatement costs to be even more influenced by the baseline emissions than the stabilisation level, as also concluded by the IPCC. The A1b costs are higher than the B2 costs, while the B1 costs are below this stabilisation level for each concentration stabilisation level. This is a direct result of the lower reduction objective, the high technology development rate and the resulting lower marginal price. The economic assumptions also obviously influence the relative cost measures, such as GDP losses or abatement costs as a percentage of GDP. The NPV of the abatement costs shows a similar trend, as indicated in Figure 6.9.

6.4 Probabilistic temperature increase projections

The different multi-gas emission envelopes for the different concentration stabilisation targets analysed in section 6.3 lead to clearly different temperature increases, both during this century and in the long term. Figure 6.7d-f shows the resulting temperature increase projections using a single value for climate sensitivity (3°C). There are a number of points to note here. Firstly, the early action AC pathway, default and delayed response emission pathways lead, as assumed, to very similar temperature increase projections by 2100. While temperature increase in 2100 is more-or-less similar, during most of the century delayed response has led to higher temperature increase than early action and default response. Secondly, the early action RC pathways lead to somewhat lower temperature projections over the period of 2000–2200 compared to the temperature increase in the other three pathways, which is a direct result of their lower CO_2-eq. concentration. Thirdly, although the CO_2-eq. concentration stabilise for the 650 and 550 ppm cases before 2150, the warming continues beyond 2250. This is because of the large thermal inertia of the climate system, which, in turn, is largely determined by how rapidly heat is mixed down into the ocean. Fourthly, due to the inertia of the climate system, the peak of concentrations (510 ppm) before stabilisation at 450 ppm CO_2-eq. does not translate into a comparable peak in global mean temperatures. In fact, the peaking concentration is the key factor that determines whether a 2°C temperature threshold will be achieved or not, rather than the stabilisation level itself (see also Meinshausen, 2006).

It should be noted, however, that the temperature response of the different stabilisation scenarios depends to a considerable extent on the climate sensitivity. Taking into account the uncertainty in the climate sensitivity, we present the temperature in probabilistic terms for the default pathways under 450, 550 and 650 ppm CO_2-eq. for the baseline B2. The assumed climate sensitivity uncertainty distribution for the temperature projections in is constructed by assuming the conventional IPCC TAR 1.5°C–4.5°C uncertainty range. This represents the 90% confidence interval of a lognormal distribution – called below 'IPCC lognormal PDF' (see Wigley and Raper, 2001). Aerosol forcing and ocean diffusivity are set to their respective maximum likelihood estimators for any given climate sensitivity to find a best match with historical global mean temperature observations (see 'temperature constrained' method by Meinshausen, 2006). In these transient calculations, we included the solar forcing according to Lean et al. (1995; 2001) and volcanic forcing according to Ammann et al. (2003). Future natural forcing is assumed as the mean over the last 22 years (solar) and 100 years (volcanic).

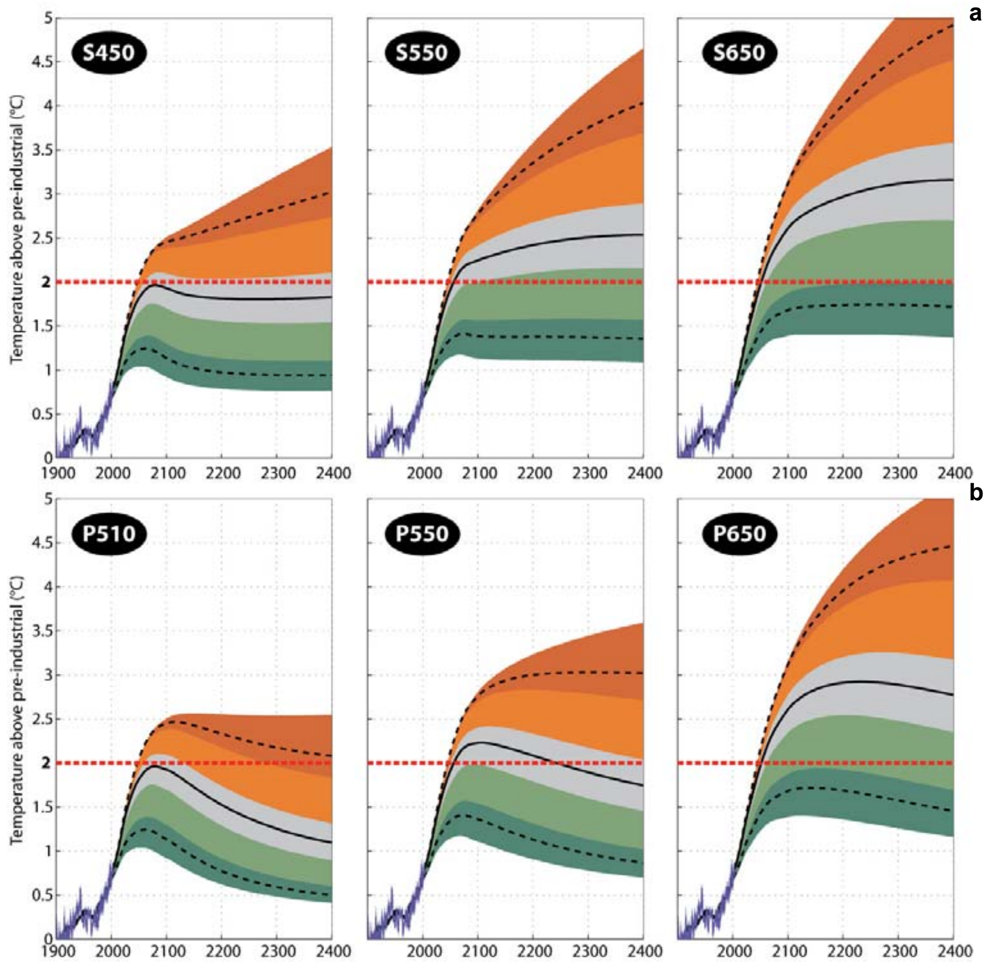


Figure 6-10 The probabilistic transient temperature implications for the stabilisation pathways at 450, 550 and 650 ppm CO_2-eq. concentration (upper row) and the pathways that peak at 510 ppm, 550 ppm and 650 ppm (lower row). The FAIR-SiMCaP pathways shown are those for the B2 baseline scenario based on a climate sensitivity that assumes the 1.5–4.5°C uncertainty range for climate sensitivity (IPCC TAR), being a 90% confidence interval of a lognormal distribution (Wigley and Raper, 2001). Shown are the median (solid lines) and 90% confidence interval boundaries (dashed lines), as well as the 1, 10, 33, 66, 90, and 99% percentiles (borders of shaded areas). The historical temperature record and its uncertainty from 1900 to 2004 is shown (blue shaded band) (Folland et al., 2001; Jones and Moberg, 2003; Jones et al., 2001).

A set of alternative climate sensitivity probability density functions (PDFs) (Andronova and Schlesinger, 2001; Forest et al., 2002; Frame et al., 2005; Gregory et al., 2002; Knutti et al, 2006; Knutti et al., 2003; Murphy et al., 2004; Piani et al., 2005) has been applied to determine the probability that the analysed pathways are in line with the avoidance of a global warming of more than 2°C relative to pre-industrial levels (Figure 6.11).[53] The pathways aimed at a 650 ppm stabilisation have very small or zero chance of limiting warming to below 2°C (refer to Figure 6.10). The probabilities for staying below 2°C are still very limited, 1– 40% for the 550 ppm stabilisation pathways with (IPCC lognormal PDF: 26%). However, a peaking at 550 ppm without subsequent stabilisation could increase those chances marginally to 3–48% (IPCC lognormal PDF: 34%). For the stabilisation pathways that peak at 510 ppm and stabilise at 450 ppm the chances are again slightly increased to 14–67% (IPCC lognormal PDF: 54%). Note that in this latter category of pathways, the peaking concentration level at 510 ppm, not the stabilisation at 450 ppm CO_2 eq., is likely to cause the maximal warming over the time horizon from 2000 to 2400.

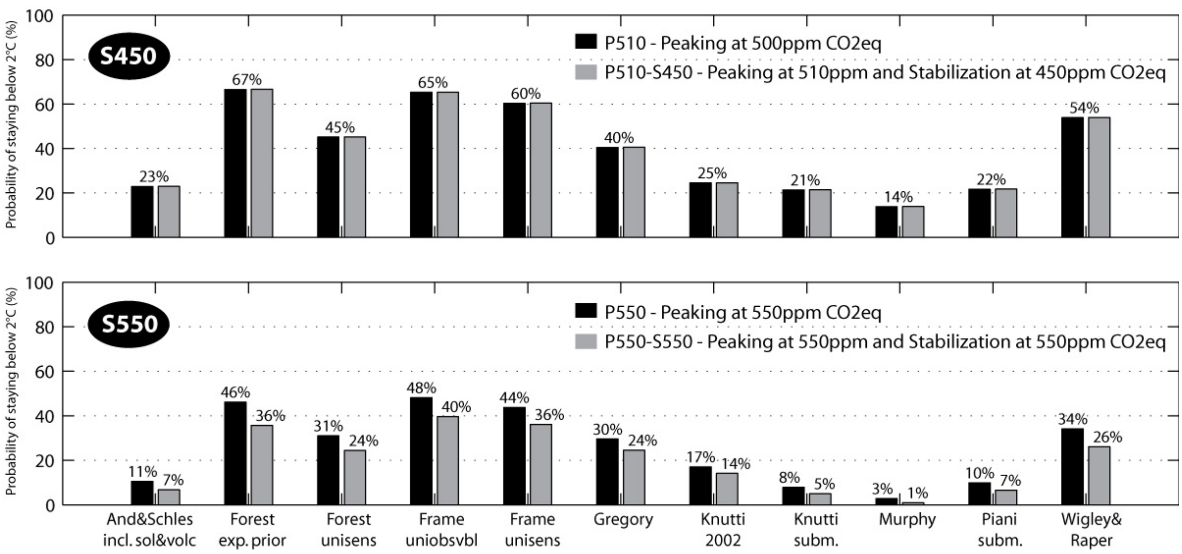


Figure 6-11 The probability of staying below 2°C global mean warming up to 2400 for the pathways that peak at 510 ppm CO_2-eq. (upper panel) and those that peak at 550 ppm CO_2-e.q for different climate sensitivity PDFs. Note that those pathways that stabilise and/or peak at 650 ppm have only negligible chances of meeting a 2°C target (23% or below). The last two bars indicate the results for the IPCC-based lognormal PDF on climate sensitivity (Wigley and Raper, 2001), which corresponds to the transient temperature evolution shown in Figure 6.10.

[53] Note that the cited probabilities and likelihoods are only indicative. Furthermore, the underlying probability density distributions on climate sensitivity only reflect the fact that our knowledge is uncertain. The climate sensitivity is not a random variable.

Table 6-2 Comparison of climate risks versus abatement costs for the different multi-gas pathways for stabilising at 450, 550 and 650 ppm CO_2-eq. concentration.

		Climate risks[a]		**Abatement costs**[b]	
		Probability (%) of limiting warming to below 2°C for pathways with (and without) stabilisation after peaking		**Cumulative costs (NPV) as % of GDP**	**Maximum costs as % of GDP**
Stabilisation (ppm CO_2-eq.)	**Peaking (ppm CO_2-eq.)**	Central estimate[d]	Range		
450[c]	510	54 (54)	14–67 (14–67)	1.0 (0.9–1.2)	2.0 (1.6–2.6)
550	550	26 (34)	1–40 (3–48)	0.5 (0.4–0.6)	1.14 (0.9–1.3)
650	650	10 (12)	1–21 (2–23)	0.15 (0.1–0.3)	0.45 (0.4–0.7)

[a] Climate risks: the probability of exceeding 2°C warming above pre-industrial levels up to 2400 for the 'IPCC lognormal PDF' and the range across 11 climate sensitivity uncertainty distributions.
[b] Abatement costs: the NPV of abatement costs as a percentage of GDP (using a discount rate of 5%) and maximum costs as a percentage of GDP.
[c] This is in fact an overshooting scenario.
[d] Based on IPCC lognormal PDF (Wigley and Raper, 2001).

These results reconfirm two important points. Firstly, only a long-term stabilisation of 450 ppm CO_2-eq. or below (400 ppm CO_2-eq.) can be expected to avoid global warming of 2°C or more with a medium likelihood. Secondly, policy and science should increasingly focus on the peaking level of concentrations in the 21st century rather than the ultimate stabilisation level. It can be inferred from our results shown above that a reduction in the ultimate stabilisation level below 450 ppm will not alter the probabilities of exceeding 2°C – as long as the peaking level of concentrations is not lowered below 510 ppm.

As a word of caution, it should of course be noted that the above cited likelihood ranges should be taken as indications and are subject to change in the light of new evidence on the climate sensitivity and other important parameters, for example, the aerosol radiative forcing effects.

Box 6.1. Achieving temperature targets with more likelihood under lower costs: peaking profiles

Figure 6.10 and 6.11 showed that peaking instead of stabilisation concentrations, in particular peaking at 550 and 650ppm, can substantially increase the probability of achieving long-term temperature target without increasing the abatement costs (2000-2100). The reason is that due to the inertia in the climate system the transient temperature increase does not reach its equilibrium for many centuries after stabilisation of radiative forcing. Therefore, if concentrations are lowered promptly after stabilisation (by continued emission reductions at a rate of about 40-50% below the reduction rate before stabilisation), it is actually possible to prevent some of the temperature increase that would still occur after this concentration peak (see the 'Stabilisation' versus 'Peaking' profiles in Figure 6.12).

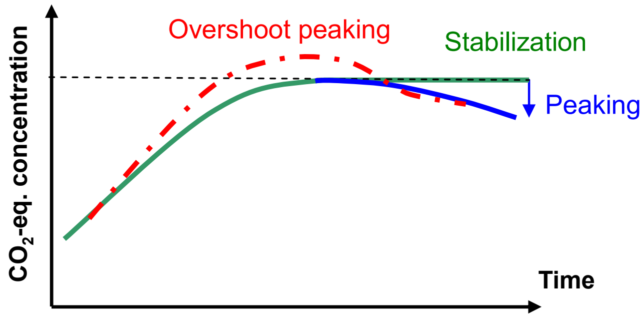
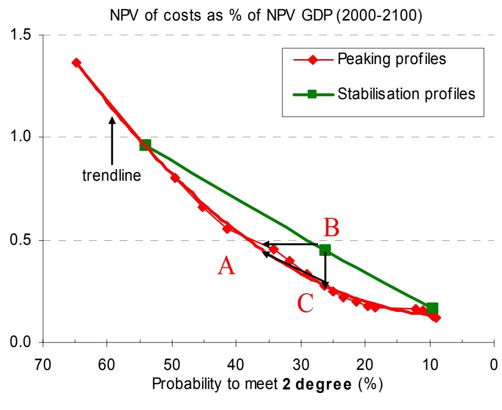


Figure 6.12. Schematic illustration of stabilisation, peaking and overshoot peaking profiles.

This discussion can be brought one step further. Figure 6.13 combines the probability estimates for meeting the 2 °C target with the costs estimates. The figure shows that to increase the probability to meet 2°C costs of climate policy need to increase as well (as greenhouse gas concentration need to be reduced further). The figure includes the results for both the normal stabilisation profiles and the stabilisation profiles. The figure shows that peaking profiles that follow more-or-less the trajectory of stabilisation profiles but continue to reduce after stabilisation can increase the likelihood of achieving temperature targets. Evidently, more reductions needs to be done after stabilisation, but given that these are in the far future (beyond 2100), and costs are discounted, they can be considered as negligible. This corresponds to going from the green line to the red line in horizontal direction. For example, stabilisation at 550 ppm (B) has a probability of about 26% of meeting 2°C, and this probability increases to 34% for a peaking at 550 ppm (A) (Figure 6.13a). A similar trend is showed in Figure 6.13b for meeting a temperature target of 3 °C.

Another way of looking at peaking, is considering emissions pathways that result in concentrations that first peak at an overshoot level as illustrated in Figure XY (overshoot peaking profiles). These profiles show a limited, temporarily overshoot (less than 50ppm) of the stabilisation level (500, 550 or 650 ppm). Such overshoot peaking profiles achieve the temperature thresholds with equal likelihood under lower mitigation costs compared to the corresponding stabilisation profiles. This corresponds with going from the green line to the red line in vertical direction. For example, arrow B to C (Figure 6.13a) shows that stabilisation at 550 ppm versus peaking at 580ppm reduces the NPV of the abatement costs from 0.45% to 0.27%, about 40%, without affecting the likelihood of achieving the 2 °C target. These profiles can also achieve the temperature thresholds with more likelihood under lower mitigation costs. More specifically, arrow C to A, i.e. peaking at 580 ppm to peaking at 550 ppm, reduces the abatement costs and increases the likelihood of achieving the 2 °C target (Figure 6.13a). Of course, this limited overshoot comes with an environmental price. The 2050-2100 temperature increase for the overshoot 580ppm profile is about 0.2°C higher compared to the temperature increase for the stabilisation 550ppm profile (climate sensitivity of 2.5 °C).

Concluding, overshoot peaking profiles reduce the abatement costs and increase the likelihood of achieving long-term temperature target. The reduction of the costs can become as high as 40%. Non-overshoot peaking profiles only increase the likelihood of achieving temperature target.



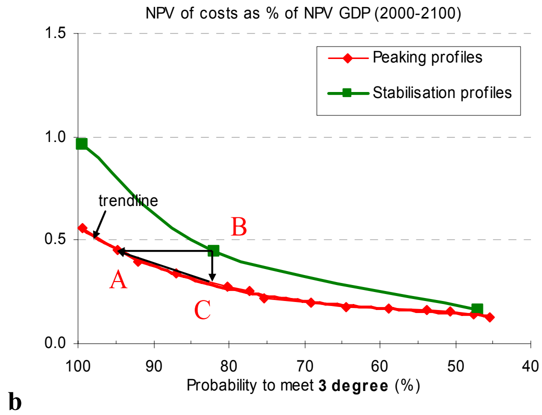


Figure 6.13 Net Present Value of abatement costs as a function of the probability to meet the EU 2 degree target (upper) and 3 degree target (lower) for the baseline B2 scenario (discount rate 5%). The dots represent the calculated outcome of the peaking profiles (from 500 to 680 ppm), whereas the red bold line represents the trend line. The squares represent the stabilisation runs at 450, 550 and 650 ppm CO_2-eq. Further details, see text.

***Note**: Here, we present the NPV (2005) of abatement costs, whereas in Van Vuuren* et al. *(2006) and in this report (Chapter 7) the NPV (2010) are presented.*

6.5 Conclusions

We have described a set of multi-gas emission envelopes (sets of emission pathways), that are compatible with GHG concentration stabilisation levels of 450[54], 550 and 650 ppm CO_2-eq. (including all major GHGs, ozone precursors and sulphur aerosols), along with an analysis of their global reduction implications, abatement costs and the probability of meeting long-term temperature targets including the EU 2°C climate target. The lower pathways presented allow overshooting, that is, concentrations peak before stabilising at lower levels, for example, rising to 510 ppm CO_2-eq. before dropping to levels such as 450 ppm CO_2-eq.

The emission pathways are calculated on the basis of a cost-optimal implementation of available reduction options over the GHGs, sources and regions. This closely reflects the existing international framework of pre-set caps on aggregated emissions and individual cost-optimising actors. We used time-dependent marginal abatement cost curves, including technological change and learning-by-doing as a function of the earlier abatements and accounting for the inertia in the energy system. Furthermore, a maximum reduction rate was assumed, reflecting the technical (and political) inertia that limits emission reductions (this rate is based on a large set of existing mitigation scenarios). In this way, the envelopes or pathways are assessed to be technically and economically feasible. These characteristics make these pathways different from many of the pathways published in the literature.

Within the emission envelope we distinguish three major types of pathways:

[54] This study should not be mistaken as making a statement that the lowest feasible peaking level is about 510 ppm CO_2-eq. From a climate impact perspective, it might be seen as desirable that future research will specifically explore the lower bounds of emission pathways that build on currently known mitigation options.

1) the delayed response pathway following the upper boundary of the envelope as long as possible and so reducing emissions less in the short-term;
2) the early action pathways following the lower boundary as long as possible (rapid change), or only following the lower boundary for about 10–20 years (average change) and then starting to follow the upper boundary, and
3) the default pathways characterised as medium-term pathways (since they are neither early nor delayed), with the reductions spread out over time as much as possible, thereby avoiding rapid early reductions and rapidly changing reduction rates over time.

The analysis of these emission pathways leads to the following conclusions:

1) The emission envelopes show that a wide range of pathways can lead to the same concentration stabilisation target. However, the range decreases for the lower concentration targets. There is a limited space left for emissions for the 450 ppm target, going from early action to our default assumptions and finally delayed response. The envelopes for 450 and 550 ppm show that the emissions are required to peak before 2015 and 2025, and are followed by strong emission reductions. For 650 ppm, the emissions may even peak around 2030–2040. The envelopes of 450 and 550 ppm do not overlap after 2015, which implies that there are no pathways that initially follow 550 ppm (early action), and can turn into a 450 ppm pathway later on. The envelopes of 550 and 650 ppm show quite a bit of overlap, in particular up to 2030. After 2030, only the 650 ppm early action (rapid change) pathways can turn to the 550 ppm delayed pathways.
2) The emission envelopes are dependent on the baseline emissions, in particular, the initial emissions and the baseline emissions of sources with limitations in the reduction potentials, in particular the land-use related sources of CO_2 and CH_4. For example, to reach 450 ppm stabilisation, the emission reductions compared to 1990 levels can be as high as 40–60% for the B1 baseline or as low as 25–45% for B2 in 2050.
3) The costs of the envelopes show a wide range. The delayed pathways show lower costs in the short term, but in the long term these pathways are more expensive than the early action and default pathways, simply because the latter pathways benefit from induced technology development and an earlier signal of change to the energy system. The early action pathways gain even more from the earlier signal to the energy system. For example, the peak of the global costs as a % of GDP is the lowest for early action (average change) (0.8% of GDP for 550 ppm), followed by the default pathway (1.1%), the delayed and early action (rapid change) response pathways (1.3%). Comparing the NPV of abatement costs for the 550 ppm target and the B2 scenario shows that discount rates of about 4–5% or less would favour an early or default pathway; if economic arguments only are taken into account, rates in excess of about 4–5% would favour

delayed response. For the 450 ppm target this threshold lies between 5 and 10%, and for 650 ppm for about 5%.

4) The NPV of abatement costs for the default scenario increase from 0.2% of the NPV of GDP (5% discount rate) for 650 ppm and 0.5% for 550 ppm to 1.0% for 450 ppm. The costs themselves reach a peak of around 2% in the 2040–2070 period for the 450 ppm target, whereas for the 550 and 650 ppm target this is only 1.1% and 0.4%, respectively.

5) On the other hand, the chances of avoiding global mean warming of 2°C and beyond are close to non-existent for 650 ppm (10%), very small for stabilisation at 550 ppm (26%) and roughly 50:50 for a peaking at 510 ppm and subsequent stabilisation around 450 ppm (54%). This assumes a climate sensitivity PDF that takes the conventional 1.5–4.5°C uncertainty range as a 90% confidence interval of a lognormal distribution (Wigley and Raper, 2001). Thus, to achieve a certainty of at least 50% in reaching a 2°C target, the CO_2-eq. concentration needs to peak below 510 ppm in the 21st century.

6) Reaching a 2 degree target with a higher probability would imply peaking at even lower concentration that 510 ppm CO_2-eq. and/or reducing emissions after the peak concentration even faster in order to shorten the temperature overshoot period. For example, Meinshausen (2006) indicates chances for meeting 2 degree of up to 70–80% for CO_2-eq. peaking levels of around 475 ppm. Here, we have not explored such profiles – but in literature some studies can be found that provide some insights on how scenarios may look like that aim for even lower targets (see e.g. Azar et al., 2006; Van Vuuren et al., 2006a). Further research is needed on mitigation scenarios that meet a 2 degree target at higher probabilities.

7) The analysis shows the post-2012 period up to 2030–2040 to be the most difficult phase of climate change policy, where the aim is to reach the lower and medium concentration levels (450 and 550 ppm), even assuming full participation of all countries under a climate regime, with rapidly increasing emission reduction rates and increasing abatement costs. It seems that emission pathways that focus on the 550 ppm target will soon lose the option of shifting towards stabilising at 450 ppm. Specifically, this could be as early as 2015, if the boundaries on maximum reduction rates assumed here are not exceeded. Hedging strategies may lead to relatively early action pathways focusing on 450 ppm, in order to leave as many options open as possible.

7 Stabilising greenhouse gas concentrations

D.P. van Vuuren, M.G.J. den Elzen, P.L. Lucas, B. Eickhout, B.J. Strengers, B. van Ruijven, S. Wonink, R. van Houdt

7.1 Introduction

Climate change appears to be among the most prominent sustainability problems of this century. The Third Assessment Report of the Intergovernmental Panel on Climate Change 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 larger, with expected increases in global temperature in the 2000–2100 period, ranging from 1.4°C to 5.8°C (IPCC, 2001). Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC) states as its ultimate objective: 'Stabilisation 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°C–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, 2005). 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 may, in their interpretation, weigh factors like the risks of climate change as functions of temperature increase, but also factors like adaptation costs and limits, 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 values for climate sensitivity that still have a reasonable likelihood (for example, Wigley and Raper, 2001; Murphy, 2004). Several authors indicated that these PDFs can be translated into a risk approach towards 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 stabilisation at low GHG concentrations (for instance, a probability greater than 50% requires stabilisation at least below 450 ppm CO_2-

eq).[55] The stabilisation 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 that aim to identify mitigation strategies for achieving different levels of GHG emission reductions have been published (see, for example, 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 disregarded abatement options that reduce non-CO_2 gases and the use of carbon plantations. Furthermore, the number of studies looking at stabilisation levels below 550 ppm CO_2-eq. is very limited. There are a few studies that explore the feasibility to stabilise CO_2 alone at 350–450 ppm CO_2; the lowest multi-gas stabilisation studies in literature focus on 550 ppm CO_2-eq. (see section 2). This implies that very little information exists on mitigation strategies that could stabilise 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 stabilising at 550 ppm CO_2-eq. is far lower than for higher stabilisation targets (see Morita et al., 2000; 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 reduction, such as hydrogen and carbon capture and storage (CCS) (Edmonds et al., 2004; IEA, 2004a; 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 stabilise GHG emissions at low levels (Morita and Robinson, 2001; Metz and Van Vuuren, 2006).

This paper explores different multi-gas stabilisation 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 stabilisation 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.). As such, the study also goes beyond our own research that has not covered stabilisation scenarios below 550 ppm CO_2-eq. (Van Vuuren et al., 2006b).[56] The paper adds to the existing literature in an important way by exploring pathways to those GHG stabilisation 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 stabilising GHG concentrations at 650, 550 and 450 ppm CO_2-eq. and below?

[55] 'CO_2 equivalents' expresses the radiative forcing of other anthropogenic radiative forcing agents in terms of the equivalent CO_2 concentration that would result in the same level of forcing. In this paper, the definition of CO_2-eq. concentrations includes the Kyoto gases, tropospheric ozone and sulphur aerosols.

[56] Earlier we published emission profiles that would lead to stabilisation 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).

- 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 of this paper will be on mitigation strategies, abatement costs and climate consequences from a global perspective. In a related paper, we focused on the regional costs and abatement strategies[57] (Den Elzen et al., 2006a). For costs, we considered direct abatement costs due to climate policy and do not capture macro-economic costs; for benefits we focused on the impact on global mean temperature and co-benefits for air pollutants. In our analysis, we deliberately used an integrated approach, dealing with a wide range of issues that are relevant in the context of stabilisation scenarios, including land-use consequences and changes in the energy system. Although several of these issues have been studied earlier for single stabilisation scenarios, here we would like to see how they are related to the GHG stabilisation 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 description, see section 7.3). A similar framework (using FAIR instead of FAIR–SiMCaP) has been used to study mitigation strategies, for example in the context of EU climate policy targets (Criqui et al., 2003; Van Vuuren et al., 2003). 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), covering not only the energy sector but also land use, forestry and industry. It is therefore suitable for studying the type of mitigation strategies required to stabilise radiative forcing from GHG and for studying the possible environmental and economic consequences of such strategies. We use this framework to explore stabilisation strategies based on three different baseline scenarios – updated implementations of the IPCC SRES B2, B1 and A1b scenarios. We perform an extensive sensitivity analysis for the different options to map out some of the main uncertainties.

We first provide a brief overview of earlier work on stabilisation scenarios. We then explain the methods used to develop the new scenarios before discussing the first results from our three default scenarios and the associated benefits and co-benefits. Next, we 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. We continue by comparing our results to earlier studies and examine the implications of the uncertainties that have been identified. Finally, we present our overall findings.

[57] Regional costs also depend on possible agreements about regional reduction targets and they therefore constitute a separate topic that cannot be dealt with in the context of this paper.

7.2 Earlier work on stabilisation scenarios

A large number of scenario studies have explored global mitigation strategies for stabilising 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).[58] In the literature on mitigation scenarios, there are several recurring themes. These include:

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

In this paper, we will briefly discuss the available literature and indicate how these issues are handled. The IPCC Third Assessment Report (TAR) (Hourcade and Shukla, 2001; Morita and Robinson, 2001) provides an overview of the stabilisation scenarios as available at that time.

On the issue of stabilisation targets, many studies in the past have focused on stabilising CO_2 concentration levels. Consistent with this, new multi-gas studies focus mostly on the comparable measure for the stabilisation of radiative forcing (expressed in W m^{-2} or CO_2-eq.) (Van Vuuren et al., 2006c). 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) stabilising 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 will involve lower costs than the corresponding stabilisation scenarios. For the lower stabilisation 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 stabilisation levels from 750 to 450 ppm CO_2 for 'CO_2-only' studies. There are only a few studies that have looked into

[58] 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, mitigation or stabilisation 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 these may still unintentionally have a significant impact on GHG emissions (e.g., other environmental policies, trade policies). Mitigation scenarios (or climate policy scenarios) purposely assume climate policies to explore their impact. Stabilisation scenarios are a group of scenarios that include mitigation measures intended to stabilise atmospheric GHG concentrations.

stabilising concentrations at low concentration levels. Exceptions include the work of Nakicenovic and Riahi (2003), Azar et al. (in press) and Hijioka et al. (in press). These studies show that, in principle, low stabilisation levels (below 450 ppm CO_2) can be achieved at mitigation costs in the order of 1-2% of Gross Domestic Product (GDP). However, both studies started from relatively low-emission baseline scenarios.

In multi-gas studies, the range is actually much more limited, with studies typically only looking at 650 ppm CO_2-eq. (Van Vuuren et al., 2006c; Weyant et al., in press). The lowest scenarios currently found in the literature aim at 550 ppm CO_2-eq. (Criqui et al., 2003; Van Vuuren et al., 2006b) and these only give a very low level of probability to limit 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 for such low stabilisation levels are emission pathway studies that do not specify the type of mitigation measures leading to the required emissions reductions (Den Elzen and Meinshausen, 2005; Meinshausen, 2006; Meinshausen et al., in press).

Different measures are used for the costs of climate policies. Partial equilibrium models (such as energy system models) 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, by contrast, generally report reductions of GDP or private consumption relative to the baseline scenario. For the 30–40 stabilisation scenarios analysed in TAR, the assessment revealed very small costs for stabilising at 750 ppm but stated typical GDP losses of 1–4% for 450 ppm (Hourcade and Shukla, 2001). Costs were found to be a function of the GHG stabilisation 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 stabilisation 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 postponed abatement action compared to earlier pathways developed by the IPCC and were more cost-effective because of the benefits of technology development, more CO_2 absorption by the biosphere and ocean, and discounting future costs. Their arguments were confirmed in the analysis of the EMF-14 (Energy Modelling Forum) study (as reported by (Hourcade and Shukla, 2001). Other authors, however, responded that this conclusion would depend on the assumptions about discounting, technological change, inertia and uncertainty (Ha-Duong et al., 1997; Azar, 1998; Azar and Dowlatabadi, 1999). For low-range concentration targets, Den Elzen and Meinshausen (2005) reported that delaying the peak in global emissions beyond 2020 leads to very high reduction rates later in the century and therefore to probable high costs. Assuming 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 going on, 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, much 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 Modelling 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., 2006c; Weyant et al., in press). 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^{-1} (IPCC, 2005) and therefore reduce mitigation costs considerably (Edmonds et al., 2004; IEA, 2004a). Recent work on hydrogen as an energy carrier has shown that hydrogen may also reduce mitigation costs but this conclusion depends very much on the assumption of technology development (Edmonds et al., 2004). Bioenergy in combination with CCS could be an attractive technology if very ambitious stabilisation targets are adopted (Azar et al., in press). Finally, there is still an ongoing debate about whether accounting for technological change (induced learning compared with exogenous assumptions) in itself results in different conclusions about optimal climate policies. Some studies claim that induced technological change leads to very significant cost reductions and justifies a preference for early action (Azar and Dowlatabadi, 1999; 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 of this study is to determine whether a multi-gas approach can be used to achieve the stabilisation of GHG concentrations at lower levels than those usually considered in mitigation studies. Our scenarios, based on the emission pathways developed by Den Elzen and Meinshausen (2005) and Den Elzen et al. (2006b) should be characterised as medium-term pathways (since they are neither early nor delayed). However, we will also analyse one early-action and one delayed-response case for 550 ppm CO_2-eq. In terms of the objective of climate policy, we focus on the stabilisation of concentration (and thus not temperature) to increase the comparability with other studies. Den Elzen et al. (2005) indicate how the results of the emission pathways compare to alternative peaking scenarios. In view of the debate on new mitigation options, the model framework used in this study covers a large range of mitigation options (such as non-CO_2, CCS, carbon plantations, hydrogen, bioenergy, nuclear, solar and wind power), and several technologies are described in terms of induced technological change. The aim of this study is to identify a portfolio of measures that contribute to the reduction of emissions with the aim of achieving the selected concentration targets, and to assess the costs associated with this portfolio. Given the major uncertainties involved in each of the mitigation options, we will analyse how some of these uncertainties impact the overall results.

7.3 Methodology

7.3.1 Overall methodology

For the construction of the stabilisation scenarios, we use an interlinked modelling framework consisting of the IMAGE 2.3 integrated assessment model (IMAGE-team, 2001b), which includes the TIMER 2.0 energy model (De Vries et al., 2001) coupled to the climate policy model FAIR–SiMCaP (Den Elzen and Lucas, 2005; Den Elzen and Meinshausen, 2005).[59] These models have been linked for the purposes of this analysis in a way similar to that described earlier by Van Vuuren et al. (2003),[60] as shown in Figure 1. Appendix F provides additional information on the different models used.

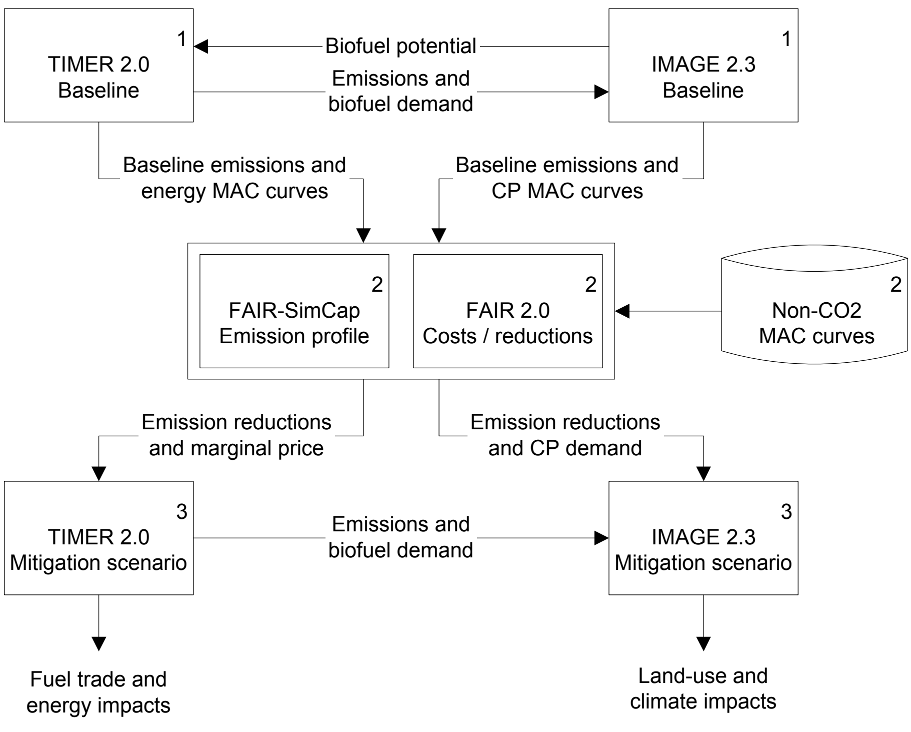


Figure 7-1 Linkage and information flows of the applied modelling framework (note CP = carbon plantations).

[59] IMAGE 2.3 is an updated version of IMAGE 2.2, the difference being the possibility of exploring impacts of bioenergy and carbon plantations. TIMER 2.0 is an updated version of TIMER 1.0. The main differences are additions with respect to hydrogen, bioenergy and modelling of the electric power sector. The FAIR–SiMCaP model is the combination of the climate policy support tool FAIR and the SiMCaP model.

[60] In the present framework, FAIR–SiMCaP is used for the calculations of the global emission pathways instead of the IMAGE 2.2 model.

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 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 the grid level. At the 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, part 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–SiMCaP 1.1 model is a combination of the multi-gas abatement-cost model of FAIR 2.1 and the pathfinder module of the SiMCaP 1.0 model. 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).[61] The SiMCaP pathfinder module uses an iterative procedure to find multi-gas emission pathways that correspond to a predefined climate target (Den Elzen and Meinshausen, 2005). Calculations in all three main models are done for 17 regions of the world.[62]

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

Construct a baseline emission scenario using both the IMAGE and the TIMER model. 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.

Develop global emission pathways that lead to a stabilisation of the atmospheric GHG concentration using the FAIR–SiMCaP 1.1 model. The concentration calculations are done using the MAGICC 4.1 model that is included in the FAIR-SiMCaP 1.1 model. (Wigley and Raper, 2001). 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, an approach consistent with climate policies under the Kyoto Protocol and US domestic climate policy (White House, 2002). Furthermore, the model calculates the international permit price, the regional emission reductions, and the global and regional costs of emission reductions.

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.

---

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

[62] Canada, the 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), Southeast Asia and East Asia (incl. China) (IMAGE-team, 2001a).

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

7.3.2 Baseline emissions

The baseline scenarios used in this study are based on IPCC SRES scenarios (Nakicenovic et al., 2000b). This set of baseline scenarios explores different possible pathways for GHG emissions and can roughly be categorised along two dimensions: the degree of globalisation compared to regionalisation, 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, 2001b). Although the scenarios are still broadly consistent with the literature, new insights have emerged for some parameters. For instance, population scenarios and economic growth assumptions for low-income regions are now generally lower than assumed in SRES (Van Vuuren and O'Neill, in press). 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.

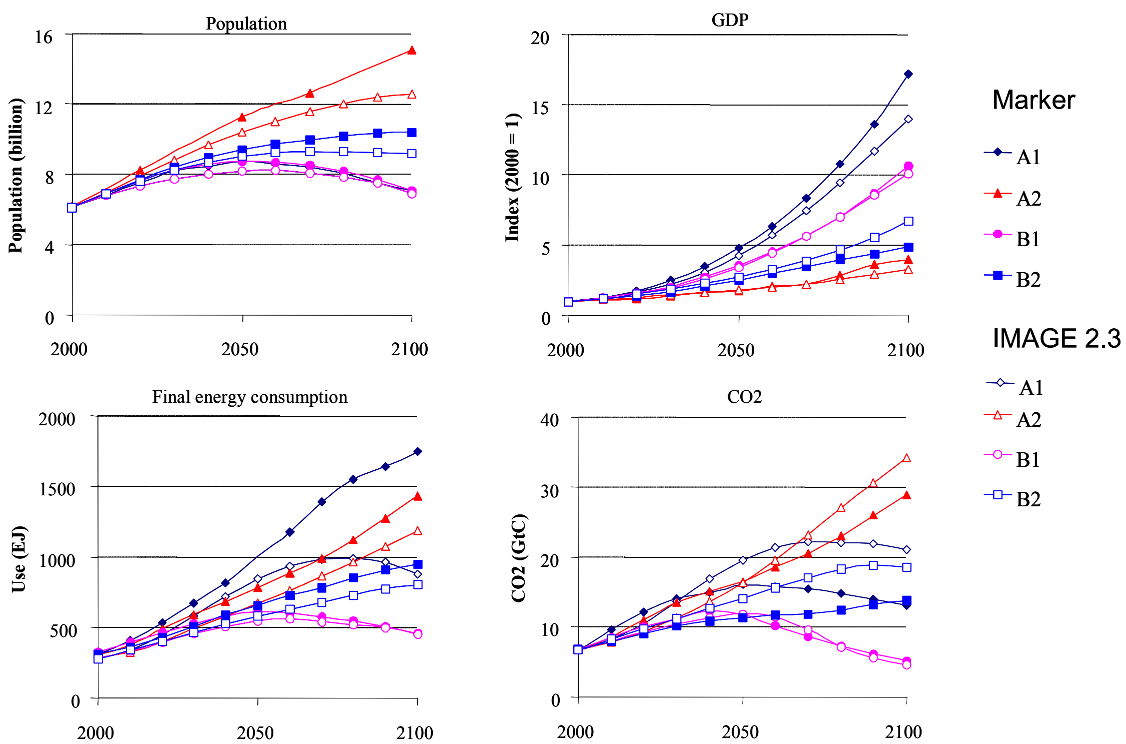


Figure 7-2 Driving forces and fossil fuel CO_2 emissions of the IMAGE 2.3 SRES scenarios in comparison to the IPCC SRES Marker scenarios (Nakicenovic et al., 2000a).

The new implementation of the B2 scenario 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 roughly follows the reference scenario of the World Energy Outlook 2004 for the first 30 years (IEA, 2004b). After 2030, economic growth converges to the B2 trajectory of the previous IMAGE scenarios (IMAGE-team, 2001b). 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 globalisation and rapid technology development. As the scenario also assumes material-intensive lifestyles, energy consumption grows rapidly. The B1 scenario describes a world characterised by strong globalisation 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, respectively, the Global Orchestration and Techno-garden scenarios of the Millennium Ecosystem Assessment (MA, 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 are based on the earlier implementation of the SRES scenarios.

7.3.3 Assumptions in the different subsystems and marginal abatement costs

We adopt a hybrid approach to determining the abatement efforts among the different categories of abatement options. Firstly, 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 than 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-SiMCaP.

The TIMER, IMAGE and FAIR-SiMCaP models have been linked so that output of one model is the input of the second model (see Figure 7.1). In addition, the model-specific assumptions in the different models have also been harmonised. 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 bioenergy calculations start with the same land-use scenario (implementation factors prevent them using the same land) and the same land price equations. A social discount rate of 5% yr^{-1} is used to calculate the net present value for the mitigation scenarios.

In the energy system, investment decisions are compared using a discount rate of 10% yr^{-1}, which provides a better reflection of the medium-term investment criteria used in making such investments. Table 7.1 summarises some of the assumptions made. All costs are expressed in 1995US$.

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 40% (i.e., 40% of maximum potential is used)	Carbon uptake increased by 25% + implementation factor increased to 50%
Non-CO_2	20% increase of costs; 20% decrease of potential	Expert judgment as described in Lucas et al. (2005). Total reduction potential of non-CO_2 gases slightly above 50%.	20% decrease of costs; 20% increase of potential.
Hydrogen	No hydrogen penetration	Default assumptions lead to hydrogen penetration by the end of the century	Optimistic assumptions for fuels cells and H_2 production costs (10% reduction of investment costs) lead to penetration around 2050
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.
Bioenergy	Less available land for bioenergy (50% less)		Bioenergy 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 US$ tC^{-1}.	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 do not improve as fast (following MA's Global Orchestration scenario).
Baseline	IMAGE 2.3 A1b	IMAGE 2.3 B2	IMAGE 2.3 B1
All	All of the above, excluding land use and baseline	All of the above, excluding land use and baseline	All of the above, excluding land use and baseline

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.[63] There are several responses in TIMER to adding an emission permit price. In energy supply, options with high carbon emissions (such as coal and oil) become more expensive compared to options with low or zero emissions (such as natural gas, CCS, bioenergy, nuclear power, solar and wind power). The latter therefore gain market share. In energy demand, investments in efficiency become more attractive. The induced reduction of CO_2 emissions is recorded for sight years from 2010 to 2100 (in ten-year steps). Two 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. Depending on the pathway of the actual permit price in the stabilisation scenario, FAIR combines the linear price MAC curves and the block price MAC curves.[64] In this way, it is possible to take into account (as a first-order approximation) the time pathway of earlier abatement.

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 (other sectors) (see De Beer, 1998).[65] In low-income countries, we assume that lower efficiency in industry and other sectors is 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 six to seven years. The difference between demand and supply investment criteria is based on historical evidence (barriers to demand-side investments 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, that could possibly 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, that is, 1000 US\$ tC-eq^{-1}.

---

[63] The 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 paper, 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 by other type of policies.

[64] FAIR looks 30 years back in time and, by comparing the tax profile in that period to the one assumed in the tax profiles used in TIMER, constructs a linear combination of the two types of response curves. A rapidly increasing tax in FAIR will lead to the use of the linear tax, while a more constant tax level in FAIR will imply the use of the block tax.

[65] 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 that are available to them that have shorter pay-back time periods than their official criterion. 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., in prep.). 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 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 that, under the SRES scenarios, the cumulative abandoned agricultural area ranges from 725–940 Mha in 2100, potentially sequestering 116–146 GtC over the century (the term agricultural land in this paper covers both crop and pasture land). The costs of the reductions vary over a wide range.

Non-CO_2 gases

For non-CO_2, the starting point of our analysis consists of the MAC curves provided by EMF-21 (Weyant et al., in press). 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 0–200 US$ tC-eq^{-1}, and does not include technological improvements over time. Lucas et al. (in prep.) have extended this set on the basis of a literature survey and an expert judgement about long-term abatement potential and costs (see also Van Vuuren et al., 2006b). The long-term potential is significantly higher than the current potential as a result of technology development and the removal of implementation barriers. The overall potential amounts to about 3 GtC-eq. yr^{-1} (with the lion’s share available below 200 US$ tC-eq^{-1}).

7.3.4 Emission pathways

This study uses the global multi-gas emission pathways that meet the GHG concentration stabilisation targets 450, 550 and 650 ppm CO_2-eq. (Den Elzen and Meinshausen, 2005). These are technically feasible emission pathways, as we calculated them using the MAC curves discussed above. In general terms, three main criteria were used when developing the pathways. Firstly, a maximum reduction rate was assumed reflecting the technical (and political) inertia that limits emission reductions. Fast reduction rates would require the early replacement of existing fossil-fuel-based capital stock, and this may involve high costs. Secondly, the reduction rates compared to the baseline were spread out over time as far as possible – but avoiding rapid early reduction rates. Thirdly, the reduction rates were only allowed to change slowly over time. The selected values are based on the reduction rates 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., in press). In the case of the 650 and 550 ppm CO_2-eq. pathways, the resulting pathway leads to stabilisation below the target level and without overshoot between 2100 and 2200. 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 stabilising at 450 ppm CO_2-eq. before 2200. This overshoot is justified by reference to present concentration levels, which are already substantial, and the attempt to avoid drastic sudden reductions in the emission pathways presented.

7.4 Stabilising GHG concentrations at 650, 550 and 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 also increase[66], from about 10 GtC-eq. today to 23 GtC-eq. in 2100 (Figure 7.3). Figure 7.3 also shows that compared to 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 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).

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

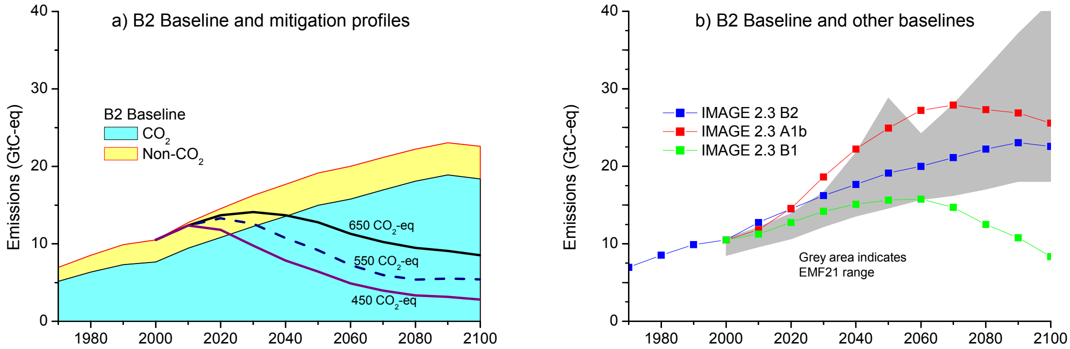


Figure 7-3 Global CO_2-eq. emissions (all sources[a]) for the B2 baseline emission and pathways to stabilisation at a concentration of 650, 550 and 450 ppm CO_2-eq. (panel a; left) and the B2 baseline emissions compared to alternative baselines (panel b; right).

[a] For the EMF-21 scenarios (Van Vuuren et al., 2006c;Weyant et al., in press).

Figure 7.3a shows that, in order to reach the selected emission pathway that leads to stabilisation 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 stabilise at a level that is 40% above current emissions in the next three to four 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 stabilisation at 450 ppm CO_2-eq., short-term reductions become even more stringent, with global emissions peaking around 2020 at a level of 20% above 2000 levels.

7.4.2 Abatement action in the stabilisation scenarios

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 the short term, in all stabilisation scenarios, a substantial share of the reduction is achieved 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 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). Alternative approaches, for example, long-term cost optimisation under a radiative forcing target, may result in a different mix (Van Vuuren et al., 2006c). 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).

Table 7-2 Emissions in 2000 and in 2100 for the B2 baseline and the stabilisation scenarios.

	2000	2100			
		Baseline	Stabilisation Scenarios (ppm CO_2-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**

More detailed analysis across the different sources shows that, for CH_4, relatively large reductions are achieved with landfills and the production of coal, oil and gas. In total, under the 450 ppm CO_2-eq. stabilisation scenario, emissions are reduced by 70% compared to the baseline. In the less stringent 650 ppm stabilisation 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 most stringent 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.

The use of carbon plantations contributes about 0.9 GtC yr^{-1} 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 yr^{-1}). In 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 is not shown in figures – but can be found in Strengers et al. (in prep.)). The trees used vary according to the location and include *Populus Nigra* (East Asia and Europe), *Picea Abies* (Canada, the USA and the former Soviet Union) and *E. Grandis* (South America, Central Africa and Indonesia). In all three scenarios, high sequestration rates (more than 0.1 GtC yr^{-1}) are achieved only after 2030–2035 due to limited land availability early on. Some of the mitigation by carbon plantations can be achieved at relatively low costs – and form a substantial part of the potential used in the 650 ppm CO_2-eq. stabilisation scenario. The potential of carbon plantations does depend more on external assumptions (e.g., the implementation fraction) than on the stabilisation target.

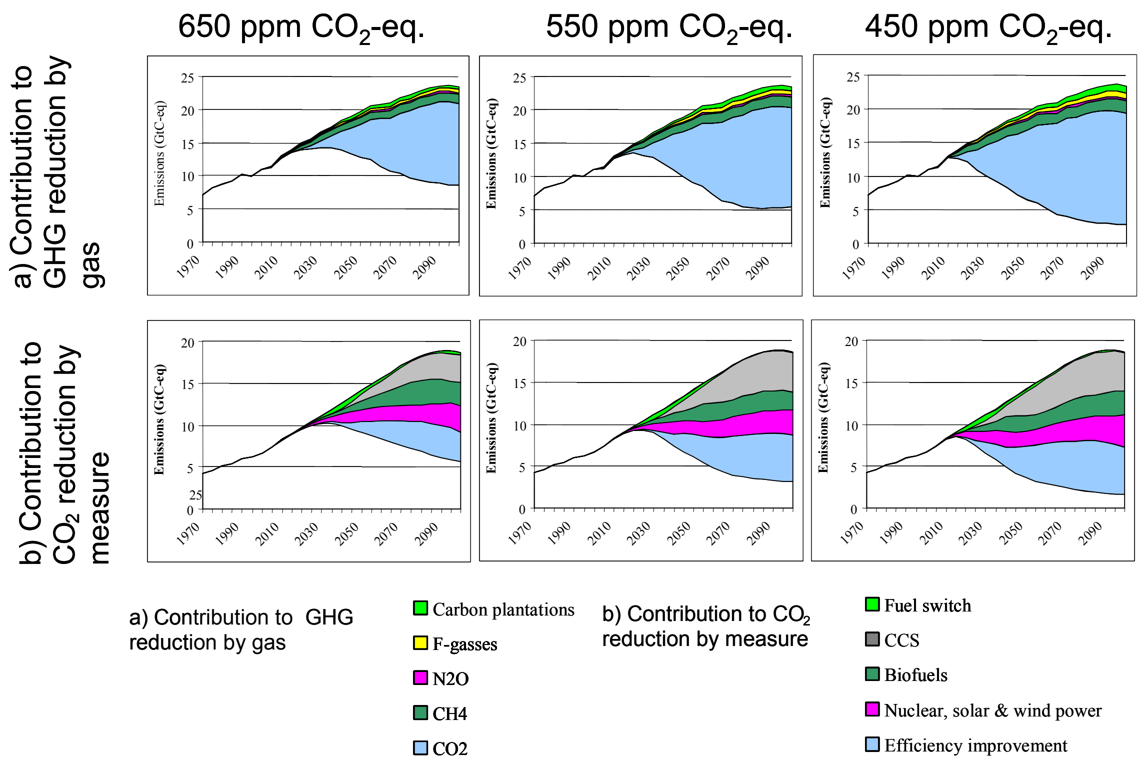


Figure 7-4 Emission reductions for total GHG emissions contributed by gas (upper panel; a) and for energy CO_2 emissions contribute by reduction measure category (lower panel; b) applied to stabilisation scenarios at 650, 550 and 450 ppm CO_2-eq.

Abatement action in the energy system

Figure 7.5 shows that the climate policies required to reach the stabilisation 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%. 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 that use CCS. There is also a substantial reduction for oil. Reductions for natural gas are less substantial, while other energy carriers – in particular solar, wind and nuclear-based electricity and modern biomass – gain market share.[67]

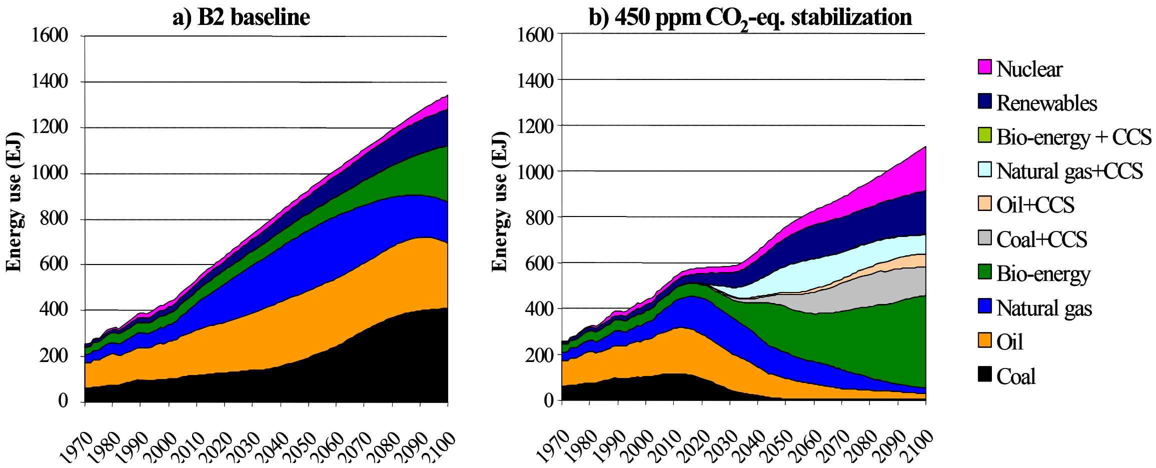


Figure 7-5 Primary energy use in the B2 baseline (left; panel a) and the 450 ppm CO_2-eq. stabilisation scenario (right; panel b). Note: Nuclear, solar, wind and hydro power have been reported at a virtual efficiency of 40%; bioenergy includes traditional biofuels; renewables include hydro, solar and wind power.

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., 2002). In the more densely populated regions, we find that under our medium assumptions reservoirs from depleted fossil fuel resources will be filled

[67] Modern biomass includes gaseous or liquid fuels produced from plants or trees. It differs from traditional biomass (gathered wood, straw, dung, charcoal, etc.).

near the end of the century so that these regions will also use aquifers as a storage option.[68] 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 aquifer capacity is uncertain.

Bioenergy use also accounts for a large proportion of the emission reductions. In the baseline scenario of this study about 200 EJ of bioenergy are used. In the most stringent stabilisation scenario, bioenergy use increases to 350 EJ. In terms of crops, the bioenergy is produced from a mixture of crops (sugar cane, maize and woody bioenergy depending on the region). The use of bioenergy requires land where, in the baseline, there would be natural vegetation sequestering carbon. The decrease in carbon sequestration by bioenergy production compared to natural vegetation regrowth amounts to about 1-5 kg C per GJ of bioenergy produced, depending on the region and biome (this number represents the annual average across the whole scenario period, by taking the cumulative bioenergy production and the cumulative difference in carbon uptake between the land used for bioenergy 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 shown in Figure 7.4 indicates the net contribution.

Solar, wind and nuclear power also account for a considerable proportion of the required reductions. 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 scenario both categories increase their market share. For hydropower, we assumed no response to climate policy (given the fact that in the baseline most regions are already approaching their maximum potential levels – and 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, in the model the increase in nuclear power 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 in the century – but a much smaller share compared to the baseline later. The main reason for the decreasing impact is that cost reductions of zero-carbon energy supply options reduce the effectiveness

[68] In our analysis we have used the reservoir estimates as estimated by Hendriks *et al.* 2002, including their estimates for aquifers. Hendriks *et al.* (2002) restricted the potentially available storage capacity in aquifers severely 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.

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. The contribution of efficiency does vary strongly by region and over time. In Western Europe, for instance, in the model the annual rate of real efficiency improvement in the baseline is about 1.1% yr^{-1} in the first half of the century, and 0.8% yr^{-1} over the century as a whole (these numbers refer to the underlying efficiency indicators in the model, not to the energy intensity (energy over GDP) that improves 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% yr^{-1} and 1.0% yr^{-1} 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% yr^{-1} in the first 40 years and 1.8% yr^{-1} over the century. Climate policies could push up these numbers to 2.9% yr^{-1} and 2.1% yr^{-1} respectively.

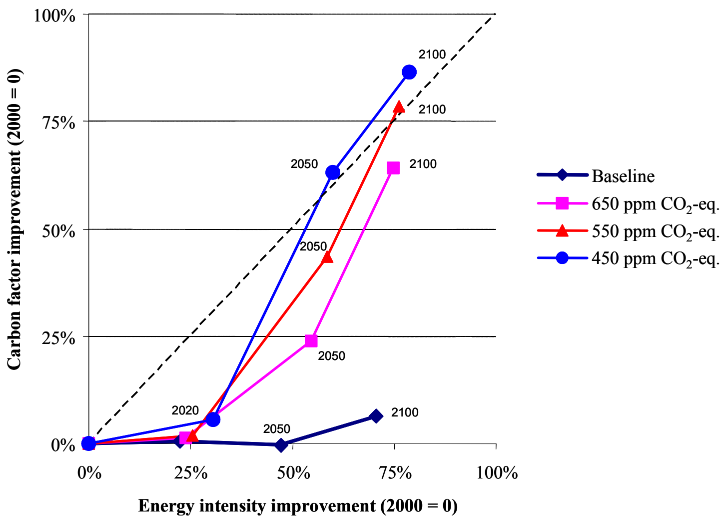


Figure 7-6 Relative changes in global energy intensity (energy/GDP) and the carbon factor (CO_2/energy) in the B2 baseline and the three mitigation cases compared to 2000 values. Note: The diagonal line indicates equal reduction in the energy intensity and carbon factor compared to 2000. Values are indicated for all the scenarios: 2020, 2050 and 2100. The ovals indicate the outcomes of the mitigation cases for similar years.

An alternative way to look at these data is to use the Kaya indicators of energy intensity (US\$ GJ^{-1}) and the carbon factor (kg C per 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 decades that some de-carbonisation occurs as high oil prices induce a transition to bioenergy. 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 (kg C per GDP). 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 (this can be seen in Figure 7.6 since the mitigation scenario 2020 points move parallel to the diagonal in the figure compared to the baseline scenario points), changes in the carbon factor compared to the baseline (in other words, changes in energy supply) in 2050 and 2100 contribute much more to lower emission levels than energy intensity. Under the 450 ppm scenario, the carbon factor decreases by about 85% compared to baseline by the end of the century.

7.4.3 Costs

Abatement costs

As cost metrics, we will focus on marginal permit prices and abatement costs. The latter are calculated on the basis of the marginal permit prices and represent the direct additional costs due to climate policy, but do not capture macro-economic costs (nor the avoided damages of climate change). Figure 7.7 shows that the scenarios involving stabilisation at 650 and 550 ppm CO_2-eq. ppm are characterised by a rather smooth increase in the marginal price followed by a drop by the end of the century. The latter 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 stabilisation scenario, the marginal price rises steeply during the first part of the century – reaching a marginal price of over 600 US$ tC-eq^{-1} by 2050 – and finally stabilises at 800 US$ tC-eq.$^{-1}$ by the end of the century. The high marginal 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 permit prices of 'only' 200–300 US$ tC-eq^{-1}.

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. stabilisation 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 stabilising climate costs due to a somewhat lower permit price and a stabilising emission gap between the baseline and the mitigation scenario. The same trend is observed for the other stabilisation scenarios, although at higher costs. The abatement costs of the 550 ppm CO_2-eq. stabilisation scenario increase to 1.2% of GDP, while the abatement costs of the 450 ppm CO_2-eq. stabilisation scenario increase to 2.0% of 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 waste-water management).

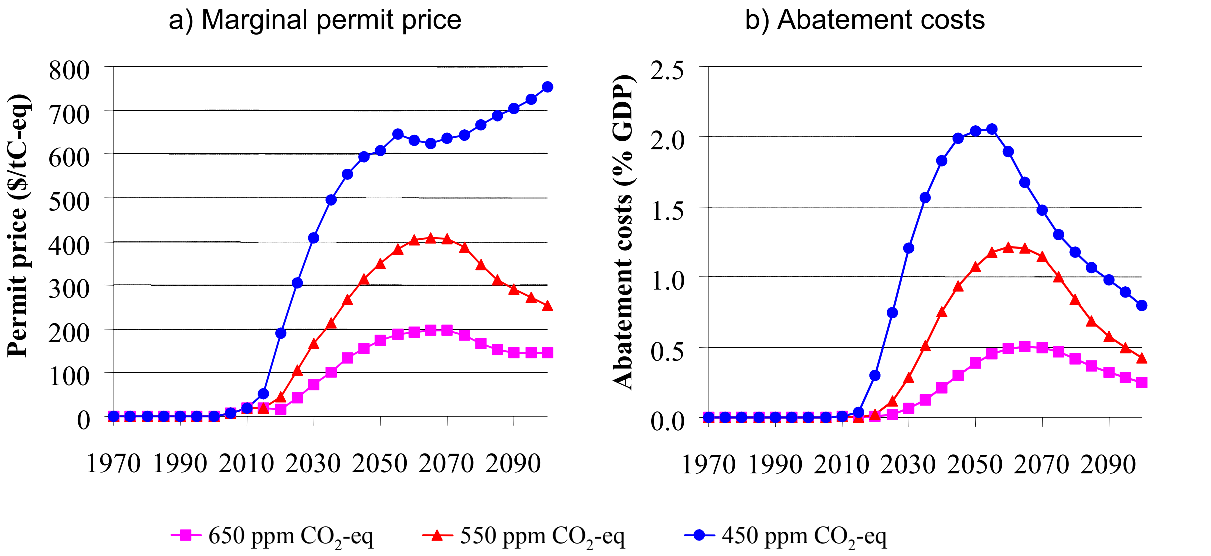


Figure 7-7 Marginal carbon-equivalent price for stabilising greenhouse gas concentrations at 650, 550 and 450 ppm CO_2-eq. from the B2 baseline (left; panel a) and abatement costs as a percentage of GDP for these scenarios (right; panel b).

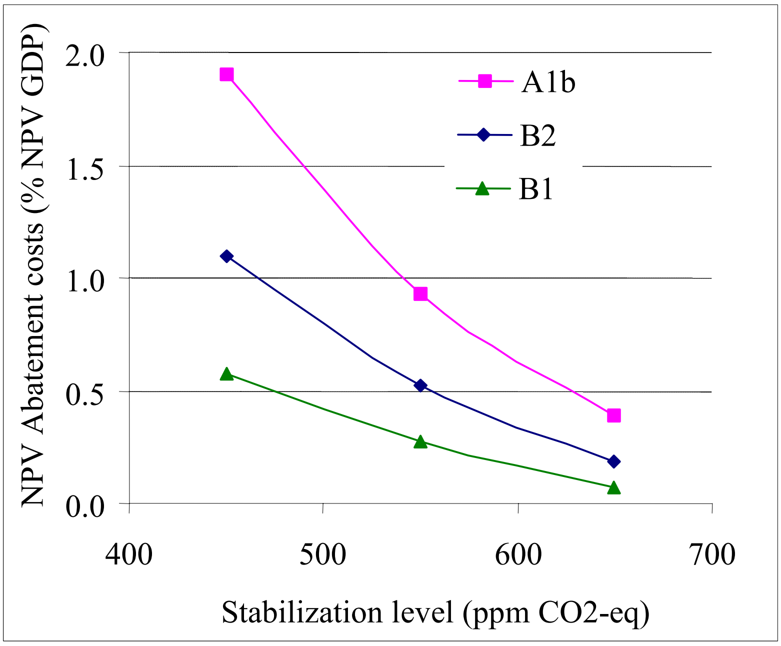


Figure 7-8 Net present value (NPV) of abatement costs for different stabilisation levels as percentages of the NPV of GDP, starting from different baseline scenarios (discount rate 5%).

The net present value of the abatement costs follows a similar trend (across the different stabilisation 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 stabilisation at 650 ppm to 1.1% of GDP in the 450 ppm case.

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.

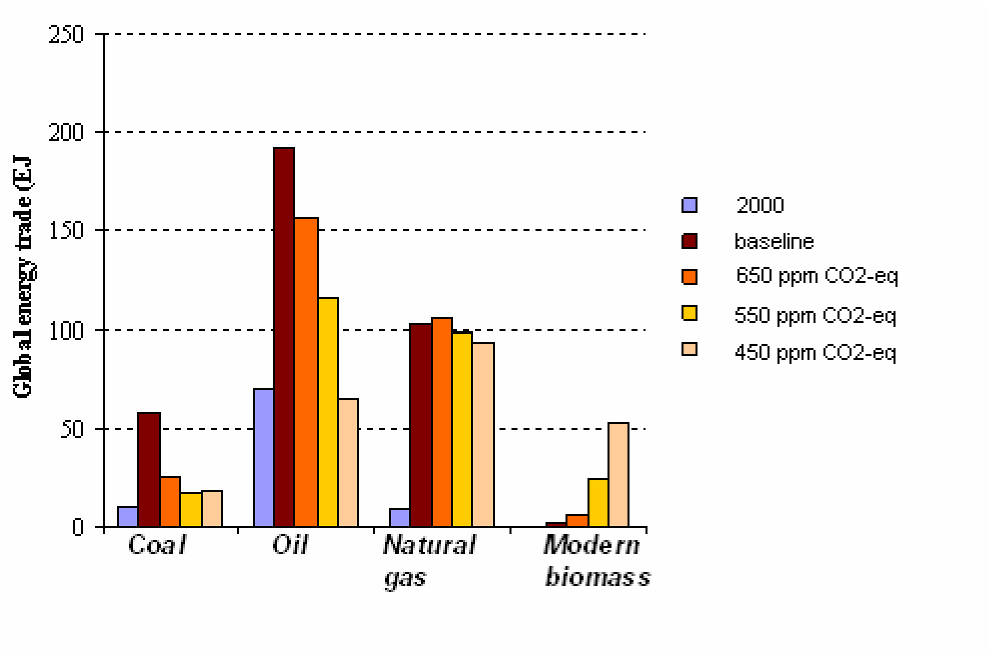


Figure 7-9 World volume of fuel trade between the 17 world regions (EJ) for year 2000, baseline (B2) and stabilisation scenarios (650, 550 and 450 ppm CO_2-eq.).

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 area is the role played by the bioenergy trade. This trade increases substantially and major exporting regions (including, for instance, South America and the former Soviet Union) could benefit from this. Currently, oil-importing regions (such as the USA, Western Europe and Asia) could become major bioenergy importing regions.

7.5 Benefits and co-benefits

7.5.1 Climate benefits of stabilisation

The three multi-gas stabilisation scenarios analysed here lead to clearly different temperature increases, both during this century and in the long run. 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. stabilisation scenarios are still approaching the stabilisation 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 stabilisation scenarios in the literature.

Table 7-3 Overview of several key parameters for the stabilisation scenarios explored.

	2100 Concentration (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

It should be noted, however, that the temperature results of the different stabilisation scenarios do depend to a considerable extent on the uncertain relationship between the GHG concentrations and temperature increase. This implies that impacts on temperature 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 stabilisation levels explored in this paper (the corridor shown is a result of the fact that Meinshausen considered several PDFs published in the literature). In the case of a 2°C target, the 650 ppm scenario gives a probability of meeting this target between 0–18% depending on the PDF used. By contrast, the 450 ppm scenarios result 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%; 450 ppm a range from 40–90%.

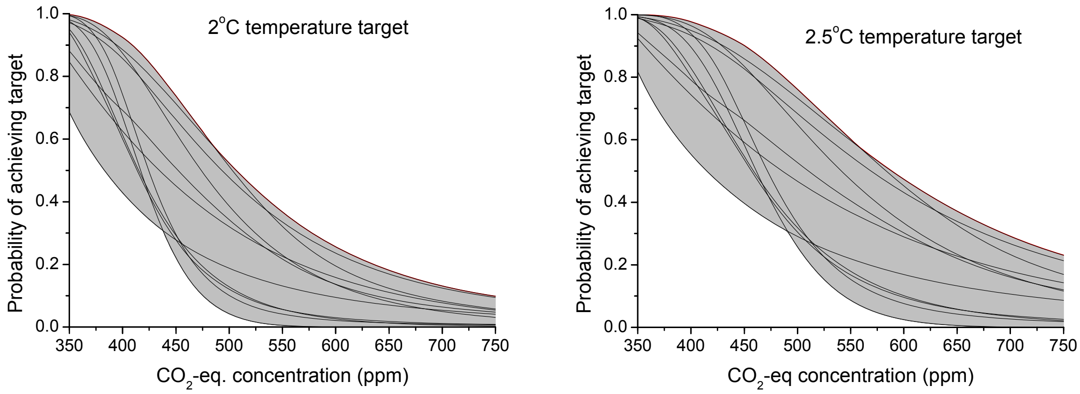


Figure 7-10 Probability of equilibrium temperature change staying within the 2°C or 2.5°C limit compared to the pre-industrial level for different CO_2-eq. concentration levels (following calculations of (Meinshausen, 2006). Note: The lines indicate the probability function as indicated in the individual studies quoted by (Meinshausen, 2006); the grey area indicates the total range between the highest and lowest study.

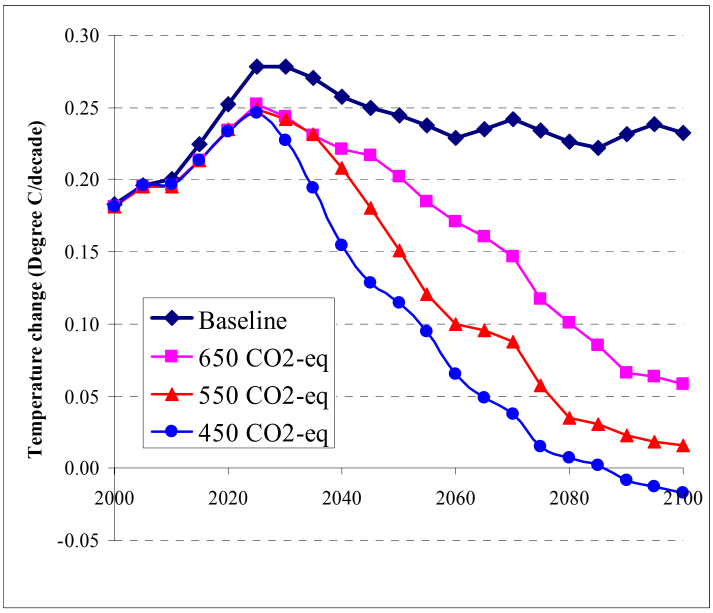


Figure 7-11 Rate of temperature change for 2000–2100 assuming a 2.5ºC climate sensitivity.

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, in particular in the second half of the century. In the 650 ppm stabilisation scenario, the rate drops below 0.2°C per decade around 2050 and below 0.1°C in 2080. In the 550 and

650 stabilisation 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 (until 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 sulphur cooling (as already emphasised by Wigley (1991).[69] According to 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 here is mostly due to the increased potential to reduce non-CO_2 GHGs, in combination with the higher overall rates of GHG emission reductions. 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., 2006c). As reducing CH_4 is much less coupled to reducing sulphur 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 sulphur cooling. This is somewhat comparable to the 'alternative' mitigation scenario suggested by Hansen et al. (2000).

7.5.2 Co-benefits and additional costs

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 at the 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 at all scales. Current studies indicate that, when climate policies are in place, in the short-term (in particular the Kyoto period) potential co-benefits could be substantial, with financial savings in the order of 20–50% of the abatement costs of the climate policy (e.g., Van Vuuren et al., 2006a). 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), and simply quantifying the impact of changes in the energy system on emissions.

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-fuel-fired power plants and reducing oil inputs into transport and replacing them with either fossil-fuel 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 emission reductions are smaller than those of CO_2. The figures show that there are clear co-benefits for regional

[69] The impact of sulphur emissions on temperature increase is calculated in IMAGE based on the pattern scaling methodology that was developed by (Schlesinger et al., 2000).

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.

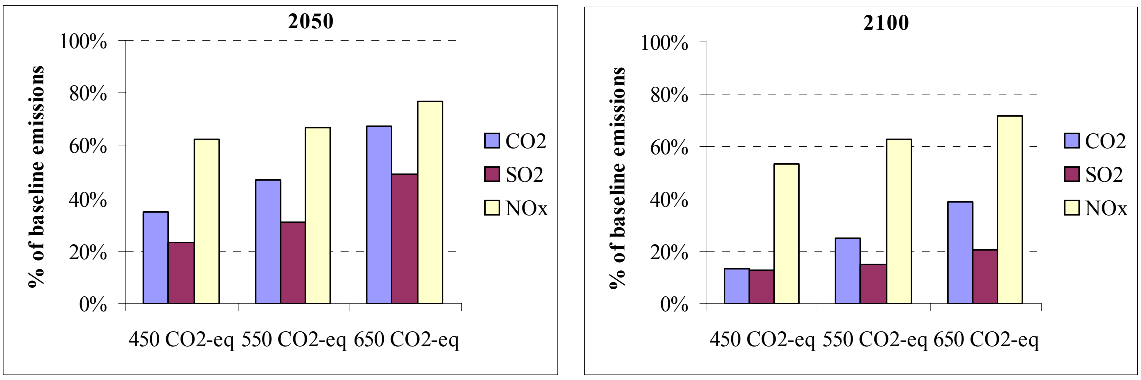


Figure 7-12 Reduction of CO_2 emission compared to the baseline (baseline = 100%) in the three B2 stabilisation scenarios compared to reductions of SO2 and NOx emissions compared to baseline (2050 on left; 2100 on right).

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 bioenergy crops the modelling 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. In our scenarios significant amounts of agricultural land 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 stabilising food demand (due to a stabilising population) and continuing yield increases (IMAGE-team, 2001b; 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 scenario. The scenarios described here are based on the yield improvements reported in the Millennium Ecosystem Assessment (Carpenter and Pingali, 2005).

In the mitigation scenarios, the most significant change compared to the baseline is the increased demand for land for bioenergy: from 3.9 million km^2 in the baseline scenario to 9.3 million km^2 in the 450 ppm CO_2-eq. stabilisation scenario. This means that the bioenergy 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., in prep.). It should be noted that the agricultural land area for food and feed crops increases slightly, simply because some of the more productive areas are now used for either bioenergy or carbon plantations. 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 stabilisation scenarios as most of the bioenergy and carbon plantation potential is also used as part of the portfolio for stabilisation 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 bioenergy production and carbon plantations is mostly abandoned agricultural land (including both crop and pasture land), with also a considerable area coming from natural grass land. In the former case, at best secondary forest would 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 biodiversity, therefore, is likely to be much smaller than the reduction suggested by looking at the land-use impacts alone.

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 CO_2-eq	550 ppm CO_2-eq	450 ppm CO_2-eq
Agricultural Land	43.5	44.7	45.3	45.6
Land for Bioenergy	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

7.6 Uncertainties in stabilising emissions

In the discussion of existing literature in Section 7.2, it was concluded that several categories of uncertainties can substantially influence the results of stabilisation scenarios. Here, we will discuss two of these: the baseline scenario and the 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 led to higher and lower emissions respectively. Hourcade and Shukla (2001) showed the baseline to be just as important for mitigation costs as stabilisation 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 – little international cooperation and little focus on environmental issues – provides a very unfavourable 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 in 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 stabilisation levels are larger for the A1b scenario and smaller for the B1 scenario (see also Figure 7.3).

The costs of stabilisation from these baselines for the low-range stabilisation targets explored in this study are shown in Figure 7.8. As expected (based on the 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 stabilisation cases are about double the costs of the corresponding B2 cases. By contrast, for B1, the costs of stabilisation are substantially lower. In addition, across the range considered here, costs rise more slowly for B1 than in A1b and B2 as a result of the smaller absolute gap between baseline emissions and the emissions under the stabilisation case, the high technology development rate and the resulting lower marginal 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, changes in implementation barriers and fundamental changes in the system as a whole; these may either assist or hinder certain reduction measures. 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. stabilising 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 includes 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 two. 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; Ruijven et al., in prep.). In the analysis, 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).

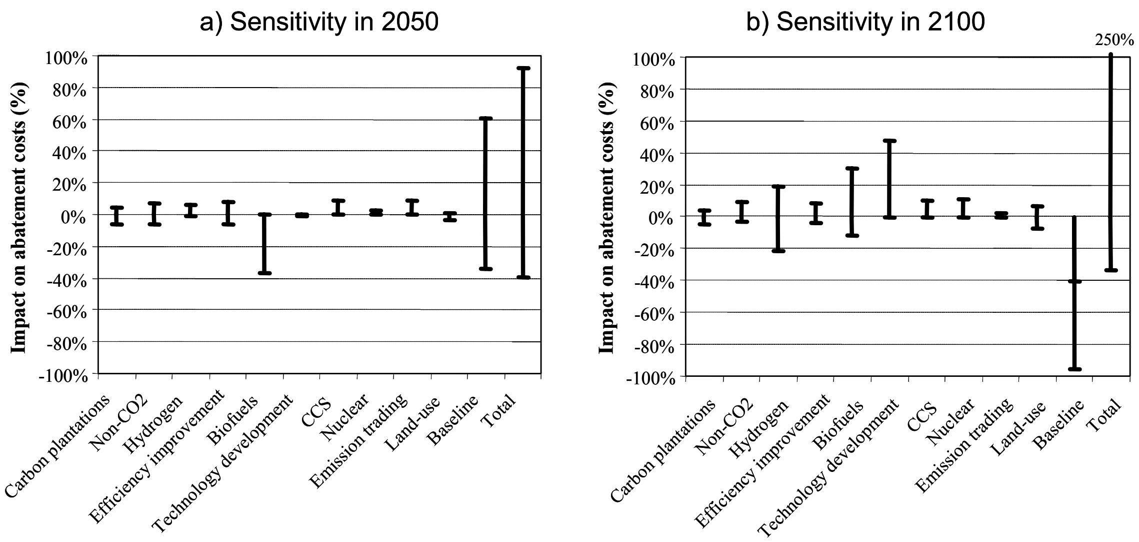


Figure 7-13 Impacts of different uncertainties on global abatement costs as a percentage of GDP for stabilisation at 550 ppm CO_2-eq., 2050 (left) and 2100 (right) (the column total is restricted to those assumptions that only impact the stabilisation scenario; it therefore does not include the impacts of baseline and land use).

Another important uncertainty concerns the potential of, and technology used for, bioenergy. As shown by Hoogwijk (2004), the uncertainty relating to bioenergy supply results in figures for potential use of between 100 and 800 EJ. In our central assumptions, the bioenergy use is about 400 EJ. We have lowered supply in our sensitivity runs for the pessimistic case. Azar et al. (in press) 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 case of restricted bioenergy supply). The influence of BECS is relatively low in the long run as the analysis is done for the 550 ppm stabilisation scenario – for which the reduction requirement in the long run 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 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 stabilisation scenarios includes the large-scale use of CCS and nuclear power. For both options, not only technological uncertainties play an important role, but also social acceptability (for instance, at the moment several countries have indicated that they do not plan to build new nuclear power plants). In this context, as a form of sensitivity analysis, we excluded both options (one by one). In each case, 2100 costs 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, bioenergy conversion, hydrogen production technologies, production of oil, natural gas and coal and costs of energy efficiency. In another paper, we showed 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 (Van Vuuren et al., 2004). In the sensitivity run, we set this second factor, induced technology change, to zero, implying that technology change in the mitigation scenario is equal to baseline development. While this factor is not important in the short run, it still represents a major uncertainty in the long run (around 50% cost increase), 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* has been examined in Strengers et al. (in prep.). These parameters are the CO_2 fertilisation 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 was found to fall by about 37% and the average cost of sinks increases 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., bioenergy), and so on may reduce the abandoned agricultural area that can actually be planted. Waterloo et al. (2001) estimated that, in the case of the Clean Development Mechanism 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 costs increase or decrease both in 2050 and 2100).

The *non-CO_2 reduction potential* is based on the EMF-21 database and extrapolated for the period up to 2100 on the basis of assumptions about technological developments, and maximum reduction potentials and accompanying costs. Although there are uncertainties in the 2010 reduction potentials and costs, the major uncertainties are associated with the assumptions about future development. 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 bioenergy. 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 estimated carbon emissions at 2.2 GtC yr^{-1}, with an uncertainty range of 1.4–3.0 GtC yr^{-1} (Houghton, 2003). Future projections for the carbon budget vary even more given uncertainties in the effect of CO_2 fertilisation, 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 (MA, 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 MAC curves for carbon plantations and energy (bioenergy). We took the yield increase of the least positive scenario in the Millennium Ecosystem Assessment (Order from Strength) as a basis for the pessimistic run, and the yield increase from Global Orchestration as the most optimistic option in the MA. This variation provides an understanding of the importance of uncertainties in technological improvement for land-use emissions and potentials for bioenergy 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 fertilisation 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 fertilisation might be substantially weaker than assumed earlier. If that 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 stabilisation level.

As discussed in Section 7.6.1, Figure 7.13 confirms that baseline development is 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). The major role played by the baseline assumptions is to be expected since they affect 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 bioenergy supply, this system is much less amenable to substantial emission reductions. While in one-by-one sensitivity analysis, the system has enough flexibility to substitute – in case all uncertainties play out in a negative way, this flexibility disappears.

In summary, among the most important parameters in terms of sensitivity of stabilisation costs are the baseline, bioenergy, the presence of hydrogen, and the existence of learning-by-doing. Other important uncertainties are future land use (agricultural yields), bioenergy (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.

7.6.3 The possibility of stabilising at even lower levels

In our analysis, we explored a set of scenarios that would lead to stabilisation 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 stabilise 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 bioenergy (both the available potential and the combination of bioenergy and CCS (BECS)) could significantly increase reduction potential and thus allow reaching lower stabilisation levels. Here, we specifically explored whether changing our assumptions for biofuels alone from the default assumption to the optimistic assumptions that allow the combination of BECS could be enough to reach the emission level of 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 biofuels which is then stored underground. These net 'negative emissions' are in particular important for low emission scenarios (see also Azar et al., (in press). The costs of BECS are a combination of the biofuel costs and CCS costs, which make 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 stabilisation levels, including and excluding BECS as an abatement option.

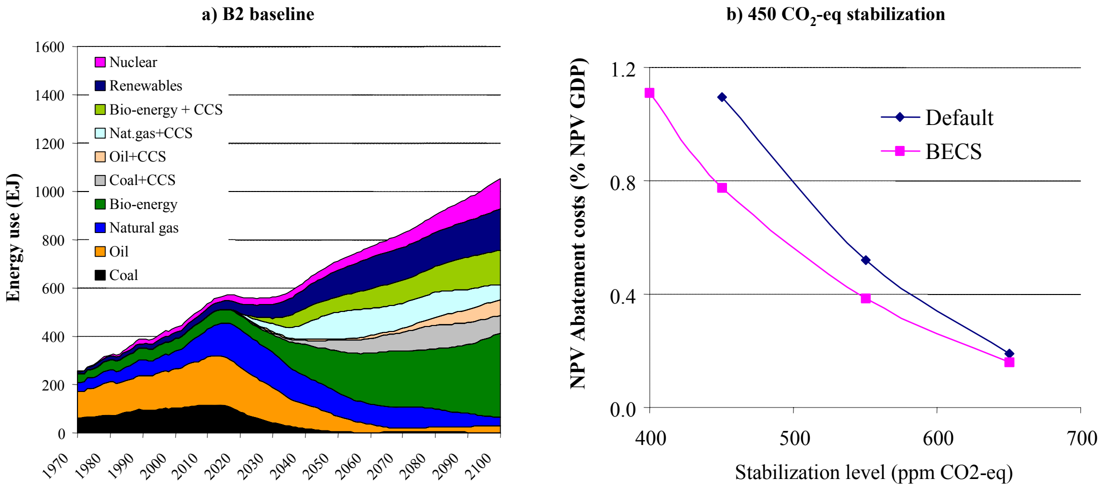


Figure 7-14 Alternative scenario for stabilising GHG concentration at 400 ppm CO_2-eq. (left panel) and the associated costs (right panel).

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 cost 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 loss of competitiveness , impacts on fuel trade, combined effects of climate policy and existing taxes, and so on. On the other hand, they may 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 (bioenergy, 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 or 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 that 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 (e.g., up to about 10 ppm for CO_2 concentration) are certainly within the uncertainty ranges.

Since this is a long-term study, many assumptions are beset with uncertainty. This, for instance, is the case for assumptions on technological progress and reduction potential. This has been addressed by an extensive sensitivity analysis (see section 7.6.2).

Finally, the most important limitation is that we do not deal with societal barriers to formulating ambitious climate policies. Such barriers may include the specific interests of different actors, inertia in international negotiations, and other societal priorities. Instead, we assume that all regions participate in climate policy (without necessarily paying for it) from 2013 onwards. This allows us to explore how ambitious climate stabilisation strategies may look. In future research it will be important to explore further which barriers exist – and how these may impact the results.

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).

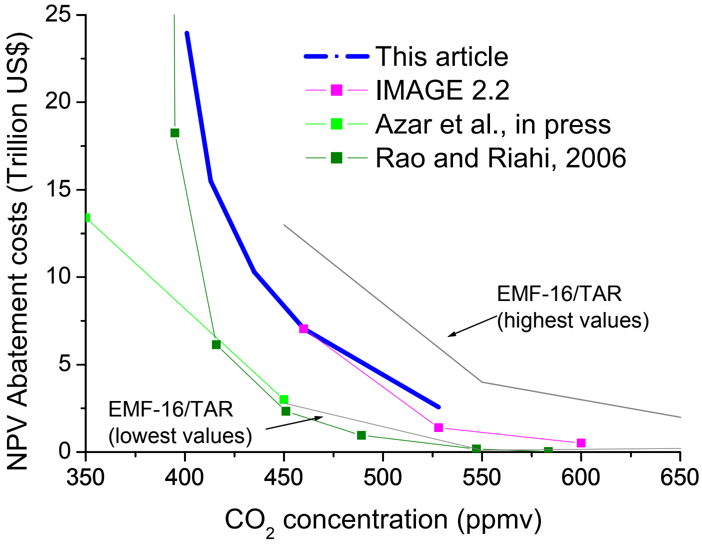


Figure 7-15 Cost levels in this paper compared to alternative studies. All studies report the net present value of mitigation costs (although some differences may result using different base years). The sources of the data shown are: EMF-16 results (Hourcade and Shukla, 2001) (note that the EMF-16 results have been summarised 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., in press) and (Rao and Riahi, 2006). From the latter two studies the data without the use of bioenergy carbon capture and storage are shown (to allow comparison).

In terms of mapping mitigation costs as a function of stabilisation levels, the main comparisons that can be made are with the studies summarised in the IPCC Third Assessment Report (TAR) (these studies focus on CO_2 only). Figure 7.15 shows the stabilisation 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. Average cost values reported in IPCC TAR are around US$ 0.8, 1.3 and 6.4 trillion for stabilising 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 US$ 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 stabilisation studies. Azar et al. (in press) 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, costs as a function of lower concentration levels are comparable – although for individual concentration levels costs may differ by a factor of five. Reasons that may cause different costs 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 stabilisation strategies, comparison can be made with the results of EMF-21 (van Vuuren et al., 2006c;Weyant et al., in press). With only a few exceptions, the results of the models that participated in EMF-21 are only available for stabilisation 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 in terms of the contribution of non-CO_2 gases and overall cost levels, but they extend them to lower levels. Given the wider range of abatement options considered (among others, a larger potential to reduce non-CO_2 gases, a larger potential for carbon plantations, more possibilities to apply CCS), the marginal costs are lower than those presented by Van Vuuren et al. (2006b).

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 importantly – climate sensitivity is very uncertain, creating a range of possible temperature outcomes for different stabilisation levels, as indicated in Figure 7.10. This paper has also shown that the potential and costs of several mitigation options are subject to major uncertainties.

Designing climate strategies that can manage different types of uncertainties will therefore be important. In this light, it is crucial to note that not all uncertainties are similar in nature. 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 favourably for major mitigation options, mid-course corrections can be made in either the portfolio of mitigation options used, the stabilisation 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, which 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), this in fact implies aiming in the short term for emission pathways that do not exclude the possibility of reaching low stabilisation levels, thus providing options to avoid severe climate impact if climate sensitivity turns out to be at the upper range of the PDF. Secondly, monitoring of the most crucial uncertain elements will be important. Obviously, this particularly relates to parameters associated with temperature increase and climate impact, but also to the costs and potential of mitigation options. Thirdly, as much as possible, it will be necessary to select a portfolio of mitigation options instead of only a few options. As shown in this paper, a portfolio is in fact already the result of the modelling that has taken place, but risk reduction is an additional argument not included in the modelling itself. A fourth element is flexibility in targets. Here, obviously, there is 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 aim of this paper was to indicate what portfolio of measures could constitute promising strategies for stabilising GHG concentrations at low levels. The lowest multi-gas scenarios currently discussed in literature look at stabilisation at 550 ppm CO_2-eq. and higher. These scenarios have only a small change of limiting global mean temperature change to 2°C or 2.5°C. The main purpose of the present article was therefore to try to identify whether stabilisation at lower concentration levels is feasible. Against this background, we developed a set of mitigation scenarios for stabilising 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 leads to the following conclusions:

- **The study shows that, technically, stabilising 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 stabilisation 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 stabilisation 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 stabilisation strategies. In fact, under favourable conditions, stabilisation at 400 ppm is also within the realm of technical possibility.

  For 650 ppm and 550 ppm CO_2-eq. stabilisation, it is possible to develop strategies that stabilise 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 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 if global emissions do not peak within the next two decades could include higher temperature change and/or more rapid emission reduction rates in the longer term (which could be costly if they require premature replacement of capital).

- **Creating the right socio-economic and institutional conditions for stabilisation will represent the single most important step in any strategy towards stabilisation of GHG concentrations.**

  The types of reductions described in this paper 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, among other things:

  - 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 importantly, 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 stabilisation 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 2°C target increases from 0–18% to 22–73%.**

  In this paper, we have mapped out some of the costs and benefits of stabilising GHGs at low levels. Costs clearly increase for lower levels of stabilisation, but so do benefits. The net present value of stabilising 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, stabilisation 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 stabilise at 450 ppm CO_2-eq. or below.

In addition to direct abatement costs, stabilisation also involves indirect costs and benefits. There are, for example, the consequences for the fuel trade. Stabilisation policies are likely to reduce the volume 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 bioenergy may compensate for some of the reduced oil exports. Carbon capture and storage 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 stabilisation scenarios are achieved through a set of measures rather than a single measure. The reasons for this result 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 sectors. In addition to these model results, there is another important advantage of a strategy based on a portfolio of measures: the reduced risk if the development of a single technology is slower than expected (or if this technology is found unacceptable altogether, which could happen to nuclear power after a major accident). There is also an important disadvantage: the dispersal of research and development (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 reduce greenhouse gas emissions.**

  Carbon capture and storage could be the single most important technology for reducing CO_2 emissions from the energy sector given its relatively low current cost 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. Carbon capture and storage still has to be proven in large-scale applications. And for CCS, nuclear power and wind power societal acceptance may play an important role in determining their real potential (see also the sensitivity analysis).

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

- **Stringent stabilisation strategies do result in co-benefits but also in additional costs.**

  The systemic changes in the energy system induced by 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 even food security.

- **Uncertainties are important.**

  Uncertainty constitutes an important factor in the development of stabilisation strategies, in particular with respect to the reduction rates required. In this paper, we also focused on other sets of uncertainties relating to the effectiveness and cost of mitigation options. These uncertainties are partly caused by uncertainty with respect to technology development, but also by public attitudes (e.g., acceptance of nuclear power, CCS or large scale bioenergy). 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, bioenergy use and technology development. Climate policies should therefore include strategies that can cope with these uncertainties.

8 Regional abatement action and costs under allocation schemes for emission allowances for achieving low CO_2-equivalent concentrations

M.G.J. den Elzen, P.L. Lucas and D.P. van Vuuren

8.1 Introduction

Increasingly, climate change resulting from human-induced emissions of greenhouse gases (GHGs) has come to be seen as a major threat to ecosystems, food supply and human health (e.g., Parry et al., 2004). Some of the major driving forces for emissions are closely related to development objectives such as economic growth and increased food production. The IPCC SRES baseline scenarios indicate that GHG emissions are likely to increase substantially over the coming century in the absence of climate policies (Nakicenovic et al., 2000), leading to a continuing rise in GHG concentrations throughout the 21st century. In order to achieve the long-term objective of the United Nations Framework Convention on Climate Change (UNFCCC) of stabilising atmospheric GHG levels at non-dangerous levels (Article 2) (UNFCCC, 1992), substantial reductions of global GHG emissions will be necessary (IPCC, 2001a). However, it is not possible to unambiguously determine the concentration levels below which this condition can be considered fulfilled. Current uncertainties in the science do not allow for defining the impacts resulting from various stabilisation levels. In fact, defining what constitutes ‘non-dangerous’ concentration levels is not a scientific issue, but an issue that is related to perceptions, values and political negotiations. Several studies indicate that a maximum temperature increase of 2^{o}C compared to pre-industrial levels could limit the risk of a large-scale disruption of the climate system (ECF and PIK, 2004; Mastandrea and Schneider, 2004; O’Neill and Oppenheimer, 2002; WBGU, 2003). Indeed, the European Union and its EU Member States have adopted a 2^{o}C target as their long-term climate objective (European Council, 1996).

The extent to which emissions need to be reduced in order to attain a global mean temperature target with some degree of certainty depends very much on climate sensitivity (the relationship between GHG concentrations and temperature increase). An important new insight is that the uncertainty range for climate sensitivity may be larger than previously considered in scenario work (e.g. Murphy et al., 2004). Moreover, the probability of high values of the climate sensitivity has increased. As a result, more stringent emission reductions will be required for a given temperature target. For example, in order to attain a probability of more than 50% of achieving the EU 2°C target, GHG concentrations need to be stabilised below 450 ppm CO_2-eq. (based on Den Elzen and Meinshausen, 2005; Hare and Meinshausen, 2004; Meinshausen, 2006). Stabilisation at 550 ppm CO_2-eq. gives only a 0–

30% probability of meeting the 2°C target (depending on the probability distribution function for climate sensitivity used). Unfortunately, there are hardly any mitigation scenarios that have explored the option of stabilising GHG concentrations at such low levels (below 550 CO_2-eq.).

The Kyoto Protocol (UNFCCC, 1997), which came into force in February 2005, is a first step towards achieving the UNFCCC objective, but further steps (i.e. emission reductions) are needed by all countries, and they need to go far beyond the level of reductions currently adopted by developed countries (Annex I Parties) under the Kyoto Protocol. At the eleventh Conference of the Parties (COP-11) in Montreal, December 2005, countries agreed to start discussing the next steps, both under the KP and the UNFCCC (see www.unfccc.int). This raises important questions about the level of commitments from developed and developing countries required in the future, about what level of differentiation between the commitments of different countries will be fair, about the appropriate timing for the participation of the developing countries and about the cost implications of these commitments.

Several studies have analysed a wide variety of system designs for allocating emission allowances / permits / assigned amounts (before emissions trading) to different world regions or countries, and the timing of participation required to ensure meeting different concentration stabilisation targets, mostly for levels of 450 ppm CO_2 or 550 ppm CO_2 -equivalent[70] (see, for example, Berk and Den Elzen, 2001; Blanchard, 2002; Criqui et al., 2003; Den Elzen and Berk, 2003; Den Elzen et al., 2005a; Den Elzen and Lucas, 2005; Den Elzen et al., 2005b; Groenenberg et al., 2004; Höhne, 2005; Höhne et al., 2005; Jacoby et al., 1999; Michaelowa et al., 2003; Nakicenovic and Riahi, 2003; Persson et al., 2006; WBGU, 2003; Winkler et al., 2002). Some lessons emerge from these studies analysing allocation-based approaches.[71] In most cases, developed countries as a group would need to reduce their emissions to between 5% and 30% below 1990 levels in 2020 and to between 60% and 90% below 1990 levels by 2050. This range depends on the timing of the global emission reductions, baseline and regime chosen. The reduction percentages for individual regions/countries vary between different regime designs and parameter settings and may also be outside of this range.[72] However, the general order of magnitude stays the same. Developing-country emissions need to be reduced compared to their baseline emissions (i.e. emissions assuming no climate policy) as soon as possible. For the advanced developing countries, this needs to happen within one or two decades. Furthermore, for many regions, the

[70] 'CO_2 equivalence' summarises the climate effect ('radiative forcing') of all human-induced greenhouse gases, tropospheric ozone and aerosols as if only the atmospheric concentrations of CO_2 change.
[71] Besides allocation-based approaches, there are also outcome-based approaches, i.e. approaches for differentiation of commitments in terms of outcomes, such as equal mitigation costs, which are not analysed in these studies, as these required macro-economic analyses.
[72] Den Elzen and Lucas (2005) have analysed ten allocation-based approaches, including ones that lead to a wider range of outcomes.

reductions that are needed are influenced more by the assumed concentration stabilisation target than by most of the regimes.

The number of studies analysing the regional abatement costs for various allocation designs for concentration stabilisation at 450 ppm CO_2 or 550 ppm CO_2-equivalent or below is limited. Of the studies cited above, Nakicenovic et al. (2003) presents regional costs for 400 and 450 ppm CO_2 only, and Persson et al. (2006) for 450 ppm CO_2 only. Criqui et al. (2003) and Den Elzen et al. (2005b) are the only studies that take all GHGs into account, presenting regional costs for different allocation schemes for 550 and 650 ppm CO_2-equivalent. Besides these studies, there are also studies with macro-economic models, that focus primarily on the Contraction and Convergence regime for higher global CO_2-only emissions targets, as carried out by Böhringer and Welsch, (1999) and Böhringer and Löschel, (2003), or for a 450 ppm CO_2-only profile and converging per capita emissions by 2024 (see also sensitivity analysis, this study), as in Bollen et al. (2004). Then there are macro-economic studies that focus on different emission scenarios for the US, Annex I (minus US) and the developing countries, for example as carried out by Buchner and Carraro (2004).

This paper is based on the analyses presented in Criqui et al. (2003) and Den Elzen et al. (2005b). It aims to provide a systematic evaluation of the regional abatement costs and the role of the abatement options and emission trading in more detail for two allocation schemes for emission allowances, or regimes for differentiating between future (post-2012) commitments under two global emission pathways for stabilising greenhouse gas concentrations. It also analyses how uncertainties in the potential and costs of various abatement options, and in the baseline, affect regional abatement costs. It updates our earlier analysis and includes new insights with respect to the datasets used, i.e. the baseline scenario, the stabilisation pathways (for 450 and 550 ppm CO_2-eq.) and improved reduction potentials and marginal abatement cost estimates for CO_2 (carbon plantation and energy-related sources) and non-CO_2 GHGs.

The two allocation approaches evaluated in this paper are:

(1) The *Multi-Stage approach*: an incremental but rule-based approach, which assumes a gradual increase in the number of parties taking on mitigation commitments and in their level of commitment as they move through several stages according to participation and differentiation rules (Berk and Den Elzen, 2001).

(2) The *Contraction and Convergence (C&C)* approach assumes universal participation and defines emission allowances on the basis of the convergence of per capita emission allowances under a contracting global emission profile (Meyer, 2000).

The C&C approach, the most widely known, has much appeal in the developing world, and it has therefore been selected here. The Multi-Stage approach has been selected because it best fulfils the various criteria (environmental, political, economic, technical, institutional) in the multi-criteria evaluation of the approaches of Höhne et al. (2003) and Den Elzen and Berk (2003).

We used the FAIR 2.0 model for the analysis. FAIR is designed for the quantitative exploration of a range of alternative climate regimes with the aim of differentiating between future commitments compatible with the long-term stabilisation of atmospheric GHG concentrations (Den Elzen and Lucas, 2003; 2005). The model uses the baseline emission scenarios from the integrated climate assessment model IMAGE 2.3[73], including the energy model TIMER 2.0.[74] Furthermore, the IMAGE model provides the potentials and abatement costs of reducing emissions from energy-related sources, and of reductions associated with carbon plantations. The TIMER model was also used to calculate the fuel trade and energy implications. All analyses were performed for 17 global regions[75] but, for the sake of clarity, the results are reported here for ten regions.

This paper is structured as follows. Section 2 presents the baseline scenario and the emission pathways. Section 3 describes the emission allowances (or assigned amounts) resulting from the allocation schemes. Section 4 presents the accompanying global and regional costs and section 5 provides more detail about the abatement options used and the impacts of fuel trade. Section 6 contains a sensitivity analysis. Finally, the conclusions are to be found in section 7.

8.2 The global emission reduction objective

The baseline scenario used for the default calculations is the updated IMAGE/TIMER implementation of the IPCC-SRES B2 scenario (Van Vuuren et al., 2005) (hereafter: ‘B2 scenario’). The B2 scenario is based on medium assumptions for population growth, economic growth and more general trends such as globalisation and technology development. In terms of quantification, the scenario roughly follows the reference scenario of the World Energy Outlook 2004 (IEA, 2004) and, after 2030, economic assumptions converge to the B2 trajectory. The population scenario is based on the UN Long-Term Medium Projection (UN,

---

[73] The IMAGE 2.2 model is an integrated assessment model consisting of a set of linked and integrated models that together describe important elements of the long-term dynamics of global environmental change, such as agriculture and energy use, atmospheric emissions of GHGs and air pollutants, climate change, land-use change and environmental impacts (IMAGE team, 2001). IMAGE 2.3 is an updated version of IMAGE 2.2, differing from it in allowing for the exploration of the impacts of bioenergy and carbon plantations.

[74] The global energy model TIMER, as part of IMAGE, describes the primary and secondary demand and production of energy, and the related emissions of greenhouse gases, on a regional scale (17 world regions). TIMER 2.0 is an updated version of TIMER 1.0 (De Vries et al., 2002). The main differences are additions with respect to hydrogen, bioenergy and modelling of the electric power sector.

[75] More specifically, Canada, USA, OECD-Europe, Eastern Europe, the former Soviet Union, Oceania and Japan (Annex I regions); Central America, South America, Northern Africa, Western Africa, Eastern Africa, Southern Africa, Middle East and Turkey, Southern Asia (incl. India), Southeast Asia and East Asia (incl. China) (non-Annex I regions) (IMAGE team, 2001).

2004). For emission and technology trends in land use, the assumptions of the Adapting Mosaic scenario of the Millennium Ecosystem Assessment were used, as they are a reasonable representation of 'business-as-usual' assumptions for land use. GHG emissions in this scenario increase from about 45 $GtCO_2$-eq. today to more than 80 $GtCO_2$-eq. in 2050 for the set of six GHGs considered in the Kyoto Protocol (fossil CO_2, CH_4, N_2O, HFCs, PFCs and SF_6) using the 100-year GWPs from IPCC (2001b). This corresponds to a medium- to high-level emission scenario compared to the IPCC SRES scenarios. As a result, the baseline reaches a GHG concentration of about 850 ppm CO_2-eq. by 2100.

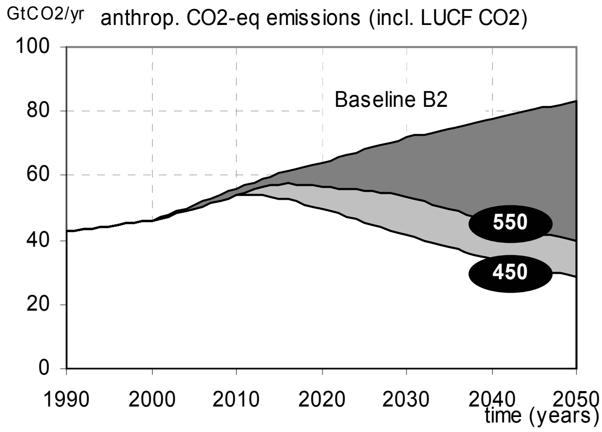


Figure 8-1 The global emission reduction objective: the difference between the baseline emissions and the stabilisation pathways at 550 and 450 ppm CO_2-eq. concentrations for the B2 scenario. Source: Den Elzen et al. (2005, in prep.).

The baseline emissions are compared to two constrained GHG emission pathways corresponding to a stabilisation of total GHG concentration at levels of about 450 and 550 ppm CO_2-equivalent respectively (Figure 8.1). These global multi-gas emission pathways were developed by Den Elzen et al. (2005, in prep.) using the methodology described in Den Elzen and Meinshausen (2005; 2006), but with updated B2 baseline scenarios and improved reduction potentials and abatement costs for non-CO_2 greenhouse gases and CO_2 (sinks and energy-related sources) (as described in section 8.4). The 450 and 550 ppm pathways represent, respectively, 45% and 20% probabilities of reaching the EU target of 2°C above pre-industrial levels (based on the mean outcome of the calculation of probabilities using 11 climate-sensitivity probabilistic distribution functions (PDFs) as conducted by Meinshausen (2006)) (see Table 8.1).[76] For the 450 ppm concentration profile, Den Elzen et al. (2005) assume a certain overshooting (or peaking). In other words, concentrations may first 'overshoot' to a concentration of up to 510 ppm and then decrease, before stabilising at 450 ppm CO_2-eq. The overshoot is based partly on the current concentration levels, which are

[76] By contrast with the 550 and 650 ppm CO2-equivalent concentration stabilisation targets, as explored in our earlier analysis (Den Elzen et al., 2005b), we now also focus on a lower concentration level (450 ppm CO2-eq.) in order to achieve greater certainty with respect to the attainment of the EU target of 2°C above pre-industrial levels.

already substantial, and the attempt to avoid sudden drastic reductions in the emission pathways presented.

Table 8-1 Change of global GHG emissions (including LULUCF CO_2) compared to 1990 and baseline emission levels, and climate risks of overshooting 2°C in equilibrium. Numbers are rounded off to the nearest decimal or half-decimal, except for range.

	2020		2050		Risks of overshooting 2°C*	
	1990	baseline	1990	baseline	Average	Range
450 ppm	15	-20	-35	-70	55%	[26%; 78%]
550 ppm	35	-10	-5	-55	80%	[63%; 99%]

* In equilibrium, based on set of 11 analysed climate sensitivity PDFs, as described in Meinshausen (2006).

These emission pathways take into account constraints on the rate of the emission reductions because technical and political inertia prevent the global GHG emission levels from changing dramatically from year to year or from decade to decade. Fast reduction rates would require the early retirement of existing fossil-fuel-based capital stock, which may be associated with high costs. Den Elzen et al. (2005, in prep.) account for this inertia in a very simple way by assuming the following two constraints on the emission pathways:

1. the global emission reduction rates should not exceed an annual reduction of 3% and 2%, respectively for the 450 and 550 ppm target (at least not over longer time periods);
2. the trend (change from one year to the next) cannot change by more than 0.3 and 0.2 percentage points per year for the 450 and 550 ppm target, respectively.

For the short term (up to 2012), the global emission pathway incorporates the implementation of the Annex I Kyoto Protocol targets and the adoption of the proposed GHG intensity target for the USA (White House, 2002). As shown in Figure 8.2, the emissions need to return to 1990 levels between 2035 en 2060, depending on the stabilisation level. It should be noted that flexibility with respect to achieving 450 ppm stabilisation is very limited since, even assuming stringent reductions by 2020, the concentration increases to 500 ppm. With respect to the 550 ppm target, there is more flexibility, but this is also limited (see Den Elzen et al., 2005, in prep.). Stabilisation at 450 ppm CO_2-eq. requires global GHG emissions (including LULUCF CO_2) to peak before 2015, followed by substantial overall reductions of as much as 40% compared to 1990 levels by 2050. Stabilisation at 550 ppm CO_2-eq. requires global GHG emissions to be 5% below 1990 levels in 2050 (Table 8.1). This 550 ppm emission pathway results in slightly lower reductions for the 2020–2050 period than those under the earlier 550 ppm pathway (Eickhout et al., 2003). This is caused by:

a. technical and political inertia preventing the fast early global reductions assumed previously; and

b. the fact that the updated pathways can be considered as intermediate pathways (since they are neither early- nor delayed-response) compared to the more early-response pathway of Eickhout et al.

These pathways are used to calculate the regional emission allowances, which are defined here as CO_2-eq. emissions, including the anthropogenic emissions of six Kyoto GHGs, but excluding LULUCF (land use, land-use change and forestry) CO_2 emissions.[77]

8.3 Regional emission allowances

This section analyses the implications of the global emission pathways for the regional emission allowances for two international regimes used to differentiate between future (post-2012) commitments: the Multi-Stage and C&C approaches.

The *Multi-Stage approach* consists of a system in which the number of countries involved and their level of commitment gradually increase over time. It is based on pre-determined participation and differentiation rules that determine when a (non-Annex I) country moves from one stage to next and how its type and level of commitment changes. The aim of this system is to ensure that countries in similar economic, development and environmental circumstances have comparable commitments under the climate regime. The Multi-Stage approach therefore results in an incremental evolution of the climate change regime. This approach was first developed by Gupta (1998). Later, in Berk and Den Elzen (2001) and Den Elzen (2002), the approach was elaborated into a quantitative scheme for defining mitigation commitments under global emission profiles compatible with the UNFCCC objective of stabilising GHG concentrations. Höhne et al. (2003; 2005) extended the Multi-Stage approach with a pledging stage for Sustainable Development Policies and Measures, while Den Elzen et al. (2005a) developed a simpler version with some new types of participation thresholds.

Here, the Multi-Stage approach is based on three consecutive stages for the commitments of non-Annex I regions beyond 2012. These are: Stage 1 – no commitment (baseline emissions), Stage 2 – emission limitation targets (intensity targets) and Stage 3 – absolute reduction targets. In Stage 3, the total reduction effort to achieve the global emission profile is shared among all participating regions on the basis of a burden-sharing key, which is based on an equal weighting of GHG emissions per capita (in tCO_2-eq. per capita) and per capita GDP income (in PPP€1000 per capita).[78] Annex I regions are assumed to be in Stage 3 after 2012. Participation thresholds are used for the transitions between stages, and are defined as the sum of per capita GDP income and of per capita CO_2-equivalent emissions, reflecting

---

[77] Emissions from these sources are highly uncertain and emission estimates from various sources are often not consistent. It has therefore also been suggested that emissions from deforestation should be dealt with using a different instrument than for other emissions (WBGU, 2003).

[78] This leads to more balanced reduction targets for all regions compared to a burden-sharing key solely based on per capita emissions as used in Den Elzen et al. (2005a; 2005b).

responsibility for climate change. Because it combines variables with different characteristics, this composite index should in principle be normalised and/or weighted. However, one-to-one weighting combined with normalisation (to make it 'unit-less') produces satisfactory results. Current (2000) index values vary widely between countries, ranging from below 2 for Eastern and Western Africa, 4 for India and 8 for China, to as high as 29 for the enlarged EU (EU-25) and 25 for the USA. The participation threshold levels for Stage 2 are 3 and 5, and for Stage 3, 10 and 12 for 450 and 550 ppm CO_2-eq., respectively. The values for these parameters are chosen so that the Annex I countries take the lead in the reduction efforts when compared to the baselines, followed by the middle- and high-income non-Annex I regions and, finally, low-income non-Annex I regions.[79]

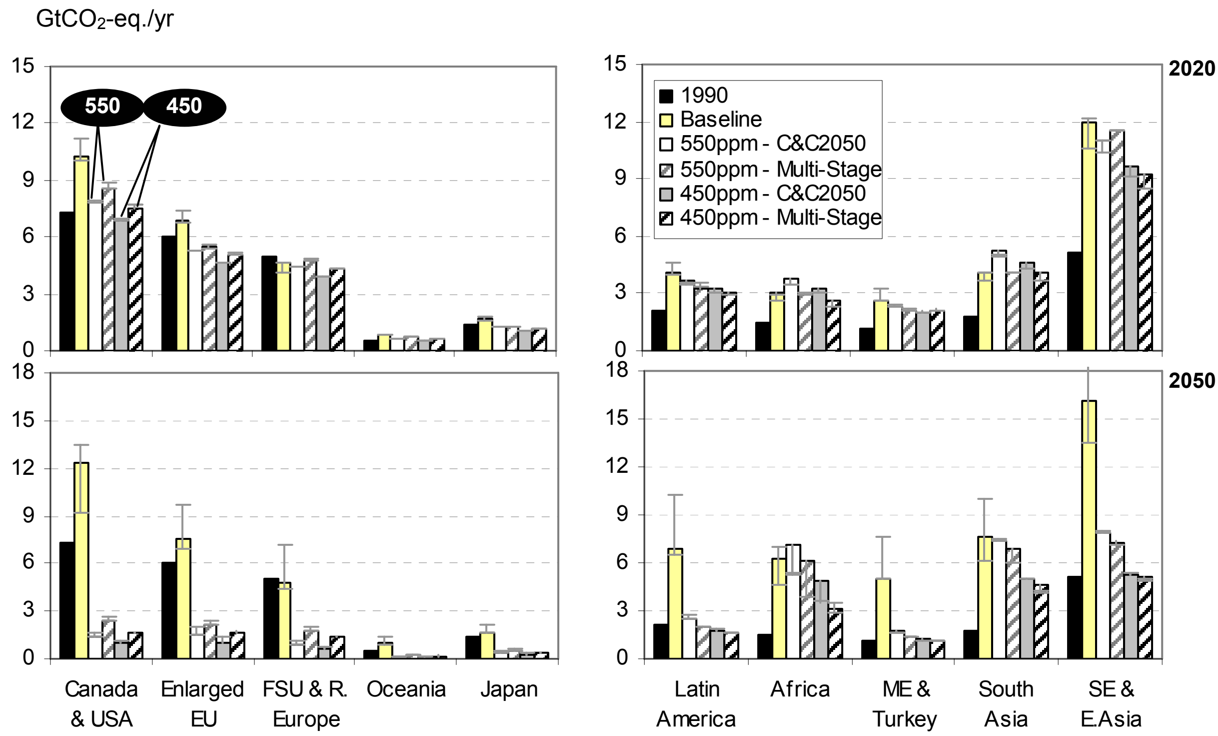


Figure 8-2 Baseline and 1990 emissions versus emission allowances (excluding LULUCF CO_2 emissions) before emissions trading from the C&C 2050 and Multi-Stage case for 2020 (top) and 2050 (bottom) in the Annex I regions (left) and non-Annex I regions (right), and the stabilisation pathways at 550 and 450 ppm CO_2-equivalent concentrations. The error bars show the full range using the A1b, B1 and B2 baseline scenarios.

The *C&C approach* assumes full participation (after 2012) and defines emission allowances on the basis of a convergence of per capita emission allowances from initial (2012) levels to equal levels in a convergence year for all countries under a global emissions profile (Meyer, 2000). In this analysis, we explore the default case with a convergence year of 2050 (C&C

[79] For a sensitivity analysis of the various parameters of the Multi-Stage approach, we refer to Den Elzen (2002) and Den Elzen et al. (2004; 2005a).

2050 case). Since the results of the approach depend so much on the convergence year chosen, we will also analyse the impact of earlier and delayed convergences (convergence years 2025 and 2075) on regional costs (section 8.4).

The Multi-Stage and C&C 2050 cases have been selected here since they were also the two central cases in our earlier study. For an analysis of the emission allowances and costs of other regimes, we refer to Den Elzen and Lucas (2005). The emission allowances (or reduction targets) under these two regimes are presented in Figure 8.2. It should be noted that these emission allowances are not the same as their final emissions, since each of the regions can trade emissions with other regions. They therefore benefit from low-cost reduction options in other regions. The figure also gives the uncertainty range (error bars) resulting from the outcomes using a high-emission growth scenario (A1b baseline) and a low-emission growth scenario (B1 baseline). This shows that, although the baseline scenarios differ considerably, the emission allowances are only affected slightly[80].

Figure 8.2 also shows that the Annex I commitments need to be intensified in all cases after 2012. The Annex I regions that participate in the Kyoto Protocol need to reduce their Kyoto gas emissions to approximately 10% below 1990 levels for 550 ppm, and to about 20–25% for 450 ppm. This implies an acceleration of their reduction rates, in particular for 450 ppm. For the enlarged EU, the reduction targets of 10% (550 ppm) and 25% (450 ppm) are comparable with the 15–30% reduction target range as suggested for the industrialised countries in 2020 by the European Council in its March 2005 conclusions (European Council, 2005). Note also that under the allocation regimes explored the Annex I regions that did not ratify the Kyoto Protocol, Oceania (Australia) and the USA, would have to reduce emissions drastically in order to attain their 2020 targets. Whether the USA will take any stronger action after the first commitment period (2008–2012) is of course highly uncertain[81].

Most non-Annex I regions need to reduce emissions slightly below their baseline emissions, but they are still allowed to increase their emissions substantially. For the low-income regions (Southern Asia, Western Africa and Eastern Africa (not shown)), the emission allowances for these regions may even exceed baseline emissions in the case of stabilisation at 550 ppm CO_2-equivalent under the C&C regime. In the case of the middle- and high-income non-Annex I regions, the reductions compared to the baseline emissions are slightly less than for the Annex I countries, but are still very substantial: about 10–30% by 2020 and 70–85% by 2050.

---

[80] Here, the A1b scenario is characterised by very high economic growth and rapid technology transfer, and a leading consumer trend is towards a fast-food, high-meat, Western-style diet, whereas the B1 scenario is characterised by rapid economic growth, an emphasis on quality of life and a rapid decline in energy- and material-intensive economic activities.

[81] There are, however, a number of reasons to assume that the USA could join a post-2012 regime that aims for emission reductions. Several states and cities are already implementing climate policies. Moreover, several proposals have been discussed in the House of Representatives and the Senate that involve climate policies, and although many of them did not obtain a majority, they may still reflect increasing support for climate policy. Drivers for such an increasing support may include an awareness of climate change impacts (e.g. the discussion about whether Hurricane Katrina was caused by climate change) but also energy security policies.

Comparing the outcomes of the regimes, we found that – at least at the regional level – the Multi-Stage case generates results that are quite similar to the C&C 2050 case. The main difference is the slightly higher reductions for the Annex I, and middle- and high-income non-Annex I regions by 2020 under C&C 2050, as these regions have to compensate for the surplus emissions (‘hot air’) of the low-income regions.

8.4 Global and regional abatement costs

8.4.1 Methodology, marginal abatement cost curves and assumptions

The regional emission reduction targets are used within the abatement cost model to calculate regional abatement action and costs, making full use of the flexible Kyoto mechanisms such as emissions trading and the distribution of reductions over the different gases and sources (Den Elzen et al., 2005b). The model uses aggregated permit demand and supply curves derived from Marginal Abatement Cost (MAC) curves for the different regions, gases and sources. The permit demand and supply curves are used to determine the equilibrium permit price (hereafter referred to as ‘permit price’) on the international trading market, its buyers and sellers, and the resulting domestic and external abatements for each region[82].

We assume that emissions can be traded freely among all regions that have accepted emission-reduction targets (although we do include transaction costs). The transaction costs associated with the use of the Kyoto mechanisms are assumed to consist of a constant US$ 2 per ton CO_2-eq. emissions plus 2% of the total costs. Due to the project basis of CDM (trading between participating and non-participating regions), only a limited amount of the abatement potential is assumed to be operationally available on the market. Availability is set at 10% of the theoretical maximum in 2010, increases linearly in time to 30% in 2030, and remains constant afterwards. The banked emission allowances of the former Soviet Union during the Kyoto period are all used to the full in the second commitment period (2015), while no banking and/or borrowing of permits between periods after Kyoto is assumed.

MAC curves − Different sets of MAC curves for different emission sources were used for the calculations and all were updated compared to our earlier study (Den Elzen et al., 2005b).

The MAC curves of energy- and industry-related CO_2 emissions were determined with the energy model TIMER 2.0 (Van Vuuren et al., 2005). This energy model calculates regional energy consumption, energy-efficiency improvements, fuel substitution, and the supply and trade of fossil fuels and the application of renewable energy technologies, as well as of carbon capture and storage. The TIMER MAC curves were established by imposing a carbon tax and recording the induced reduction of CO_2 emissions, while taking into account

[82] See Den Elzen et al. (2005b) for a discussion of the limitations and strengths of this cost methodology.

technological developments, learning effects and system inertia. There are several responses to a carbon tax in TIMER. In energy supply, options with high carbon emissions (such as coal and oil) become relatively more expensive compared to options with low or zero emissions (such as natural gas, carbon capture and storage and renewables). The latter therefore gain market share. In energy demand, investments in efficiency become more attractive. We developed the MAC curves for TIMER for sight years (in which we determined the reduction of CO_2 emissions) from 2010 to 2100 in ten-year time steps. Two different tax profiles were used to explore responses: one that assumes a linear increase from 2010 to the carbon tax value in the sight year (linear tax) and one that reaches the maximum value 30 years earlier (block tax). The second profile results in more CO_2 reductions because the energy system has a longer time period in which to respond.

FAIR uses the linear-tax MAC curves and the block-tax MAC curves, depending on the pathway of the actual carbon price in the stabilisation scenario. If a certain profile leads to a rapidly increasing price the linear tax MACs are used; for a more constant tax level the block tax MACs are used[83]. In this way, it is possible to take into account (as a first-order approximation) the time pathway of earlier abatement in a way that is consistent with the behaviour of the energy model. A relatively high tax level early in the scenario leads to high abatement costs in this period – but at the same time is also likely to lead to a transition to the block tax MAC latter in the scenario, with corresponding cost reductions resulting from the higher potential. Alternatively, a delayed response leads to lower costs early in the scenario, but will imply that linear tax MACs will continue to be used also later in the scenario – and thus not allowing the model to benefit from the reduced costs associated with the block tax MAC.

The MAC curves for carbon plantations were derived using the IMAGE 2.3 model (Strengers et al., in prep.). In this model, the potential carbon sequestration of carbon plantation is estimated and compared, using a 0.5 x 0.5 grid, to the carbon sequestered by natural vegetation for land that is abandoned from agriculture. Only those grid cells are considered where the sequestration by plantations exceeds sequestration by natural vegetation. On the basis of grid cells that are potentially attractive for carbon plantations, carbon sequestration supply curves are established and converted into MAC curves by adding land and establishment costs (for methodology, see Graveland et al., 2002; Strengers et al., in prep.). A major factor in the calculations is the degree to which potentially attractive areas can actually be used for carbon plantation. The implementation factor rises to 40% of total potential by 2050. Alongside these carbon credits from carbon plantations, the model also includes carbon credits from forest management based on a conservative, low, estimate from our earlier study.

---

[83] The model looks back 30 years in time and, by comparing the tax profile in that period to the one assumed in the block or linear tax profile used in TIMER, constructs a linear combination of the two types of response curves.

An extended set of data from the Energy Modelling Forum-21 project (Weyant et al., 2005) was used for the MAC curves for non-CO_2 emission sources. 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 agricultural sources, as well as abatement options for the halocarbons. It includes MAC curves for a limited cost range of 0–200 US$/tC-eq., and does not include technological improvements over time. Lucas et al. (in prep.) extended this set on the basis of a literature survey and expert judgements about long-term abatement potential and costs. The long-term potential is significantly higher than current potential as a result of the technology development process and the removal of implementation barriers. In addition to the end-of-pipe measures, as summarised in the non-CO_2 MAC curves, energy-related emissions of CH_4 and N_2O are also influenced by the systemic changes in the energy system induced by reducing CO_2 emissions (for instance, the reduction in the use of coal and/or gas reduces CH_4 emissions during the production and transport of these fuels). However, these extra emission reductions were omitted here, as the N_2O emissions from energy-related sources are very small and the end-of-pipe measures already eliminate 50–80% of total energy-related CH_4 emissions.

Finally, it should be noted that, in this study, we focus on direct abatement costs. These costs do not include the various linkages and rebound effects via the economy or impacts of carbon leakage. In other words, there is no direct link with macro-economic indicators such as GDP loss or other measures of income or utility loss. As a result, the costs do not take into account the impact on the fuel trade, which will be presented separately in section 8.5. Furthermore, the costs depend to a large extent on the assumptions about abatement potentials and reduction costs for the different sources, which will be explored in section 8.4. Given the large differences in income between the regions, the costs (or gains) will be presented as percentages of regional GDP levels using Purchasing Power Parity (PPP$) rates. The global costs are compared to GDP values using Market Exchange Rates (MER).

International permit price and global abatement costs

Figure 8.3 shows the international permit price and global costs. Over the 2010–2050 period, the permit price shows a sharp increase due to the rapid increase in the global emission-reduction objective (from 2 $GtCO_2$-eq. in 2010 to about 45 and 55 $GtCO_2$-eq. for 550 and 450 ppm CO_2-eq., respectively) and the exponential form of the MAC curves, with prices increasing faster for higher emission reduction objectives. The costs of the 550 ppm CO_2-eq. stabilisation scenario increase to 1.1% of GDP (uncertainty range for different baseline scenario: 0.35–1.05), while the costs of the 450 ppm CO_2-eq. stabilisation scenario actually increase to 1.7% of GDP (range: 0.75–1.75).

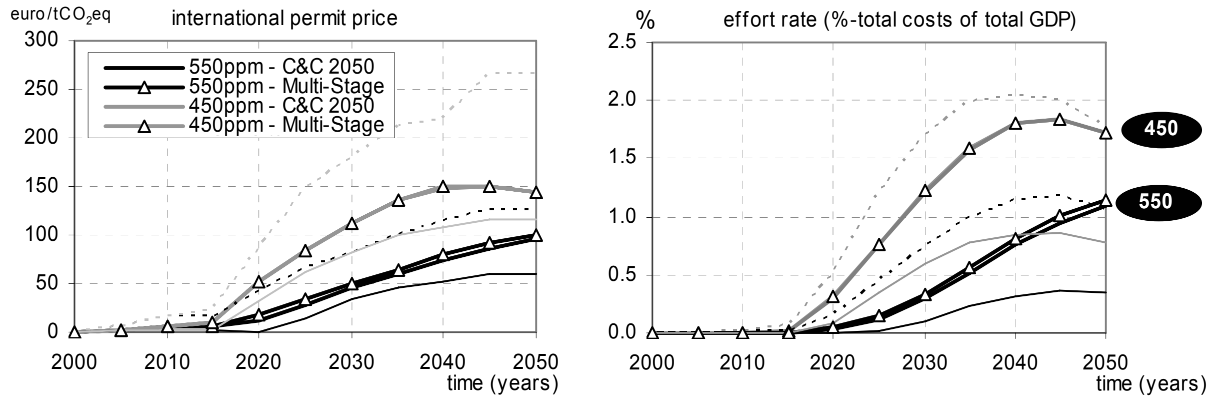


Figure 8-3 Permit price (left) and global costs (right) as % of GDP for the stabilisation pathways at 450 (grey) and 550 (black) ppm CO_2-equivalent concentrations for the B2 baseline scenario. The outcomes of the A1b baseline scenario are shown by the thin dotted lines (upper line:450; lower line: 550), and the outcome of the B1 baseline scenario by the thin lines (upper line: 450; lower line: 550).

The permit price for the C&C regime remains slightly below the permit price for the Multi-Stage regime. Under the C&C regime, it is assumed that all non-Annex I regions participate fully in emissions trading after 2012 – in other words, emissions trading functions fully – whereas participation increases with time using the Multi-Stage approach. The non-participating regions have no commitments and can therefore only participate through the Clean Development Mechanism. CDM allows participating regions to fulfil part of their reduction objective by buying emission reductions from non-participating regions on a project basis. The assumed limited availability of viable CDM projects lowers the supply of emission reductions on the international market, thereby increasing the permit price.

The global costs as a percentage of GDP are subject to the same trend as the international permit price, with increases at lower stabilisation levels. The emission pathways are associated with cost increases until 2050, and then a general decrease as GDP growth outstrips the increase in calculated costs for most of the pathways. Figure 8.3 also shows the uncertainty range, represented by the dashed lines, covered by the outcomes for a high-emission and high economic growth scenario (A1b baseline) and a low-emission and high economic growth scenario (B1 baseline). This range indicates that the global costs (as a percentage of GDP) are at least as strongly influenced by the baseline as by the concentration stabilisation level.

8.4.2 Regional abatement costs

The regional costs as percentages of GDP (which we also refer to as ‘effort rates’) at the level of the ten aggregated regions are presented in Figure 8.4 (column bars). The effort rates differ considerably according to the various stabilisation levels, regimes and regions. These differences can be explained by differences in regional reduction targets, reduction potentials and GDP (Table 8.2). The costs increase for the lower concentration stabilisation level. In general, the abatement costs for many regions (with the exception of the former Soviet Union and Western and Eastern Africa, as discussed below) are influenced more by the assumed concentration stabilisation level and the baseline emissions than by the two regimes explored here.

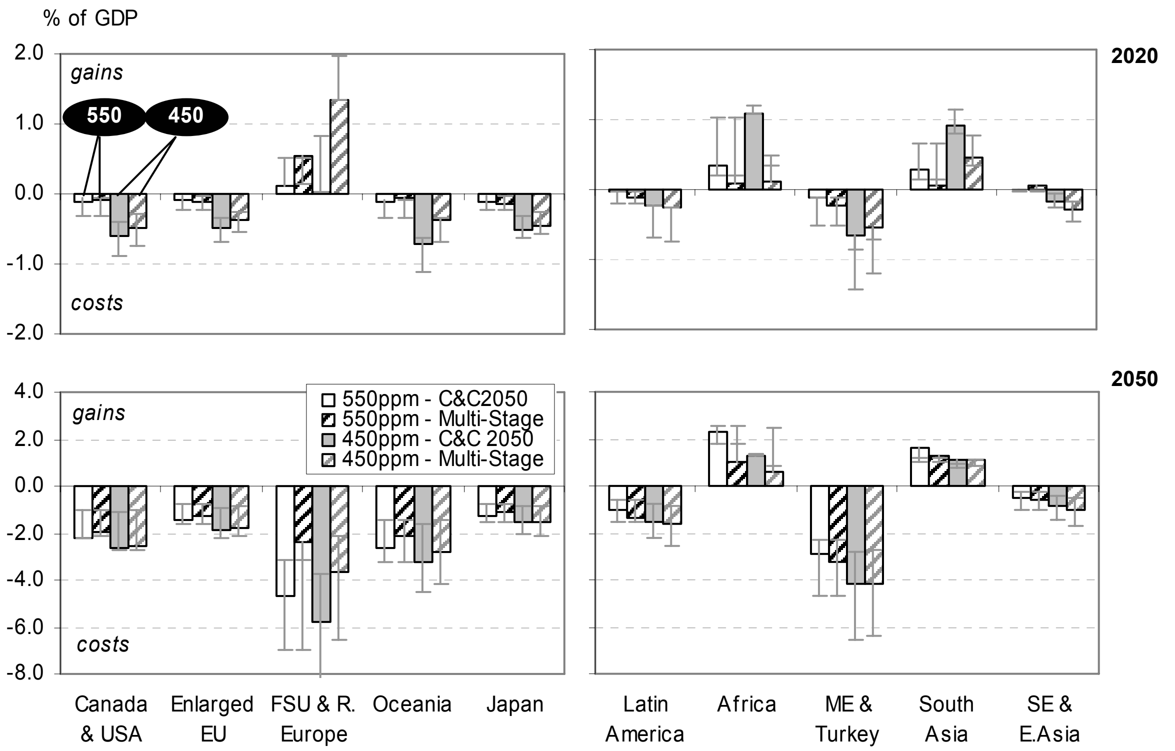


Figure 8-4 Regional costs as percentages of GDP in 2020 (top) and 2050 (bottom) from the C&C 2050 and 2075 for the stabilisation pathways at 550 and 400 ppm CO_2-equivalent concentration. The black error bars show the C&C 2025 case results. The column bars represent the result of the B2 baseline scenario, while the grey error bars show the full range using the A1b, B1 and B2 baseline scenario.

Annex I regions – The effort rates of the Annex I regions – with the exception of the former Soviet Union – increase from about 0.15 in 2020 to 1–2.5% in 2050 for the 550 ppm target, and from about 0.7% in 2020 to 1.5–3% in 2050 for the 450 ppm target. Total costs tend to be relatively high in all regimes for Canada and the USA, and Oceania (regions with the highest per capita emissions), and somewhat lower for the enlarged EU (EU-25) and Japan (regions with medium per capita emissions). Total relative costs are highest for the former Soviet Union, particularly in the long term, due to relatively high emissions per capita and medium income levels. In the short term, the former Soviet Union still gains from its financial revenues from the surplus emission allowances in the first commitment period. Under the C&C regime in particular, the former Soviet Union has relatively high costs: up to 5–6% of GDP in 2050. This is about four times the average relative cost for the world as a whole and is much higher than under the Multi-Stage regime[84]. In general, the Multi-Stage regime results in slightly lower costs for the Annex I regions (particularly for the former Soviet Union) compared to the C&C 2050 regime.

Table 8-2 World regions and the different aggregated levels and their GDP in 1000PPP$/capita.year for the B2 baseline

Annexes	Income classes*	Groups with similar costs**	Aggregated regions	2020	2050
Annex I	High income	1 – medium costs	Canada and USA	45	62
			Enlarged EU (EU-25)	31	47
			Japan	36	50
			Oceania	26	38
	Lower middle income	2 – high costs	Former Soviet Union (FSU) and R. Europe***	9	20
Non-Annex I	Middle income		Middle East (ME) and Turkey	9	13
		3 – low costs	Latin America	11	19
	Low to lower middle income		SE and East Asia (China)	9	20
	Low income	4 – gains	Africa	3	6
			Southern Asia (India)	3	7

* High income ($9266 or more), Upper middle income ($2996-9265), lower middle ($756-2995) and low income ($755 or less) (World Bank, 2001).

** This study: regions ranked on the basis of their costs compared to the global average costs.

*** R. Europe (Remaining Europe) consists of the European member states that do not belong to the EU-25.

Non-Annex I regions – There are much larger differences between the non-Annex I regions than between the Annex I regions. Over the entire period (2010–2050), the Middle East and Turkey have the highest effort rates (0.1–0.6% in 2020, and 3–4% in 2050). This is mainly due to their relatively high emission-reduction objectives (as a result of relatively high per capita emissions) and low GDP (in 2050, this is still lower than the 2000 Annex I per capita income). In 2020, the effort rate of Latin America is in general lower than those of most Annex I regions (which do not exceed 0.25%). In 2050, the more stringent reduction objective for Latin America results in higher costs that, combined with the medium income level, result in relatively high effort rates similar to those of the enlarged EU and Japan (1–1.5%). The effort rates for Africa indicate gains in all cases explored. In the C&C 2050 case, the surplus emission allowances in Africa result in high financial revenues. By contrast, in the Multi-Stage case, the delayed participation in full permit trading leads to lower gains. This

[84] Even the C&C 2050 case leads to higher costs for the former Soviet Union under the 550 ppm target compared to the costs for the Multi-Stage regime under the 450 ppm target.

applies to Africa as a whole, but if we focus in more detail on the African regions (Table 8.3), we see, particularly for the C&C 2050 case, major differences between the regions, i.e. high gains in Western and Eastern Africa and small losses in Southern and Northern Africa. The Multi-Stage regime gives more balanced results, i.e. lower gains for all individual regions (Table 8.3). Southern Asia makes even more gains from emission trading than Africa, both in 2020 (0.5–1%) and in 2050 (1–1.5%). The effort rate for Southeast and Eastern Asia (including China) is fairly low (about half the world average, and it may even be negative), as the costs of emission control are partly compensated by gains from permit trading (see also next section). In general, the C&C and Multi-Stage regimes both lead to similar costs and gains for the non-Annex I regions, except for the low-income regions, where the C&C regime can result in very high gains due to surplus emission allowances.

Table 8-3 Abatement costs for African regions as percentages of GDP in 2020 and 2050 under the two regimes and the stabilisation pathways for 550 and 400 ppm CO_2-equivalent concentration

	2020				**2050**			
	450 ppm		**550 ppm**		**450 ppm**		**550 ppm**	
African regions	C&C2050	Multi-Stage	C&C2050	Multi-Stage	C&C2050	Multi-Stage	C&C2050	Multi-Stage
Northern Africa	0.00	-0.40	0.06	-0.01	-0.77	-1.58	-0.07	-0.10
Western Africa	2.26	0.63	0.68	0.04	2.96	2.52	4.35	1.81
Eastern Africa	2.93	0.45	0.88	0.08	3.48	2.46	5.10	0.68
Southern Africa	0.37	0.11	0.15	0.21	-0.25	-0.78	0.18	1.67

The results discussed above lead to four groups of regions on the basis of similar costs (expressed as percentages of GDP):

1) regions with high per capita emissions and high income (OECD90 regions) that have medium relative costs in comparison to other regions;
2) regions with medium to high per capita emissions, but medium to low income (former Soviet Union, the Middle East and Turkey) that have relatively high costs;
3) regions with low to medium income levels and per capita emissions (Southeast and Eastern Asia (China) and Latin America) have low to average cost levels;

regions with low per capita emissions and low to medium income (Africa and Southern Asia) that have net gains from emissions trading.

The regions in the first two groups are net buyers on the international trading market so their total costs also include permit expenses from permit trading. Most regions in groups 3 and 4 are net sellers and they benefit from permit trading. They therefore have much lower costs (group 3), or even gains (group 4). As such, the results in this study underline our earlier findings (Den Elzen et al., 2005b), except for the position of Latin America, which is now placed in group 3, as its costs are lower than the world average.

The impact of the baseline – The impact of using other baseline scenarios is indicated in Figure 8.4 by the grey error bars. The figure shows that the baseline does not affect the grouping of countries as discussed before. Furthermore, it clearly shows that the regional costs are as much influenced by the baseline scenario (grey bars) as by the concentration stabilisation target. The effort rates for all regions are lowest under B1 (higher economic growth than B2) and highest under A1b (higher emission growth than B2). The baseline does not affect the costs of regions compared to the global average costs. For example, regions with relatively high costs compared to the average (former Soviet Union and the Middle East) under B2 also have high costs under B1 and A1b, and regions that gain (Southern Asia and Africa) under B2 also gain under the B1 and A1b scenarios.

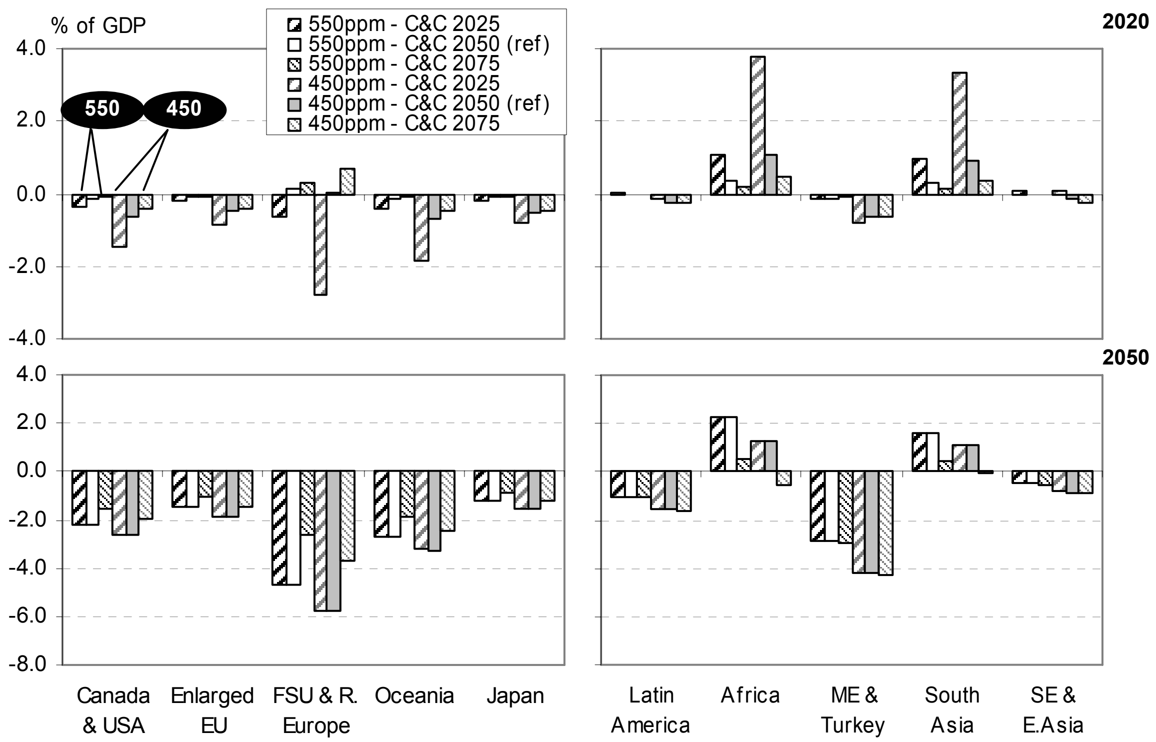


Figure 8-5 Regional costs as percentages of GDP in 2020 (top) and 2050 (bottom) from the C&C 2025, C&C 2050 and C&C 2075 for the stabilisation pathways at 550 and 400 ppm CO_2-equivalent concentration .

The impact of the choice of parameters – A further source of uncertainty is the choice of the parameters for the two approaches. For the Multi-Stage approach, the final emission allowances depend on the participation and differentiation rules or parameters. We have aimed for a set of parameters that result in the most balanced distribution of reductions and costs over the regions but, ultimately, this remains a subjective choice, and the results indicate that we have only partially succeeded.[85] For the C&C approach, there is only the parameter of the convergence year. Figure 8.5 shows the impact of earlier and later convergence, i.e. the C&C 2025 and C&C 2075 cases. The C&C 2025 case in particular leads to high costs in the short term for some Annex I regions with high per capita emissions (the USA and former Soviet Union costs in 2020 are about 1.5% and 3% respectively), and to high gains (up to 4%) for Africa and Southern Asia as a result of their large financial gains from their surplus emission allowances ('hot air'). This early convergence is likely to encounter resistance from the Annex I countries. Later convergence, as in C&C 2075, generally implies lower costs for Annex I and the middle-income non-Annex I regions. However, it also implies lower gains (550 ppm) and even costs (450 ppm) for the low-income non-Annex I countries. They also need to reduce their emissions (compared to their baseline) as early as 2020. Delayed convergence of this kind is thus likely to encounter resistance from the low-income non-Annex I countries. A convergence year of 2050 leads to the most balanced distribution of costs, but this still leads to relatively high costs for regions with high per capita emissions (i.e. the USA and former Soviet Union 2050 costs are about 3% and 5–6% respectively), something that is inherent to the convergence methodology.

The impact of the choice of the regime – Another source of uncertainty is the choice of the regimes discussed here. A wide variety of approaches to allocate emission allowances have been proposed in the literature, either with global participation from the start or with staged participation. Den Elzen and Lucas (2005) have shown that the grouping of regions with similar effort rates is quite robust for eight other approaches (including Triptych, Brazilian Proposal). This also applies to the finding that the abatement costs are more influenced by the assumed concentration stabilisation level and the baseline emissions than by the regimes explored (see also Den Elzen et al., 2005b; Höhne et al., 2005). For the remainder of our analysis, we selected the Multi-Stage case as the default case because the approach seems to result in the most even distribution of costs among all regions and it also matches the various criteria better (environmental, political, economic, technical, institutional) in the multi-criteria evaluation of Höhne et al. (2003) and Den Elzen and Berk (2003).

8.5 Detailed analysis of regional abatement options

Comparing Figures 8.2 and 8.4 leads to the conclusion that regions with comparable reduction objectives can be confronted with different cost levels (as percentages of GDP). This results partly from the diversity of regional financial flows from emissions trading, but also from differences in abatement potentials. The latter stem from differences in, for instance, economic structures, availability of land, costs of labour, technology levels, resources and shares of fossil fuels (oil, gas and coal) and non-fossil fuels (nuclear, hydro-

[85] For a sensitivity analysis of the various parameters of the Multi-Stage approach, we refer to Den Elzen (2002) and Den

power, wind, solar, biomass) in total energy production. In this section we take a closer look at abatement action per region by further analysing the Multi-Stage case for both the 450 ppm and 550 ppm stabilisation profiles.

Domestic reduction versus trading

Figure 8.6 presents the regional emission allowances and reductions for different sets of abatement options as a percentage of the region's baseline emission levels for both the 450 and 550 ppm stabilisation profiles.

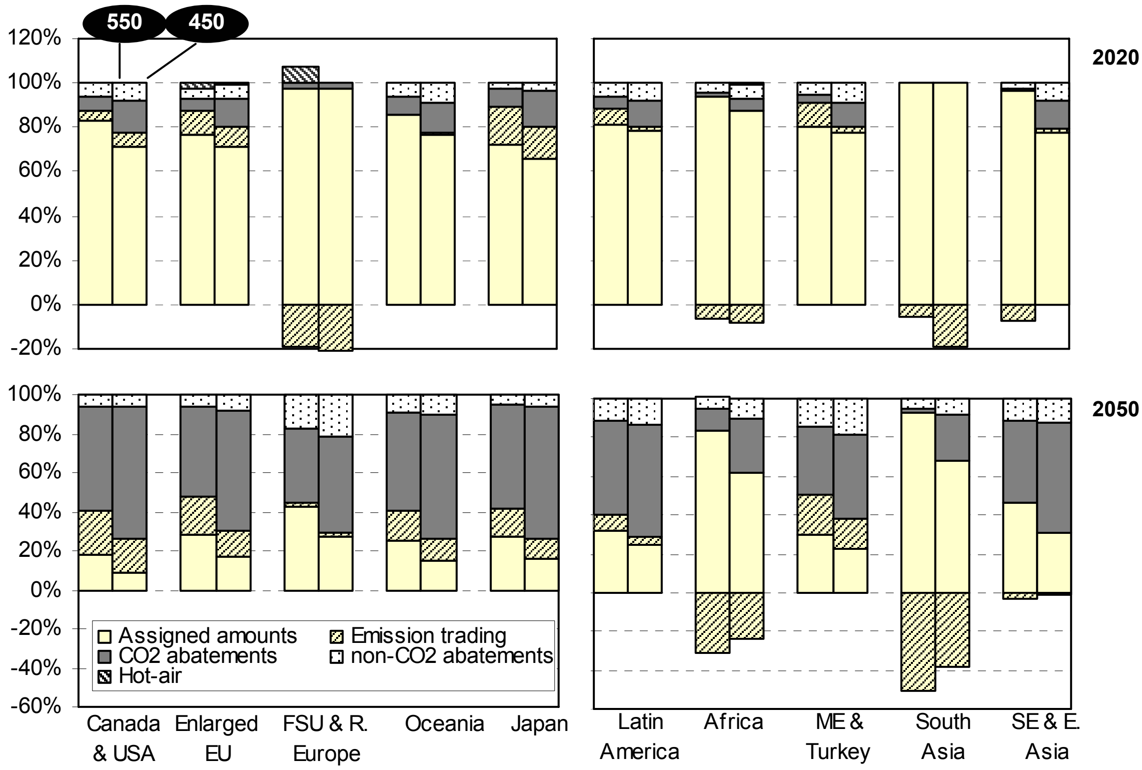


Figure 8-6 Emission allowances and emission reductions for the different mitigation options (i.e. CO_2 and non-CO_2 abatements, surplus emission allowances ('hot air') and permit trading) as percentages of the baseline emissions for the year 2020 (top) and 2050 (bottom), for the Annex I regions (left) and non-Annex I regions (right), for the Multi-Stage case. The yellow columns represent the emissions after emission trading compared to the baseline emissions.

Focusing on emissions trading, Figure 8.6 shows again that the regions in group 1 and 2 (Annex I regions) are net buyers of emission permits (permit-importing regions); that regions in group 3 (Latin America, Middle East and Turkey, and Southeast and East Asia) are relatively small net permit sellers or buyers (most of their reduction target is achieved by domestic action) and that regions in group 4 (Southern Asia and Africa) are net permit sellers

Den Elzen et al. (2004; 2005a).

(reducing more than they are obliged to in addition to selling their hot air). The relative share of emissions trading is less for the lower concentration stabilisation target and decreases in time. Obviously, the trend in domestic abatement is the opposite. For example, the enlarged EU (EU-25) domestic abatement as a percentage of the reduction objective increases from 40% in 2020 to 65% in 2050 for the 550 ppm profile, and from 60% in 2020 to 80% in 2050 for the 450 ppm profile. The explanation for this finding is that, as overall reduction levels increase, all regions will need an increasing share of their own abatement potential to meet their objectives, resulting is a decreasing and more expensive supply of abatement options on the international market.

Abatement of different gases

The reduction shares in Figure 8.6 are broken down further into CO_2 and non-CO_2 reductions. The figure clearly shows that the proportion of non-CO_2 abatements in total domestic reduction is much larger in the short term than in the long term. This larger short-term proportion can mainly be explained by the wide availability of low-cost non-CO_2 abatement options. Non-CO_2 emissions account for only 20% of total emissions and, in addition, several land-use-related emission sources have only limited reduction potential. So in the longer term, a greater proportion of reduction is found in CO_2 emissions. If we look at the regional picture, we can see that, for the regions in groups 2 and 3, the shares of CO_2 and non-CO_2 abatement are approximately the same in 2020. By contrast, CO_2 abatements dominate non-CO_2 abatements in group 1 regions (OECD countries).

Table 8-4 Percentage of non-CO_2 GHG emissions in total GHG emissions for the B2 baseline

	Canada and USA	Enlarged EU	FSU and R. Europe	Ocea nia	Japan	Latin America	Africa	ME and Turkey	South Asia	SE and E. Asia
2020	17%	13%	29%	37%	7%	38%	56%	23%	37%	24%
2050	13%	10%	29%	26%	6%	25%	42%	28%	26%	19%

Table 8-5 Percentage of non-CO2 land-use-related emissions in total non-CO2 GHG emissions for the B2 baseline

	Canada and USA	Enlarged EU	FSU and R. Europe	Ocea nia	Japan	Latin America	Africa	ME and Turkey	South Asia	SE and E. Asia
2020	58%	73%	29%	75%	76%	86%	80%	43%	92%	75%
2050	66%	71%	32%	71%	81%	82%	81%	32%	89%	78%

A similar picture is found for 2050, although for both groups the shares decrease, as explained above. The differences in these shares mainly originate from the differences in the relative contributions of CO_2 and non-CO_2 emissions to total baseline emissions (see Table 8.4). Regions with higher proportions of non-CO_2 GHGs in their baselines tend to have a higher proportion of them in a cost-effective abatement strategy, as their potential is much higher. In addition, the source of non-CO_2 emissions plays an important role (see Table 8.5). Lucas et al. (2005) show that the maximum reduction potential for the non-CO_2 emissions from energy- and industry-related sources are typically between 80% and 95%, while the maximum reduction potential for land-use related sources is much lower, typically between 35% and 70%. This effect of sources is particularly evident for the regions in group 2 – which have a very small proportion of hard-to-abate land-use-related emissions, resulting in a relatively high share of non-CO_2 emission reductions – and for the group 4 regions, where small proportions of non-CO_2 can be explained by a very large proportion of land-use-related emissions.

Reduction within the energy system

Figure 8.7 shows the contribution of different measures to reducing CO_2 emissions in the different regions.

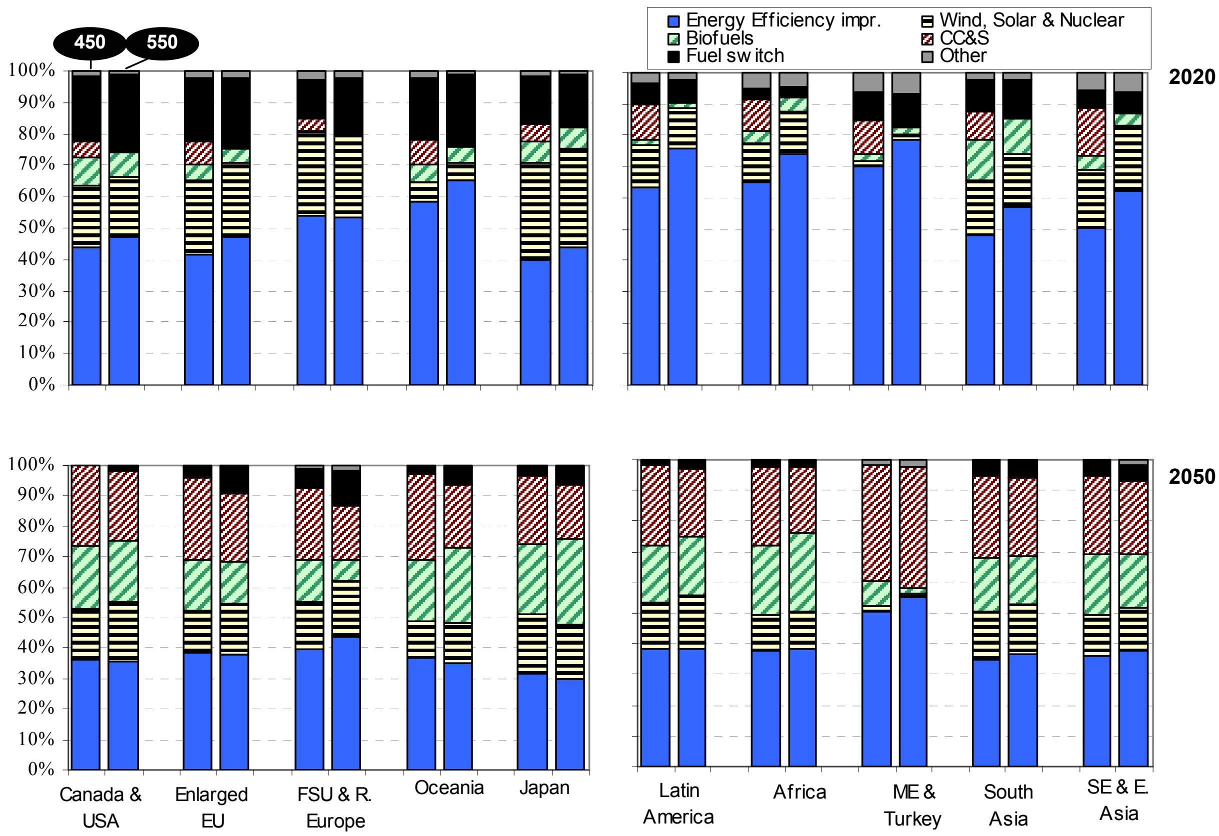


Figure 8-7 Contribution of various measures to the reduction of CO_2 emissions in the energy system (2020 top; 2050 bottom) for the 450 and 550 ppm CO_2-eq. stabilisation scenarios.

In 2020, in most regions, energy efficiency accounts for 40–60% of the reductions. The contribution from efficiency is higher in the 550 ppm CO_2-eq. case (with less stringent reductions) than in the 450 ppm case, as efficiency improvement is generally a very cost-effective option. In addition, the contribution is higher in regions where end-use efficiency is currently lower (former Soviet Union, Middle East, most developing country regions). The second important category for near-term reductions is the use of solar and wind power, or nuclear power. Thirdly, fuel switching also contributes to reduction. It is only in the 450 ppm CO_2-eq. case that carbon capture and storage (CC&S) already plays a role in 2020 reductions. In 2050, efficiency plays a significantly smaller role in emission reduction (around 40%, with the exception of the Middle East). Two options that account for the bulk of the remaining reductions are CC&S and bioenergy. CC&S is used significantly in all regions, with the highest relative contribution in the Middle East. Bioenergy is also used in all regions as a mitigation option – although its contribution is lower in fossil-fuel-exporting regions.

Impact on fuel trade

Climate policies can have considerable impacts on energy production and trade flows. Figure 8.8 shows the costs of fuel exports and imports (total imports and exports multiplied by relevant international prices) as percentages of GDP.[86,87] We assume no major changes in the energy prices to occur – and thus the results are dominated by the change in energy flows. The revenues of exporting regions are generally very substantial and can amount to 10–20% of GDP based on PPP values (and up to 30% based on MER). As importing regions generally have a much higher GDP, the ratios are lower for importing regions. Climate policy can lead to significant changes in trade flows. The clearest differences are found in the oil and coal trades, which are greatly reduced as a result of lower consumption levels. In the 450 ppm CO_2-eq. case, oil-exporting regions, in particular the Middle East, the former Soviet Union, Latin America, North America (Canadian tar sands), Africa (from South Africa) and Oceania will see their exports reduced by about 20% in 2025 and about 50% in 2050. In the 550 ppm CO_2-eq. case, these changes are smaller. At the same time, the oil costs of importing countries are significantly reduced (e.g. the Asian regions and the enlarged EU). There is a similar trend for coal, with reduced exports from Africa and Oceania. For coal, however, there is little difference between the 550 ppm CO_2-eq. and the 450 ppm CO_2-eq. case because the remaining coal is used in combination with CC&S. Interestingly, the natural gas trade is hardly affected since natural gas benefits from fuel switching and can be used in combination with CC&S. It should be noted that for specific regions (Middle East and the former Soviet Union), the reduction in revenues from fuel exports from baseline could be in the same order of magnitude as abatement costs. As the baseline itself indicates exports from the Middle East and the former Soviet Union to increase significantly, the changes compared to 2000 are much smaller. The trend for the bioenergy trade is the opposite. Figure 8.8 shows that South America, the former Soviet Union, Africa and Oceania could become major exporting

[86] For the purposes of consistency, the latter is expressed as PPP (to allow comparison with the abatement costs discussed earlier) but it should be noted that international trade will be paid for in currencies based on market exchange rates.
[87] Fossil fuel prices and fuel trade are calculated in the TIMER model. Primary energy prices are based on the resource estimates and production costs as published by Rogner, 1997. Fuel trade is based on production costs (using a multinomial logit model), although limited by scenario dependent trade restrictions (see De Vries et al., 2001). The global average crude

regions of bioenergy. The same regions that used to be major importing regions for oil (such as the enlarged EU and Asia) are expected to become major importing regions for bioenergy.

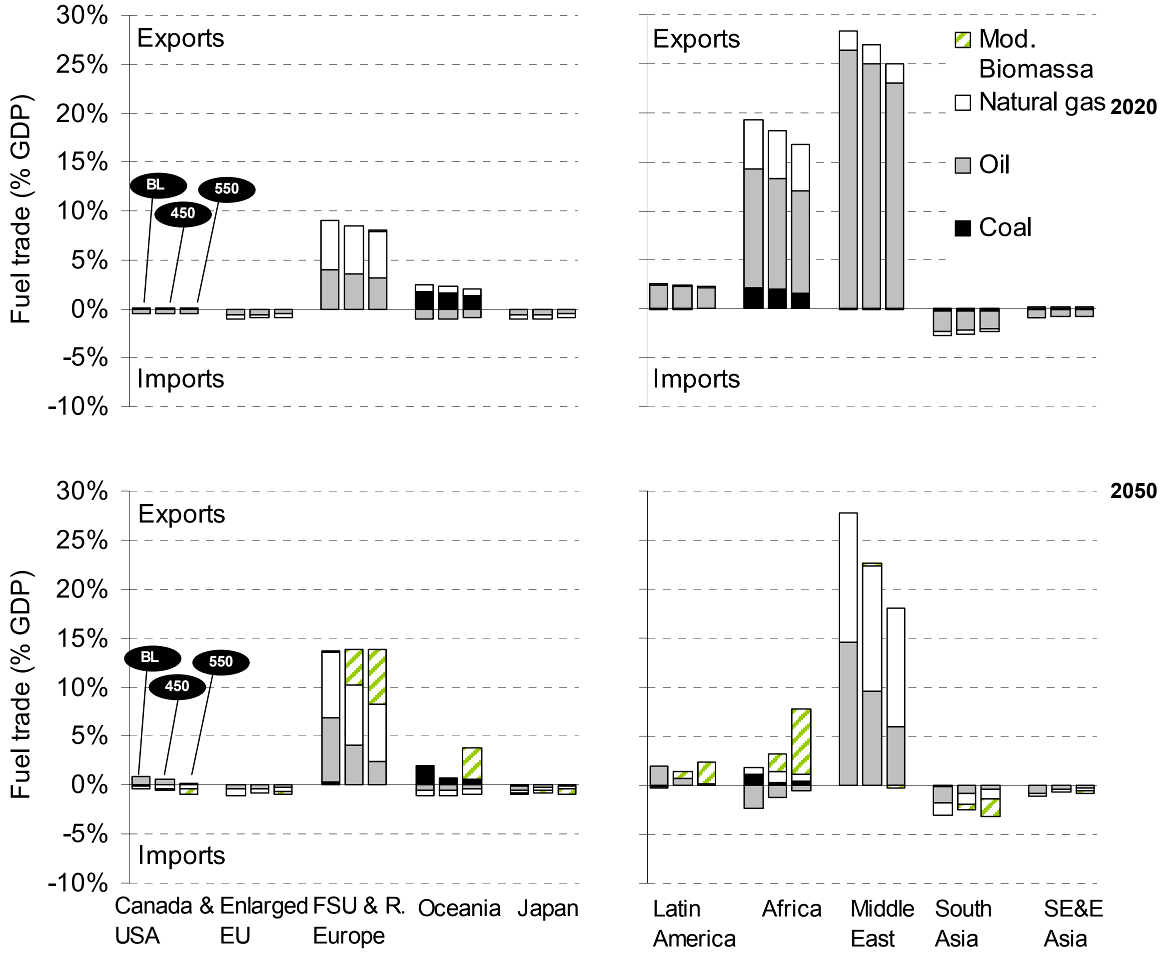


Figure 8-8 Fuel trade (EJ), baseline compared to 450 and 550 ppm CO_2-eq. stabilisation scenarios (2020 top; 2050 bottom)

8.6 Robustness of results

This section investigates to what extent the global and regional costs depend on key assumptions about the mitigation and policy options. More specifically, we focus on pessimistic and optimistic assumptions with respect to the costs and potential of carbon capture and storage, the potential of bioenergy and carbon plantation, non-CO_2 abatement potential and costs and emissions trading, as summarised in Table 8.6. We also analyse the combined cases, that is, all pessimistic and optimistic cases combined. As the reference case, we used the Multi-Stage case with the B2 baseline scenario (reference) for a 550 and

oil price increases from 3 US$/GJ in 2000 to 5.1 US$/GJ in 2050. Natural gas prices increase from 2.2 to 4.3 US$/GJ. Coal prices remain nearly constant (1.1 US$/GJ in 2000; 1.4 US$/GJ in 2050).

450 ppm CO_2-eq. stabilisation target. Figure 8.9 shows the regional costs as a percentage of GDP of the pessimistic cases (lower end of line bar) and optimistic cases (upper end of line bar) in 2050. Here, we do not show the regional costs in 2020, as the impact of the cases explored is limited compared to the impact of the concentration stabilisation levels and baseline emissions. For the purposes of comparison, this figure also shows the impact of the baseline emissions (A1b and B1). The uncertainty range is the same as in Figure 8.4. Table 8.7 states global costs as percentages of GDP. This table shows that global costs are mainly affected by different assumptions about carbon capture and storage, the availability of bioenergy and non-CO_2 abatement potential and costs, as described in more detail below, whereas the effect of carbon plantation and emissions trading is limited. The individual effect of each of these cases is still less than the impact of the baseline scenario or the stabilisation level, and it is only in the combined cases (all assumptions for the technologies and cases are either more optimistic or more pessimistic) that their impact is of the same order or even greater.

Table 8-6 Key assumptions and levels of variation used for the uncertainty analysis

Mitigation option	Pessimistic assumption	Base case	Optimistic assumption
Carbon capture and storage (CC&S)	No CC&S	Fossil fuel CC&S	—*
Potential of bioenergy	Less available land for bioenergy	Technology development for bioenergy is medium	Bioenergy can also be used in combination with sequestration technology
Potential of carbon plantation	Implementation factor: 30% (2050)	Implementation factor: 40% (2050)	Implementation factor: 50% (2050)
Non-CO_2 abatement costs and potential	Only technological development, no maximum reduction potential assumptions	80–95% maximum reduction potentials for energy- and industry-related sources and 35–70% for the land-use-related sources	High assumption for maximum reduction potentials (80–90%)
Emission trading	No trading barriers	Intermediate trading barriers	High trading barriers
All combined	All above combined	All above combined	All above combined

** No optimistic case here*

Table 8-7 The impact of variations in the key assumptions on global costs as percentages of GDP for the B2 baseline (range with optimistic case (low value) and pessimistic case (high value))

	Reference case	Baseline	No CC&S	Potential bio-energy	Potential carbon plantation	Non-CO_2 costs	Emission trading	All combined
550 ppm								
2020	0.04	[0.02;0.13]	0.024	[0.04;0.04]	[0.013;0.015]	[0.04;0.004]	[0.01;0.05]	[0.01;0.12]
2050	1.14	[0.64;1.60]	1.16	[0.7;1.14]	[1.04;1.06]	[1.02;1.26]	[1.13;1.20]	[0.63;1.5]
450 ppm								
2020	0.31	[0.17;0.51]	0.24	[0.31;0.31]	[0.3;0.31]	[0.29;0.31]	[0.30;0.33]	[0.22;0.46]
2050	1.72	[0.89;2.42]	2.16	[1.05;1.91]	[1.67;1.82]	[1.72;1.99]	[1.70;1.81]	[0.95;3.2]

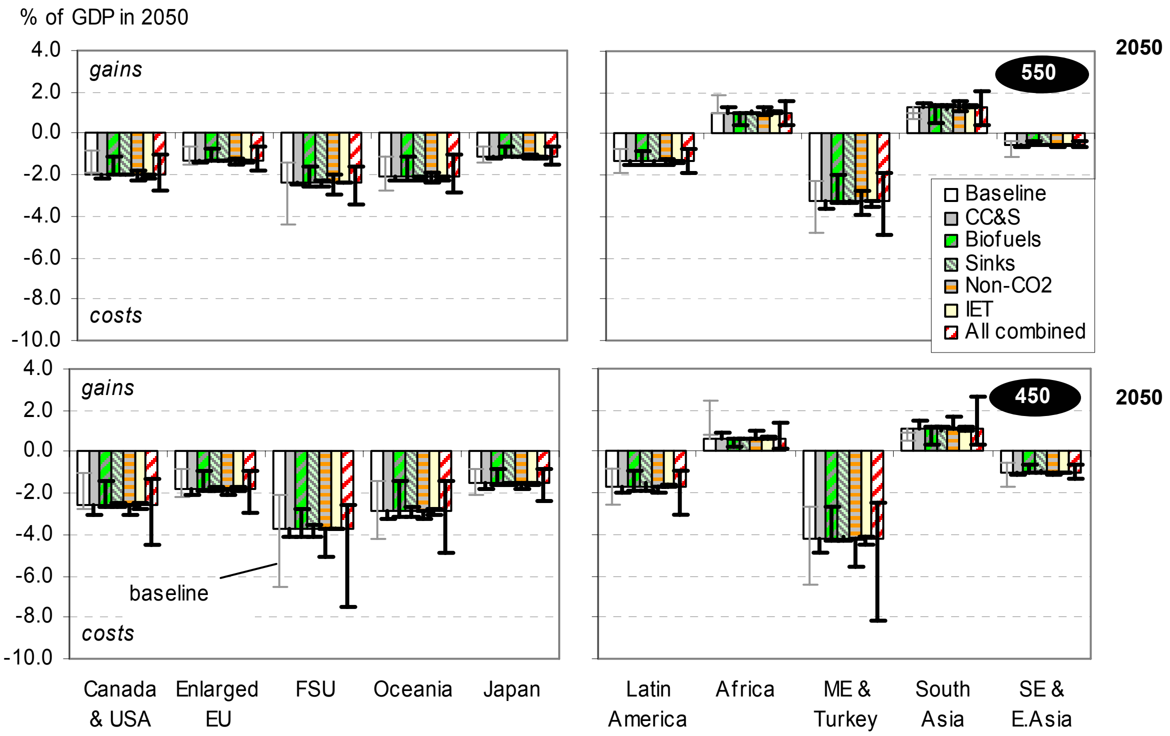


Figure 8-9 The impact of key mitigation options on regional costs as percentages of GDP in 2050 for the stabilisation pathway at 550 ppm (top) and 450 ppm (bottom) CO_2-equivalent concentrations. The broad bars on the bar chart indicate the outcome of the reference case. The grey error bars represent the outcome under the A1b (lower end) and B2 (upper end) scenarios. The black error bars show the outcomes of the pessimistic cases (lower end) and optimistic cases (upper end).

Carbon capture and storage (CC&S) – In our default assumptions, CC&S – mainly in the power sector – accounts for a major share of the emission reductions (up to one-third of the reduction of energy-related CO_2 emissions). As a result, large amounts of CO_2 (in the order of 300 GtC) need to be stored (see Van Vuuren et al., 2005). In the literature, estimates for

CC&S storage capacity typically vary from 50–10,000 GtC. In our assessment, we assumed a storage capacity in the order of 1500 GtC. Although there is obviously sufficient global storage capacity, not only empty fossil fuel reservoirs but also aquifers will need to be used as storage options in more densely populated regions (USA, Western Europe, Japan, Southeast Asia, Eastern Europe and Southern Asia). The decreasing reservoir capacity will result in slightly higher costs. To analyse the impact of uncertainty relating to CC&S capacity and the technical feasibility of this option, we explored a case in which CC&S is not allowed. As a result, global cost increases by about 20% by 2050 (this is almost independent of concentration). Coal-dependent regions in particular, such as the former Soviet Union, Eastern Asia and Oceania, are confronted with higher costs but the permit-importing regions (Annex I regions) also face higher costs as the costs of purchasing permits increases. On the other hand, the permit-exporting regions with low coal production, i.e. Africa and Southern Asia, can now benefit from increased permit sales.

Potential of bioenergy – Another important uncertainty relates to bioenergy including their potential and the presence of alternative technologies. As shown by Hoogwijk et al. (2005) the uncertainty in the biomass supply leads to a figure for potential use of between 100 and 800 EJ. Under the assumptions of the B2 scenario, the total available potential amounts to 500 EJ but this figure is highly dependent on yield assumptions. At the lower end of our range, we lowered the yield improvement assumptions in accordance with the uncertainty ranges explored by Hoogwijk et al. (2005). Azar et al. (2005) have shown that including the option of bioenergy and carbon storage (BECS) can reduce costs at low concentration levels by at least 50%. We will therefore use BECS as the high end of our range. Figure 8.9 and Table 8.7 show that a scenario with BECS (optimistic case) has a major effect on costs, in particular for the lower concentration level (35% reduction of global costs for the 450 ppm case).

Non-CO_2 abatement costs and potential – Although there are uncertainties in the 2010 reduction potentials and costs, the major uncertainties are to be found in the assumptions about future development. The assumptions about the maximum reduction potentials have most impact on final outcomes. To assess these effects from a pessimistic perspective, we included only technological developments (for most sources 2% per 5 years) and did not extend the curves towards the assumed maximum potentials. To assess the effects from an optimistic perspective, we assumed that new technologies will emerge in time which can result in more abatement, in particular for the land-use-related sources, than assumed in our standard run. Here, all maximum potentials were set at 80% (or higher if already assumed). The impact of a more optimistic assumption is evidently the highest in regions where non-CO_2 emissions form a large share of the overall GHG emissions (see Table 8.4), such as the former Soviet Union, and the Middle East and Turkey. Furthermore, the effect is more pronounced for the lower 450 ppm CO_2-eq. stabilisation profile, as this profile is accompanied by higher costs, and also higher non-CO_2 cuts.

8.7 Conclusions

In this article, we have analysed the abatement-cost implications of two post-Kyoto climate regimes for differentiating between future commitments under global emission pathways stabilising GHG concentrations at 450 and 550 ppm CO_2-eq. in the long term. The two regimes consist of the Multi-Stage and Contraction and Convergence approaches. The study also analyses how uncertainties in the potential and costs of various abatement options and the baseline affect regional abatement costs. The analysis builds upon new insights with respect to the datasets used, i.e. the baseline scenario, the stabilisation pathways, and estimates of improved reduction potentials and marginal abatement costs. It also includes a more in-depth analysis of the abatement options, the required changes in the energy system and the impact on fuel trade.

The following conclusions can be drawn:

To achieve the low CO_2-equivalent concentrations, the developed regions need to reduce their emissions substantially below 1990 levels and the developing regions need to make reductions compared to their baseline emissions as soon as possible.

The developed countries as a group would need to reduce their emissions by 10–25% below 1990 levels by 2020 and to 60–90% below 1990 levels by 2050 in order to stabilise greenhouse gas concentrations at 450 and 550 ppm CO_2-eq., respectively. We find a range of reduction targets similar to those quoted in earlier studies (see Introduction). Obviously, those for the 450 ppm target (which has not been analysed before) are on the lower side of the range. The fact that we analyse lower concentration stabilisation targets but arrive at a similar short-term range is caused by: (i) technical and political inertia preventing faster global reductions, and (ii) the adopted global emission pathways being characterised as a more intermediate pathway (since they are neither early- nor delayed-response pathways) compared to the earlier-response pathways in the earlier studies. Developing-country emissions need to differ from their baseline (no climate policy) emissions as soon as possible. In the advanced developing countries, this needs to happen as early as 2020 under all regimes explored. Without early participation (in some form) of all major greenhouse gas emitters, these targets are certainly beyond our reach. In many regions, the reductions needed are influenced more by the concentration stabilisation target than by the regime approaches explored.

Under the regimes explored, the abatement costs as percentages of GDP vary significantly by region, with high costs for the Middle East and Turkey and the former Soviet Union, medium costs for the OECD, and low costs or even gains for other non-Annex I regions.

The global average costs of the 550 ppm CO_2-eq. stabilisation scenario increase to 1.1% of GDP by 2050, while the global average costs of the 450 ppm CO_2-eq. stabilisation scenario rise to as much as 1.7% of global GDP. These global costs are subject to considerable uncertainty associated with the baseline emissions, which may halve or increase (by a factor of 1.5) the abatement costs for certain concentration stabilisation targets.

The regional costs are also mainly influenced by the assumed concentration stabilisation level and the baseline scenario, and to a lesser extent by the regimes explored. This regime dependency is particularly a feature of the low-income non-Annex I regions, where the costs or revenues from emissions trading play an important role, but also for the former Soviet Union. In the regimes explored, we see that the Multi-Stage regime leads to slightly lower costs for the Annex I regions (in particular the former Soviet Union) than the C&C 2050 regime. In the non-Annex I regions, the C&C 2050 and Multi-Stage regime both lead to similar costs and gains, except for the low-income regions with high gains (as high as 5% of GDP) under the C&C 2050 case due to their surplus emission allowances. The Multi-Stage approach seems to result, relatively speaking, in the most even distribution of costs amongst all regions, although substantial differences remain.

Four groups of regions with similar relative costs (expressed as percentages of GDP) can be identified. These are:

- the OECD regions with medium costs (about 1.5 times the world average);
- the former Soviet Union, plus the Middle East and Turkey, with high costs (about 2–3 times the world average);
- Southeast and East Asia (including China) and Latin America, with relatively low costs (50–80% of the world average); and
- Southern Asia (incl. India) and Africa, with net gains from emissions trading. These gains from global emissions trading can provide an incentive for this last group to take on quantified emission-limitation commitments, while simultaneously alleviating the costs at the global level.

Regional abatement strategies to meet low stabilisation targets require a portfolio of mitigation options. Especially in the former Soviet Union and the Asia region – but also in other parts of the world, non-CO_2 abatement options are important in the short term in reducing emissions. Carbon capture and storage, energy efficiency improvements, bioenergy use and the use of renewables dominate reductions in the long term in all regions.

In the short term, non-CO_2 reductions are the most important source of reductions in greenhouse gas emissions; in the long run, CO_2 reductions from energy production remain important. A large proportion of the non-CO_2 abatement options can be used at relatively low costs. For fossil-fuel-exporting regions (the former Soviet Union and the Middle East) the largest proportion of emission reductions comes from cheap abatement options for oil and gas production: mainly CH_4 recovery for energy production. For most OECD regions and Latin America, the CH_4 from enteric fermentation, landfills and energy production (including coal) and F-gases (mainly HFCs) are the most important non-CO_2 options. For Asian regions, reductions from fertiliser use and domestic sewage emissions are also important.

In the long term, efficiency improvements and CC&S will become the most important options for reducing CO_2 emissions from the energy sector. These options are used in almost all regions. In addition, modern bioenergy now also forms a way to reduce energy CO_2 emissions – in particular in regions with large potential bioenergy.

Under low stabilisation pathways fossil-fuel-exporting regions are not only confronted with relatively high abatement costs, but are also likely to be affected by revenue losses of coal and oil exports of a similar magnitude exports, while some regions could experience increased bioenergy exports (i.e. the former Soviet Union and South America).

The cost measure used in this paper does not include the impact on the fuel trade. The mitigation scenarios are likely to have different fuel trade impacts across regions. Under low stabilisation pathways fossil fuel exporting regions such as the Middle East and former Soviet Union will experience substantial loss in oil and coal export revenues (compared to baseline), which may be in the same order of magnitude as their direct abatement costs. The other side of this coin is that, in several importing countries (OECD regions and Asia), the reduced energy imports could compensate for some of the direct abatement costs of climate policies. Regions that could export bioenergy, i.e. the former Soviet Union, South America, Western Africa and Oceania, could see a major increase of their bioenergy export revenues.

The regional abatement costs are sensitive to assumptions about the potential and costs of carbon capture and storage, the availability of bioenergy and non-CO_2 abatement potentials. If all assumptions for these technologies are either more optimistic or more pessimistic, their combined effect on abatement costs may be larger than the effect of the assumed baseline and concentration stabilisation target.

The cost calculations are subject to considerable uncertainty. As mentioned above, the baseline emissions are a crucial uncertainty. Another source of uncertainty is the effectiveness and costs of mitigation measures. These uncertainties originate in part from uncertainty with respect to technology development, but sometimes also from societal decisions (carbon capture and storage; bioenergy). The main uncertainties are those relating to potential and costs of carbon capture and storage, the availability of bioenergy and non-CO_2 abatement potential and costs. In the short term, their impact on regional abatement costs is limited. However, in the long term, these uncertainties could have a significant effect. The individual impact of each of these uncertainties is still less than the impact of the baseline scenario or the stabilisation level assumptions. However, if all assumptions for these technologies are either more optimistic or more pessimistic, their combined effect may be larger.

References

Chapter 1

Corfee Morlot, J., J. Smith, S. Agrawala and T. Franck: 2005. Article 2, Long-Term Goals and Post-2012 Commitments: Where Do We Go From Here with Climate Policy? Climate Policy, 5(3).

Den Elzen, M. G. J. and P. Lucas: 2005. The FAIR model: a tool to analyse environmental and costs implications of climate regimes.' Environmental Modeling and Assessment, 10(2): 115-134.

Den Elzen, M. G. J. and M. Meinshausen: 2005. Meeting the EU 2 degree target: Global and regional emission implications. MNP Netherlands Environmental Assessment Agency, Bilthoven, The Netherlands. www.mnp.nl/en

ECF and PIK: 2004. What is dangerous climate change? Initial Results of a Symposium on Key Vulnerable Regions, Climate Change and Article 2 of the UNFCCC. European Climate Forum and Postdam Institute for Climate Impact Research. http://www.european-climate-forum.net/pdf/ECF_beijing_results.pdf

EU: 1996. Communication of the Community Strategy on Climate Change. Council of the EU.

EU: 2005. Council of the European Union, Presidency conclusions, March 22-23. http://ue.eu.int/ueDocs/cms_Data/docs/pressData/en/ec/84335.pdf

Hourcade, J. C. and P. Shukla: 2001. 'Global, Regional and National Costs and Ancillary Benefits of Mitigation'. in Climate Change 2001: Mitigation. B. Metz, O. Davidson, R. Swart and J. Pan. Cambridge University Press, Cambridge.

IMAGE-team: 2001. The IMAGE 2.2 implementation of the SRES scenarios. A comprehensive analysis of emissions, climate change and impacts in the 21st century Bilthoven, the Netherlands.

IPCC: 2001. Climate Change 2001 - Synthesis Report. Cambridge University Press, Cambridge.

Leemans, R. and B. E. Eickhout: 2004. 'Another reason for concern: regional and global impacts on ecosystems for different levels of climate change.' Global Environmental Change, 14: 219-228.

Mastandrea, M. D. and S. H. Schneider: 2004. 'Probabilistic Integrated Assessment of dangerous climate change.' Science, 304: 571-574.

Meinshausen, M.: 2006. 'On the risk of overshooting 2oC'. in Avoiding Dangerous Climate Change. H. J. Schellnhuber, W. Cramer, N. Nakicenovic, T. Wigley and G. Yohe. Cambridge University Press, Cambridge, UK.

Metz, B. and D. P. Van Vuuren: 2006. 'How, and at what costs, can low-level stabilisation be achieved? –An overview'. in Avoiding Dangerous Climate Change. H. J. Schellnhuber, W. Cramer, N. Nakicenovic, T. Wigley and G. Yohe. Cambridge University Press, Cambridge.

MNP: 2005. Limits to Global Warming. Netherlands Environmental Assessment Agency (MNP), Bilthoven.

Morita, T., N. Nakicenovic and J. Robinson: 2000. 'Overview of mitigation scenarios for global climate stabilisation based on new IPCC emission scenarios (SRES).' Environmental Economics and Policy Studies, 3: 65-88.

Morita, T. and J. Robinson: 2001. 'Greenhouse gas emission mitigation scenarios and implications'. in Climate Change 2001: Mitigation. B. Metz, O. Davidson, R. Swart and J. Pan. Cambridge University Press, Cambridge.

O'Neill, B. C. and M. Oppenheimer: 2002. 'Climate Change:Dangerous Climate Impacts and the Kyoto Protocol.' Science, 296: 1971-1972.

Swart, R., J. Mitchell, T. Morita and S. Raper: 2002. 'Stabilisation scenarios for climate impact assessment.' Global Environmental Change, 12(3): 155-165.

UNFCCC: 1992. United Nations Framework Convention on Climate Change, http://www.unfccc.int/resources.

Van Vuuren, D.P., B. Eickhout, P.L. Lucas and M.G.J. den Elzen (2006). Long-term Multi-gas scenarios to stabilise radiative forcing. Exploring costs and benefits within an integrated assessment framework. The Energy Journal. (accepted for publication).

Chapter 2:

Benítez, P.C. and Obersteiner, M.: 2005, 'Site identification for carbon sequestration in Latin-America: A grid-based economic approach', For. Pol. Econ. in press

Benítez-Ponce, P.C.,'Essays on the Economics of Forestry-Based Carbon Mitigation', PhD Thesis, Wageningen University, p77-78

Bruinsma, J.E.: 2003. 'World Agriculture: Towards 2015/2030. An FAO Perspective.' Earthscan, London, 432 pp.

Criqui, P., P. Russ and D. Debye, 2006. Short-term impact of a multi-gas approach in policy scenario analysis and consequent operational implications - The POLES-Gecs modelling system. Energy Journal, in press.

Den Elzen, M.G.J. and Lucas, P.: 2003, FAIR 2.0- De decision-support tool to assess the environmental and economic consequences of future climate regimes. Report 550015001/2003, RIVM/MNP, Bilthoven

Graveland, C., Bouwman, A.F., de Vries, H.J.M., Eickhout, B. and Strengers, B.J.: 2002, 'Projections of multi-gas emissions and carbon sinks, and marginal abatement cost functions modeling for land-use related sources. Report 461502026, National Institute of Public Health and the Environment (RIVM), Bilthoven

GTAP: 2004, 'The GTAP 6 Data package'. Purdue University, USA

Heath, J. , Ayres, E., Possell, M. , Bardgett, R.D., Black, H.I.J., Grant, H. Ineson, and P., Kerstiens, G.: 2005, 'Rising Atmospheric CO_2 Reduces Sequestration of Root-Derived Soil Carbon'. Science 309.1711-1713

Hoogwijk, M., Faaij,A.,Eickhout, B., de Vries, B., and Turkenburg, W.: 2005, 'Potential of biomass energy out to 2100, for four IPCC SRES land-use scenarios', Biomass & Bioenergy, 29, 225-257

IMAGE team: 2001, 'The IMAGE 2.2 implementation of the SRES scenarios: A comprehensive analysis of emissions, climate change and impacts in the 21st century.' RIVM CD-ROM Publication 481508018, National Institute of Public Health and the Environment, Bilthoven

IPCC: 1996, 'Climate change 1995. Economic and social dimensions of climate change.' Intergovernmental Panel on Climate Change (IPCC). Cambridge, p248 and p349.

Jakeman, G., and B.S. Fisher, 2006. Benefits of Multi-Gas Mitigation: an application of the Global Trade and Environment Model (GTEM). Energy Journal, in press.

Körner, Ch., Asshoff, R., Bignucolo, O., Hattenschwiler, S., Keel, S.G., Pelaez-Riedl,S., Pepin, S., Siegwolf, R.T. W., and Zotz, G: 2005, 'Carbon Flux and Growth in Mature Deciduous Forest Trees Exposed to Elevated CO_2', Science 309,1360-1362

Kunte, A., Hamilton, K., Dixon, J. and Clemens, M.: 1998, Estimating National Wealth: Methodology and results. Indicators and environmental valuation. World bank, Washington DC, US

Leemans, R., Eickhout, B.J., Strengers, B., Bouwman, A.F. and Schaeffer, M.: 2003, 'The consequences for the terrestrial carbon cycle of uncertainties in land use, climate and vegetation responses in the IPCC SRES scenarios', Science in China 43, 1-15.

MA: 2006. 'Ecosystems and human well-being: Scenarios. Findings of the Scenarios Working Group', Island Press, Washington.

McCarl, B.A., and U.A. Schneider, 2001. The Cost of GHG Mitigation in U. S. Agriculture and Forestry, Science, 294: 2481-2482.

Metz, B., Berk, M., Kok, M., Van Minnen, J.G., De Moor, A. and Faber, A.: 2001, 'How can the European Union contribute to a CoP-6 agreement? An overview for policy makers', International Environmental Agreememt: Politics, Law and Economics 1, 167-185.

Mitchell, J.F.B., Karoly, D.J., Hegerl, G., Zwiers, F.W. and Marengo, J.: 2001, 'Detection of climate change and attribution of causes.' Chapter 12 WGI, IPCC Third Assessment Report on Climate Change, Cambridge University Press

Morita, T., Robinson, J., Adegbulugbe, A., Alcamo, J., Herbert, D., Lebre la Rovere, E., Nakicenivic, N., Pitcher, H., Raskin, P., Riahi, K.,Sankovski, A., Solkolov, V., Vries, B. de and Zhou, D.: 2001, 'Greenhouse gas emission mitigation scenarios and implications.' In: B. Metz, O. Davidson, R. Swart and J. Pan (Editors), Climate Change 2001: Mitigation; Contribution of Working Group III to the Third Assessment Report of the IPCC. Cambridge University Press, Cambridge, Chapter 2 pp. 115-166

Nabuurs, G.J., Schelhaas, M.J., Mohren, G.M.J. and Field, C.B.: 2003, 'Temporal evolution of the European forest sector carbon sink from 1950-1999', Gobal Change Biology 9, 152-160.
Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Grübler, A., Jung, T.Y., Kram, T., Emilio la Rovere, E., Michaelis, L., Mori, S., Morita, T., Pepper, W., Pitcher, H., Price, L., Riahi, K., Roehrl, A., Rogner, H.-H., Sankovski, A., Schlesinger, M.E., Shukla, P.R., Smith, S., Swart, R.J., van Rooyen, S., Victor, N. and Dadi, Z. (Eds): 2000, 'IPCC Special Report on Emissions Scenarios.' Cambridge University Press
Nilsson, S. and Schopfhauser, W.: 1995, 'The carbon-sequstration potential of a global afforestation program', Climatic Change 30, 267-293.
Ravindranath, N. and Somashekhar, B.: 1995, 'Potential and Economics of Forestry Options for Carbon Sequestration in India', Biomass and Bioenergy 8, 323-336.
Richards, K.R. and Stokes, C.: 2004, 'A review of forest carbon sequestration cost studies: A dozen years of research', Climatic Change. 63, 1-48.
Sathaye, J., Makundi, W., Dale, L., Chan. P., and Andrasko, K.: 2005. 'GHG Mitigation Potential, Costs and Benefits in Global Forests: A Dynamic Partial Equilibrium Approach', Energy Journal
Sathaye, J.A., Markundi, W., Andrasko, K., Boer, R., Ravindranath, N.H., Sudha, P., Rao, S., Lasco, R., Pulhin, F., Masera, O., Ceron, A., Ordonez, J., Deying, X., Zhang, X. and Zuomin, S.: 2001, 'Carbon mitigation potential and costs of forestry options in Brazil, China, India, Indonesia, Mexica, the Philippines and Tanzania', Mitigation & Adaptation Strategies for Global Change 6, 185-211.
Sathaye, J., W. Makundi, L. Dale, P. Chan and K. Andrasko, 2006. GHG Mitigation Potential, Costs and Benefits in Global Forests: A Dynamic Partial Equilibrium Approach. Energy Journal, in press
Sohngen, B. and R. Sedjo, 2006. Carbon sequestration costs in global forests. Energy Journal, in press.
Schlamadinger, B. and Marland, G.: 1997, 'The role of forest and bioenergy strategies in the global carbon cycle', Fuel en Energy Abstracts 38, 116-120.
Sohngen, B. and Mendelsohn, R.: 2003, 'An Optimal Control Model of Forest Carbon Sequestration', American Journal of Agricultural Economics, 85(2), 448-457.
Strengers, B., Leemans, R., Eickhout, B., De Vries, B. and Bouwmann, L.: 2004, 'The land-use projections and resulting emissions in the IPCC SRES scenarios as simulated by the IMAGE 2.2. model', GeoJournal 61, 381-393.
Trines, E.: 2003, 'Abatement and independent verification costs of sinks CDM projects: An inventory of experience', Treeness Consultant,
Van Minnen, J.G., Strengers, B. and Eickhout, B.: 2006, 'Evaluating the role of carbon plantations in mitigating climate change, considering different land-use requirements: Methodology & first results', Climatic Change. submit.,
Van Vuuren, D., den Elzen, M., Lucas, P., Eickhout, B., Strengers, B., van Ruijven, B., Wonink, S., van den Houdt, R., Berk, M. and Oostenrijk, R.: 2005, 'Stabilising greenhouse gas concentrations. Assessment of different strategies and costs using an integrated assessment framework', Climatic Change. submit.,
Van Vuuren, D.P. and O'Neill, B.C.: 2005. The consistency of IPCC's SRES scenarios to 1990-2000 trends and recent projections. Climatic Change, in press.
Waterloo, M.J., Spiertz, P.H., Diemont, H., Emmer, I., Aalders, E., Wichink-Kruit, R. and Kabat, P.: 2001, 'Criteria potentials and costs of forestry activities to sequester carbon within the framework of the clean development meachanism', Alterra Green world Reserach, Wageningen, the Netherlands
Watson, R.T., Noble, I.R., Bolin, B., Ravindranth, N.H., Verado, D. and Dokken, D.J. (Eds): 2000, 'IPCC Special report on Land Use, Land-Use Change, and Forestry', Cambridge University Press, p. 377.
Xu, D., Zhang, X. and Shi, Z.: 2001, 'Mitigation potential for carbon sequestration through forestry activities in Southern and Eastern China', Mitigation & Adaptation Strategies for Global Change 6, 213-232.

Chapter 3:

Abed K.A. and A.A. El-Mallah. 1997. Capacity Factor of wind turbines, Energy, 22(5) 487-491.
Alcamo, J., R. Leemans and E. Kreileman, Eds. 1998. Global change scenarios of the 21st century - Results from the Image 2.1 Model. Elsevier Science Ltd., Oxford,
Alcamo, J., P. Mayerhofer, R. Guardans, T. van Harmelen, J. van Minnen, J. Onigkeit, M. Posch and B. de Vries, 2002. An integrated assessment of regional air pollution and climate change in Europe: findings of the AIRCLIM project. Env Science and Policy. 5 257-272.
ATLAS, 2005. Historical and future costs of electricity produced by renewable energy technologies. http://europe.eu.int/comm/energy_transport/atlas/homeu.html
Berndes, G., M. Hoogwijk and R. van den Broek, 2003. The contribution of biomass in the future global energy supply: a review of 17 studies. Biomass and Bioenergy. 25 (1): 1-27.
Brink, B. ten, et al. (2006). Cross-roads of Planet Earth's Life: Exploring means to meet the 2010-biodiversity target. In preparation. MNP Bilthoven
BWEA (British Wind Energy Association), 2000. Planning for wind energy - A guide for regional targets
Cabooter, Y., L. Dewilde and M. Langie, 1999. An inventory of locations suitable for wind energy in Flanders regions. European Wind Energy Conference, Nice
Damen, K. and A. Faaij, 2004. A Life Cycle Inventory of existing biomass import chains for "green" electricity production. To be submitted.
De Vries, B., J. Bollen, L. Bouwman, M. den Elzen, M. Janssen and E. Kreileman (2000). Greenhouse-gas emissions in an equity-, environment- and service-oriented world: an IMAGE-based scenario for the next century. Technological Forecasting & Social Change 63(2-3)
De Vries, H. J. M., D. P. van Vuuren, M. G. J. den Elzen and M. A. Janssen, 2001. The Targets Image Energy model regional (TIMER) - Technical documentation. National Institute of Public Health and the Environment (RIVM), Bilthoven, the Netherlands
EIA (Energy Information Agency), 1999. Assumptions to the annual energy outlook 1999 - renewable Fuels Module
Elliot, D.L. and M.N. Schwartz, 1993. Wind Energy Potential in the United States. Pacific Northwest Laboratory
Ericsson, K. and L. J. Nillson, 2003. International biofuel trade - A study of the Swedich import. Biomass and Bioenergy. in press
EWEA/Greenpeace, 2002. Windforce 12, A blueprint to achieve 12% of the world's electricity from wind power by 2020. EWEA/Greenpeace,
Fellows, A., 2000. The potential of wind energy to reduce carbon dioxide emissions. Garrad Hassan, Glasgow,
Grubb, M. J. and N. I. Meyer, 1993. Wind energy: Resources, systems, and regional strategies. In: T. B. Johansson, H.Kelly, A. K. N. Reddy and R. H. Williams, Renewable energy: Sources for fuels and electricity. Island Press, Washington, D.C.,
Hall, D. O., F. Rosillo-Calle, R. H. Williams and J. Woods, 1993. Biomass for energy: supply prospects. In: T.B.Johansson, H. Kelly, A. K. N. Reddy and R. H. Williams, Renewable energy - Sources for fuels and electricity. Island Press, Washington,
Hamelinck, C., 2004. Outlook for advanced biofuels. Science, Technology and Society. Utrecht University,
Harmon, C., 2000. Experience curves of photovoltaic technology. IIASA, Laxenburg,

Hendriks, C., M. Harmelink , K. Burges and K. Ransel, 2004. Power and heat productions: plant developments and grid losses. Ecofys, Utrecht,

Hofman, Y., D. de Jager, E. Molenbroek, F. Schilig and M.Voogt, 2002. The potential of solar electricity to reduce CO_2 emissions. Ecofys, Utrecht,

Hoogwijk, M., 2004. On the global and regional potential of renewable energy sources. Utrecht University, http://www.library.uu.nl/digiarchief/dip/diss/2004-0309-123617/full.pdf

Hoogwijk, M., A. Faaij, B. Eickhout, B. de Vries and W. Turkenburg, 2005. Potential of biomass energy out to 2100, for four IPCC SRES land-use scenarios Biomass and Bioenergy 29 225 - 257.

Hoogwijk, M., H.J.M. de Vries and W. C. Turkenburg, 2004. Assessment of the global and regional geographical, technical and economic potential of onshore wind energy. Energy Economics. 26 889-919.

Hoogwijk, M., D. van Vuuren, H.J.M. de Vries and W. C. Turkenburg, 2006. Exploring the impact on cost and electricity production of high penetration levels of intermittent electricity on OECD Europe and the USA (submitted for publication)

IEA, 2000. Experience curves for Energy Technology Policy. International Energy Agency, Paris

IMAGE-team, 2001. The IMAGE 2.2 implementation of the SRES scenarios. A comprehensive analysis of emissions, climate change and impacts in the 21st century. National Institute for Public Health and the Environment (RIVM), Bilthoven, the Netherlands

Johansson, T. B., H. Kelly, A. K. N. Reddy and R. H. Williams, Eds. 1993. Renewable Energy: Sources for Fuels and Electricity. Island Press, Washington, D.C.

Junginger, M., A. Faaij and W. Turkenburg, 2005. Global experience curves for wind farms. Energy Policy. 33 133 - 150

Kobos, P. H., J. D. Erickson and T. E. Drennen, 2005. Technological learning and renewable energy costs; implications for US renewable energy policy. Energy Policy. in press

Loveland, T. R. and A. S. Belward, 1997. The IGBP-DIS global 1 km cover data set Discover. First results. Int. J. Remote Sens. 18 3289-3295

Nakicenovic, N., J. Alcamo, G. Davis, B. de Vries, J. Fenhann et al., 2000. Special Report on Emissions Scenarios (SRES). Cambridge University Press, Cambridge, UK

Nemet, G. F., 2005. Beyond the learning curve: factors influencing cost reductions in photovoltaics. Energy Policy (in press)

New, M., M. Hulme and P. Jones, 1997. A 1961-1990 mean monthly climatology of global land areas. Climate Research Unit, Norwich

New, M., M. Hulme and P. Jones, 1999. Representing twentieth century space-time climate variability, Part I: Development of a 1961-91 mean monthly terrestrial climatology. American Meteorological Society. March 1999 820 - 856

Palmer, K.L. and Burtraw, D. (2005). “The Environmental Impacts of Electricity Restructuring: Looking Back and Looking Forward,” *Environment & Energy Law & Policy Journal,* forthcoming.

REN21, 2005. Renewables 2005 Global status report. Worldwatch Institute - Renewable Energy Policy Network 2005, Washington DC

Rogner, H. H., 2000. Energy resources. In: WEA 2000

solarbuzz, 2002. SolarBuzz module prices. www.solarbuzz.com

Sørensen, B., 2000. Renewable Energy - 2nd edition. Academic Press

Strengers, B. J., R. Leemans, B. Eickhout, B. de Vries and A. F. Bouwman, 2004. The land use projections in the IPCC SRES scenarios as simulated by the IMAGE 2.2 model. GeoJournal 61(2004)381-393

Turkenburg, W. C., 2000. Renewable energy technologies. in J. Goldemberg, World Energy Assessment. UNDP, Washington D.C.
WEA (World Energy Assessment) 2000. Energy and the challenge of sustainability. UNDP - United Nations Development Programme, New York
Weingart, J. M., 1978. The Helios strategy: An heretical view of the potential role of solar energy in the future of a small planet. Technological Forecasting and Social Change. 12(1978)273-315
WEC (World Energy Council), 1994. New Renewable Energy Resources - A Guide to the future. Kogan Page Limited, London
WBGU (German Advisory Council on Global Change), 1999. World in transition - Conservation and sustainable use of the biosphere
WCPA (World Commission on Protected Areas), 2000. Protected Areas: Benefits Beyond Boundaries - WCPA in Action

Chapter 4:

AEA Technology Environment, 1998. Options to reduce nitrous oxide emissions (final report). AEAT-4180: Issue 3
Bates, J. and Haworth, A., 2001. Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change. Economic Evaluation of Emission Reductions of Methane in the Waste Sector in the EU - Bottom-up Analysis, AEAT, Abingdon, UK
Blok, K., De Jager, D. and Hendriks, C., 2001. Economic evaluation of sectoral emission reduction objectives for climate change - summary report for policy makers, Ecofys Energy and Environment, Utrecht, The Netherlands
Brink, J.C., 2003. Modelling cost-effectiveness of interrelated emission reduction strategies - The case of agriculture in Europe, Wagening University, Wageningen, the Netherlands.
Clemens, J. and Ahlgrimm, H.-J., 2001. Greenhouse gases from animal husbandry: mitigation options. Nutrient Cycling in Agroecosystems, 60: 287-300.
COHERENCE, 1999. Economic Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change, Final Report for European Commission. Prepared by COHERENCE (Belgium) with support of ECOFYS (the Netherlands) National University of Athens (NTUA) and ECOSIM (UK)
De Beer, J., Phylipsen, D. and Bates, J., 2001. Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change Economic Evaluation of Carbon Dioxide and Nitrous Oxide Emission. Reductions in Industry in the EU. Bottom-up Analysis. Final Report. Ecofys, Utrecht, January 2001.
DeAngelo, B.J., DelaChesnaye, F.C., Beach, R.H., Sommer, A. and Murray, B.C., 2006. Methane and nitrous oxide mitigation in agriculture. Energy Journal (in press).
Delhotal, K.C., DelaChesnaye, F.C., Gardiner, A., Bates, J. and Sankovski, A., 2006. Mitigation of methan and nitrous oxide emissions from waste, energy and industry. Energy Journal (in press).
den Elzen, M.G.J. and Lucas, P.L., 2005. The FAIR model: A tool to analyse environmental and costs implications of regimes of future commitments. Environmental Modeling & Assessment, 10(2): 115 - 134.
den Elzen, M.G.J., Lucas, P.L. and van Vuuren, D.P., 2005. Abatement costs of post-Kyoto climate regimes. Energy Policy, 33(16): 2138-2151.
den Elzen, M.G.J., Meinshausen, M. and van Vuuren, D.P., 2006. Multi-gas emission envelopes to meet long-term greenhouse gas concentration targets: trade-off between costs and climate risks. Global Environmental Change (submitted).
EPA, 1999. U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions, USEPA, Washington, DC
EPA, 2001. U.S. High GWP Gas Emissions 1990–2010: Inventories, Projections, and Opportunities for Reductions. report no. EPA 000-F-97-000, US-EPA

Fuglestvedt, J.S. et al., 2003. Metrics of Climate Change: Assessing Radiative Forcing and Emission Indices. Climatic Change, 58(3): 267-331.
Graus, W., Harmelink, M. and Hendrinks, C., 2004. Marginal GHG-abatement curves for agriculture, Ecofys, Utrecht, the Netherlands
Graveland, C., Bouwman, A.F., de Vries, B., Eickhout, B. and Strengers, B.J., 2002. Projections of multi-gas emissions and carbon sinks, and marginal abatement cost functions modelling for land-use related sources. Report no. 461502026, National Institute for Public Health and the Environment, Bilthoven, the Netherlands
Hansen, J. et al., 2005. Efficacy of climate forcings. Journal of Geophysical Research, 110: D18104, doi:10.1029/2005JD005776.
Hansen, J., Sato, M., Ruedy, R., Lacis, A. and Oinas, V., 2000. Global warming in the twenty-first century: an alternative scenario. PNAS., 97(18): 9875-9880.
Harnisch, J. and Gluckman, R., 2001. Final Report on the European Climate Change Programme Working Group Industry Work Item Fluorinated Gases. Prepared on behalf of the European Commission (DG ENV and DG ENTR), Ecofys/Enviros, Germany
Hayhoe, K. et al., 1999. Costs of multigreenhouse gas reduction targets for the USA. Science, 286: 905-906.
Heijnes, H., Van Brummelen, M. and Blok, K., 1999. Reduction of the emissions of HFC's, PFC's and SF6 in the European Union. Final report, Ecofys, Utrecht, the Netherlands
Hendriks, C. and de Jager, D., 2001. Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change. Economic Evaluation of Methane Emission Reduction in the Extraction, Transport and Distribution of Fossil Fuels in the EU Bottom-up Analysis. Final Report., Ecofys, Utrecht, the Netherlands
Hendriks, C., De Jager, D. and Blok, K., 1998. Emission reduction potential and costs for methane and nitrous oxide in the EU-15. Interim report by order of the DG XI. EC., Ecofys, Utrecht, the Netherlands
Hourcade, J.C. and Shukla, P., 2001. Global, Regional and National Costs and Ancillary Benefits of Mitigation. In: B. Metz, O. Davidson, R. Swart and J. Pan (Editors), Climate Change 2001: Mitigation. Cambridge University Press, Cambridge.
Hyman, R.C., Reilly, J.M., Babiker, M.H., De Masin, A. and Jacoby, H.D., 2002. Modeling non-CO_2 greenhouse gas abatement. Environmental Modeling and Assessment, 8(3): 175 - 186.
IEA, 2004. World Energy Outlook, International Energy Agency, Paris, France
IMAGE-team, 2001. The IMAGE 2.2 implementation of the SRES scenarios. A comprehensive analysis of emissions, climate change and impacts in the 21st century. CD-ROM publication 481508018, National Institute for Public Health and the Environment, Bilthoven, the Netherlands.(http://www.mnp.nl/en)
Jensen, J. and Thelle, M.H., 2001. What are the gains from a multi-gas strategy? FEEM Working Paper No. 84.2001
Klein Goldewijk, K., Olivier, J.G.J., Peters, J.A.H.W., Coenen, P.W.H.W. and Vreuls, H.H.J., 2005. Greenhouse Gas Emissions in the Netherlands 1990-2003, National Inventory Report 2005. Report no. 773201009, National Institute for Public Health and the Environment, Bilthoven, the Netherlands
Lantin, S., Wassmann, R., Buendia, L. and Neue, H., 2003. Implementing Mitigation Technologies in Rice Cultivation, International Rice Research Institute
Lucas, P.L., Den Elzen, M.G.J. and Van Vuuren, D., 2005. Multi-gas abatement analysis of the Kyoto Protocol. Report no. 550006001, Netherlands Environmental Assessment Agency (MNP), Bilthoven, the Netherlands.(http://www.mnp.nl/en)
Manne, A.S. and Richels, R.G., 2001. An alternative approach to establishing trade-offs among greenhouse gasses. Nature, 5: 675-677.
Marks, J., Chase, J. and Rand, S.D., 2005. New developments in international and US programs for PFC reductions in aluminium, NCGG-4.
Morita, T. et al., 2001. Greenhouse gas emission mitigation scenarios and implications. In: B. Metz, O. Davidson, R. Swart and J. Pan (Editors), Climate Change 2001: Mitigation. Cambridge University Press, Cambridge.

Mosier, A.R., Duxbury, J.M., Freney, J.R., Heinemeyer, O. and Minami, K., 1998. Assessing and mitigating N2O emissions from agricultural soils. Climatic Change, 40(1): 7-38.
Nakicenovic, N. et al., 2000. Special Report on Emissions Scenarios. IPCC Special Reports. Cambridge University Press, Cambridge.
Olivier, J.G.J. and Berdowski, J.J.M., 2001. Global emissions sources and sinks. In: J. Berdowski, R. Guicherit and B.J. Heij (Editors), The Climate System. A.A. Balkema Publishers/Swets & Zeitlinger Publishers, Lisse, The Netherlands, pp. 33-78.
Olivier, J.G.J. et al., 2002. Applications of EDGAR. Including a description of EDGAR 3.2: reference database with trend data for 1970-1995. report no. 773301001/NRP report 410200 051, National Institute for Public Health and the Environment, Bilthoven, the Netherlands.(http://www.mnp.nl/en)
Olivier, J.G.J. et al., 2005. Recent trends in global greenhouse gas emissions: regional trends 1970-2000 and spatial distribution of key sources in 2000. Environmental Sciences, 2(2-3): 81-99.
Reilly, J. et al., 1999. Multi-gas assessment of the Kyoto Protocol. Nature, 401: 549-555.
Reimer, R.A., Slaten, C.S., Seapan, M., Koch, T.A. and Triner, V.G., 1999. Implementation of Technologies for Abatement of N2O Emissions Associated with Adipic Acid Manufacture, Presentation at the Second International Symposium on Non-CO_2 Greenhouse Gases, September 8-10, 1999, Noordwijkerhout, The Netherlands.
Rosegrant, M.W., Cai, X. and Cline, S.A., 2002. World water and food to 2025: Dealing with scarcity. International Food Policy Research Institute, Washington DC.
Schaefer, D.O., Godwin, D. and Harnisch, J., 2006. Estimating future emissions and potential reductions of HFCs, PFCs and SF6. Energy Journal (in press).
Schwarz, W. and Leisewitz, A., 1999. Emissions and Reduction Potentials of Hydrofluorocarbons, Perfluorocarbons and Sulphur Hexafluoride in Germany. UBA-FB, Öko-Recherche, Frankfurt am Main, Germany
Shindell, D.T., Faluvegi, G., Bell, N. and Schmidt, G.A., 2004. An emissions-based view of climate forcing by methane and tropospheric ozone. Geophysical Research Letters, L04803, doi:10.1029/2004GL021900.
Strengers, B.J., Van Minnen, J.G. and Eickhout, B., in prep. The role of carbon plantations in mitigating climate change: potentials and costs.
Tol, R.S.J., 1999. The marginal costs of greenhouse gas emissions. Energy Journal, 20(1): 61-81.
UN, 2004. World Population to 2300, United Nations, New York.
Van den Brink, R.W. et al., 2002. Combined Catalytic Removal of NOx and N2O in the nitric acid industry. ECN-C--02-009, ECN, the Netherlands
Van Vuuren, D. et al., 2003. Regional costs and benefits of alternative post-Kyoto climate regimes: Comparison of variants of the Multi-Stage and Per Capita Convergence regimes. Report no. 728001025, National Institute for Public Health and the Environment, Bilthoven, the Netherlands.(http://www.mnp.nl/en)
Van Vuuren, D.P. et al., 2006a. Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. Climatic Change (forthcoming).
Van Vuuren, D.P., Eickhout, B., Lucas, P.L. and Den Elzen, M.G.J., 2006b. Long-term multi-gas scenarios to stabilise radiative forcing - Exploring costs and benefits within an integrated assessment framework. Energy Journal (in press).
Van Vuuren, D.P., Weyant, J.P. and De la Chesnaye, F.C., 2006c. Multigas scenarios to stabilise radiative forcing. Energy Economics, 28: 102-120.
Wartmann, S. and Harnisch, J., 2005. Reductions of SF6 emissions from high and medium voltage electrical equipment in Europe. Final Report to CAPIEL 28 June 2005. Project No.: dm70047.2, Ecofys GmbH, Nürnberg, Germany
WBCSD/WRI, 2005. Greenhouse gas protocol.
Weyant, J.P. and De la Chesnaye, F.C., 2006. Overview of EMF - 21: Multigas Mitigation and Climate Change. Energy Journal (in press).
WSC, 2005. Semiconductor manufacturers reduce PFC emissions. World's chipmakers on track to achieve 2010 goals for cutting emissions (World Semiconductor Council), Press release 19 May 2005.

Chapter 5:

Argote, L. and D. Epple: 1990. 'Learning Curves in Manufacturing.' Science, 247: 920 - 924.
Arnason, B. A. and T. I. Sigfuasson: 2000. 'Iceland - A future hydrogen economy?' Int. J. Hydrogen Energy, 25: 389 - 394.
Azar, C., K.Lindgren and B. A. Andersson: 2000. Hydrogen or methanol in the transportation sector. Department of Physical Resource Theory, Chalmers University of Technology, Goteborg.
Azar, C., K. Lindgren and B. A. Andersson: 2003. 'Global energy scenarios meeting stringent CO_2 constraints - cost-effective fuel choices in the transportation sector.' Energy Policy, 31: 961-976.
Barreto, L., A. Makihira and K. Riahi: 2003. 'The hydrogen economy in the 21st century: a sustainable development scenario.' Int. J. Hydrogen Energy, 28: 267 - 284.
Bolton, J. R.: 1996. 'Solar photoproduction of hydrogen: a review.' Solar Energy, 57(1): 37 - 50.
Caprioglio, P.: 1974. 'Prospects for a hydrogen economy.' Energy Policy, 2(3): 244-245.
Clark II, W. W. and J. Rifkin: 'A green hydrogen economy.' Energy Policy, In Press, Corrected Proof.
Damen, K., M. v. Troost, A. Faaij and W. Turkenburg: 2006. 'A comparison of electricity and hydrogen production systems with CO_2 capture and storage. Part A: Review and selection of promising conversion and capture technologies.' Progress in Energy and Combustion Science, 32(2): 215-246.
de Vries, H. J. M., D. P. van Vuuren, M. G. J. den Elzen and M. A. Janssen: 2001. The TIMER IMage Energy Regional (TIMER) Model. National Institute for Public Health and the Environment (RIVM), Bilthoven.
den Elzen, M. G. J. and P. Lucas: 2003. FAIR 2.0 - A decision-support tool to assess the environmental and economic consequences of future climate regimes. National Institute of Public Health and the Environment, Bilthoven, the Netherlands.
den Elzen, M. G. J. and M. Meinshausen: 2005. Meeting the EU 2^{o}C climate target: global and regional emission implications. Netherlands Environmental Assessment Agency (MNP), Bilthoven.
Dunn, S.: 2001. Hydrogen futures: Toward a sustainable energy system. Worldwatch Institute, Washington.
Dutton, G.: 2002. Hydrogen Energy Technology. Tyndall Centre for Climate Change Research, Norwich.
Edmonds, J., J. Clarke, J. Dooley, S. H. Kim and S. J. Smith: 2004. 'Stabilisation of CO_2 in a B2 world: insights on the roles of carbon capture and disposal, hydrogen, and transportation technologies.' Energy Economics, 26(4): 517-537.
European Commission: 2003. Hydrogen Energy and Fuel Cells, A vision for our future. High Level Group for Hydrogen and Fuel Cells, Brussels.
Glatzmaier, G., D. Blake and S. Showalter: 1998. Assessment of methods for hydrogen production using concentrated solar energy. NREL, Golden, Colorado, USA.
GM: 2001. Tank-to-wheel energy utilization for a North American vehicle. General Motors Corporation.
GM: 2002. Well-to-wheel analysis of energy use and greenhouse gas emissions of advanced fuel / vehicle systems - A European Study. L-B systemtechnik, Ottobrun, Germany.
Hamelinck, C. N. and A. P. C. Faay: 2001. Future prospects for production of methanol and hydrogen from biomass. Utrecht University, Utrecht.
Hammerschlag, R. and P. Mazza: 2005. 'Questioning hydrogen.' Energy Policy, 33(16): 2039-2043.
Hendriks, C., M. Harmelink, Y. Hofmans and D. de Jager: 2002. Climate neutral energy carriers in the regulatory energy tax. Ecofys, Utrecht.
Hoogwijk, M.: 2004. On the global and regional potential of renewable energy sources. Science Technology and Society. Utrecht University, Utrecht: 256.
IEA/AFIS: 1996a. Automotive fuels survey, Distribution and use. Innas BV, Breda.
IEA/AFIS: 1996b. Automotive Fuels Survey, Raw materials and conversion. Innas BV, Breda.
IMAGE-team: 2001. The IMAGE 2.2 implementation of the IPCC SRES scenarios. A comprehensive analysis of emissions, climate change and impacts in the 21st century. National Institute for Public Health and the Environment, Bilthoven, the Netherlands.

International Energy Agency: 2004. World Energy Outlook 2004. International Energy Agency, Paris.
Keith, D. W. and A. E. Farrel: 2003. 'Rethinking Hydrogen Cars.' Science, 301: 2.
Lovins, A.: 2003. Twenty Hydrogen Myths. Rocky Mountain Institute, Snowmass.
Lucas, N. J. D.: 1976. 'Hydrogen and nuclear power.' Energy Policy, 4(1): 25-36.
Mintz, M., S. Folga, J. Molburg and J. Gillete: 2002. Cost of some Hydrogen Fuel Infrastructure Options. Argone National Laboratory, Chicago.
Momirlan, M. and T. N. Veziroglu: 2002. 'Current status of hydrogen energy.' Renewable and Sustainable Energy Reviews, 6: 141 - 179.
Morris, D.: 2003. A better way to get from here to there; A commentary on the hydrogen economy and a proposal for an alternative strategy. Institute for Local Self-Reliance, Minneapolis.
National Research Council: 2004. The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs. The National Academies Press, Washington, DC.
Ogden, J. M.: 1999a. 'Developing an infrastructure for hydrogen vehicles: a Southern California case study.' Int. J. Hydrogen Energy, 24: 709 - 730.
Ogden, J. M.: 1999b. 'Prospects for building a hydrogen energy infrastructure.' Annual Reviews of Energy and the Environment, 24: 227-279.
Padro, C. E. G. and V. Putsche: 1999. Survey of the economics of hydrogen technologies. National Renewable Energy Laboratory, Golden, Colorado.
Reijnders, H. T. J., A. de Groot and P. Lako: 2001. Evaluatie van waterstof-gebaseerde concepten en systemen. ECN, Petten.
Rogner, H. H.: 1998. 'Hydrogen technologies and the technology learning curve.' Int. J. Hydrogen Energy, 23(9): 833 - 840.
Shell: 2001. Energy needs, Choices and Possibilities: Scenarios to 2050. Shell International, London.
Thomas, C. E., B. D. James and F. D. Lomax: 1998. 'Market penetration scenarios for fuel cell vehicles.' Int. J. Hydrogen Energy, 23(10): 949 - 966.
Tillemans, F. W. A. and A. de Groot: 2002. Evaluation of benefits and barriers of hydrogen in residential districts. ECN, Petten.
TNO: 1975. Waterstof als energiedrager, toekomstige mogelijkheden in Nederland. TNO, Den Haag.
Tsuchiya, H. and O. Kobayashi: 2004. 'Mass production cost of PEM fuel cell by learning curve.' International Journal of Hydrogen Energy, 29(10): 985-990.
Turton, H. and L. Barreto: 'Long-term security of energy supply and climate change.' Energy Policy, In Press, Corrected Proof.
U.S. Department of Energy: 2002. A National Vision of America's Transition to a Hydrogen Economy, to 2030 and beyond. United States Department of Energy, Washington, DC.
van den Brink, R.: 2003. Scenario's voor duurzame energie in verkeer en vervoer, beoordeling op verschillende criteria van duurzaamheid. RIVM, Bilthoven.
van Ruijven, B. J.: 2003a. Hydrogen Energy, Technologies and Transition. Utrecht University, Dep. of Science, Technology and Society, Utrecht.
van Ruijven, B. J.: 2003b. Hydrogen in the future global energy system. Environmental Science. Utrecht University, Utrecht: 102.
van Vuuren, D. P. and H. J. M. de Vries: 2001. 'Mitigation scenarios in a world oriented at sustainable development: the role of technology, efficiency and timing.' Climate Policy, 1: 189 - 210.
van Vuuren, D. P., H. J. M. de Vries, M. M. Hoogwijk and B. J. van Ruijven: 2005. TIMER 2.0 - Technical Documentation. RIVM-MNP, Bilthoven.
van Vuuren, D. P., M. G. J. Den Elzen, P. L. Lucas, B. Eickhout, B. J. Strengers, B. J. van Ruijven, S. Wonink and R. van Houdt: in prep. 'Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs.'
Wurster, R. and D. W. Zittel: 1994. Hydrogen energy. L-B systemtechnik, Ottobrun, Germany.

Chapter 6:

Ammann, C.M., Meehl, G.A., Washington, W.M. and Zender, C.S.: 2003, ‘A monthly and latitudinally varying volcanic forcing dataset in simulations of 20th century climate’, Geophysical Research Letters 30(12), 1657.

Andronova, N.G. and Schlesinger, M.E.: 2001, 'Objective estimation of the probability density function for climate sensitivity', Journal of Geophysical Research-Atmospheres 106(D19), 22.
Azar, C. and Dowlatabadi, H.: 1999, 'A review of technical change in assessment of climate policy', Annual Review of Energy and the Environment 24, 513-544.
Azar, C., Lindgren, K., Larson, E. and Möllersten, K.: 2006, 'Carbon Capture and Storage From Fossil Fuels and Biomass – Costs and Potential Role in Stabilizing the Atmosphere ', Clim. Change 74(1-3), 47-79.
Bruckner, Thomas, Petschel-Held, Gerhard, Leimbach, Marian and Toth, Ferenc L., 2003. Methodological Aspects of the Tolerable Windows Approach. Climatic Change, 56(1-2): 73-89.
De Vries, H.J.M., D.P. van Vuuren, den Elzen, M.G.J. and Janssen, M.A.: 2002. The Targets Image Energy model regional (TIMER) - Technical documentation. MNP-report 461502024, Netherlands Environmental Assessment Agency (MNP), Bilthoven, the Netherlands.
Den Elzen, M.G.J. and Lucas, P.: 2005, 'The FAIR model: a tool to analyse environmental and costs implications of climate regimes', Environmental Modeling and Assessment 10(2), 115-134.
Den Elzen, M.G.J., Lucas, P. and van Vuuren, D.P.: 2005, 'Abatement costs of post-Kyoto climate regimes', Energy Policy 33(16), pp. 2138-2151.
Den Elzen, M.G.J. and Meinshausen, M.: 2005. Meeting the EU 2°C climate target: global and regional emission implications. MNP-report 728001031 (www.mnp.nl/en), Netherlands Environmental Assessment Agency (MNP), Bilthoven, the Netherlands.
Den Elzen, M.G.J. and Meinshausen, M.: 2006. Multi-gas emission pathways for meeting the EU 2°C climate target. In: H.J. Schellnhuber, W. Cramer, N. Nakicenovic, T. Wigley and G. Yohe (eds.), Avoiding Dangerous Climate Change. Cambridge University Press, Cambridge, UK, pp. 299-310.
Eickhout, B., den Elzen, M.G.J. and van Vuuren, D.P.: 2003. Multi-gas emission profiles for stabilising greenhouse gas concentrations. MNP-report 728001026, Netherlands Environmental Assessment Agency (MNP), Bilthoven, the Netherlands.
O. Edenhofer, K. Lessmann, C. Kemfert, M. Grubb and J. Koher (2006) Induced Technological Change: Exploring its Implications for the Economics of Atmospheric tabilization: Synthesis Report from the Innovation Modeling Comparison Project. The Energy Journal 57-107.
Enting, I.G., Wigley, T.M.L. and Heimann, M.: 1994. Future emissions and concentrations of carbon dioxide. Mordialloc, Australia.
Folland, C.K. et al.: 2001, 'Global temperature change and its uncertainties since 1861', Geophysical Research Letters 28(13), 2621-2624.
Forest, C.E., Stone, P.H., Sokolov, A., Allen, M.R. and Webster, M.D.: 2002, 'Quantifying Uncertainties in Climate System Properties with the Use of Recent Climate Observations', Science 295, 113-117.
Frame, D.J., Booth, B.B.B., Kettleborough, J.A., Stainforth, D.A., Gregory, J.M., Collins, M. and Allen, M.R.: 2005, 'Constraining climate forecasts: The role of prior assumptions', Geophysical Research Letters 32(9).
Gregory, J.M., Stouffer, R.J., Raper, S.C.B., Stott, P.A. and Rayner, N.A.: 2002, 'An observationally based estimate of the climate sensitivity', Journal of Climate 15(22), 3117-3121.
Gritsevskyi, A. and Nakicenovic, N.: 2000, 'Modeling uncertainty of induced technological change', Energy Policy 28(13), 907-921.
Ha-Duong, M., Grubb, M.J. and Hourcade, J.C.: 1997, 'Influence of socioeconomic inertia and uncertainty on optimal CO_2-emission abatement', Nature 390(6657), 270-273.
Hammit, J.K., Lempert, R.J. and Schlesinger, M.E.: 1992, 'A sequential-decision strategy for abating climate change', Nature 357(315).
Hansen, J., Sato, M., Ruedy, R., Lacis, A. and Oinas, V.: 2000, 'Global warming in the twenty-first century: An alternative scenario', PNAS 97(18), 9875-9880.
Hare, W.L. and Meinshausen, M.: 2006, 'How Much Warming are We Committed to and How Much can be Avoided?' Clim. Change 75(1-2), 111-149.
Höhne, N.: 2005. Impact of the Kyoto Protocol on Stabilization of Carbon Dioxide Concentration, Scientific Symposium "Avoiding Dangerous Climate Change" (www.stabilisation2005.com/).
Hourcade, J.-C. and Shukla, P.R.: 2001. Global, regional and national costs and ancillary benefits of mitigation. In: B. Metz, Davidson, O., Swart, R., Pan, J. (ed.), Climate Change 2001: Mitigation;

Contribution of Working Group III to the Third Assessment Report of the IPCC. Cambridge University Press, Cambridge, UK.
IMAGE-team: 2001. The IMAGE 2.2 implementation of the SRES scenarios. A comprehensive analysis of emissions, climate change and impacts in the 21st century. CD-ROM publication 481508018, Bilthoven, the Netherlands.
Jones, P.D. and Moberg, A.: 2003, 'Hemispheric and large-scale surface air temperature variations: An extensive revision and an update to 2001', Journal of Climate 16(2), 206-223.
Jones, P.D. et al.: 2001, 'Adjusting for sampling density in grid box land and ocean surface temperature time series', Journal of Geophysical Research-Atmospheres 106(D4), 3371-3380.
Knutti, R., Meehl, G.A., Allen, M.R. and Stainforth, D.A.: 2006, 'Constraining climate sensitivity from the seasonal cycle in surface temperature', Journal of Climate (in press).
Knutti, R., Stocker, T.F., Joos, F. and Plattner, G.K.: 2003, 'Probabilistic climate change projections using neural networks', Climate Dynamics 21(3-4), 257-272.
Kreileman, E. and Berk, M., 1997. The safe landing analysis: Users manual, Netherlands Environmental Assessment Agency (MNP), Bilthoven, the Netherlands, Bilthoven.
Lasky, M.: 2003. The Economic Costs of Reducing Emissions of Greenhouse Gases: A Survey of Economic Models.Technical Paper Series, Congressional Budget Office, Washington, DC.
Lean, J., Beer, J. and Bradley, R.S.: 1995, 'Reconstruction of solar irradience since 1610: Implications for climate change', Geophysical Research Letters 22, 3195-3198.
Lean, J.L.: 2001, 'Solar irradiance and climate forcing in the near future', Geophysical Research Letters 28(21), 4119-4122.
Lucas, P.L., van Vuuren, D.P., Olivier, J.G.J. and den Elzen, M.G.J.: 2006. Long-term reduction potential of non-CO_2 greenhouse gases. In: D.P. van Vuuren et al. (eds.), Stabilizing greenhouse gas concentrations at low levels: assessment of options and costs. Netherlands Environmental Assessment Agency (MNP), Bilthoven, the Netherlands.
Manne, A.S. and Richels, R.G.: 2001, 'An alternative approach to establishing trade-offs among greenhouse gases', Nature 410, 675-677.
Meinshausen, M.: 2006. What Does a 2°C Target Mean for Greenhouse Gas Concentrations? A Brief Analysis Based on Multi-Gas Emission Pathways and Several Climate Sensitivity Uncertainty Estimates. In: H.J. Schellnhuber, W. Cramer, N. Nakicenovic, T. Wigley and G. Yohe (eds.), Avoiding Dangerous Climate Change, Cambridge, UK.
Meinshausen, M., Hare, W.L., Wigley, T.M.L., van Vuuren, D.P., den Elzen, M.G.J. and Swart, R.: 2006, 'Multi-gas emission pathways to meet climate targets', Clim. Change 75(1-2), 151-194.
Morita, T. and Robinson, J.: 2001. Greenhouse gas emission mitigation scenarios and implications. In: B. Metz, O. Davidson, R. Swart and J. Pan (eds.), Climate Change 2001: Mitigation. Cambridge University Press, Cambridge.
Murphy, J.M., Sexton, D.M.H., Barnett, D.N., Jones, G.S., Webb, M.J., Collins, M. and Stainforth, D.A.: 2004, 'Quantification of modelling uncertainties in a large ensemble of climate change simulations', Nature 430, 768-772.
Nakicenovic, N. et al.: 2000. Special Report on emissions scenarios. IPCC Special Reports. Cambridge University Press, Cambridge, UK.
O'Neill, B.C. and Oppenheimer, M.: 2004, 'Climate change impacts are sensitive to the concentration stabilization path', PNAS 101(47), 16411-16416.
Piani, C., Frame, D.J., Stainforth, D.A. and Allen, M.R.: 2005, 'Constraints on climate change from a multi-thousand member ensemble of simulations', Geophysical Review Letters 32(L23825).
Rao, S. and Riahi, K.: 2006, 'The role of non-CO_2 greenhouse gases in climate change mitigation: long-term scenarios for the 21st century', Energy Journal, in press.
Repetto, R. and Austin, D.: 1997. The Costs of Climate Protection: A Guide for the Perplexed.World Resources Institute, Washington, D.C.
Strengers, B.J., van Minnen, J.G. and Eickhout, B.: 2006. The role of carbon plantations in mitigating climate change: potentials and costs. In: D.P. van Vuuren et al. (eds.), Stabilizing greenhouse gas concentrations at low levels: assessment of options and costs. Netherlands Environmental Assessment Agency (MNP), Bilthoven, the Netherlands.
Swart, R., Berk, M., Janssen, M., Kreileman, E. and Leemans, R.: 1998. The safe landing analysis: risks and trade-offs in climate change. In: J. Alcamo, R. Leemans and E. Kreileman (eds.),

Global change scenarios of the 21st century. Results from the IMAGE 2.1 model. Elseviers Science, London, pp. 193-218.
Swart, R., Mitchell, J., Morita, T. and Raper, S.: 2002, 'Stabilisation scenarios for climate impact assessment', Global Environmental Change 12(3), 155-165.
Toth, F., Bruckner, T., Füssel, H-M, Leimbach, M. and Petschel-Held, G., 1997. The Tolerable Windows Approach to Integrated Assessment, IPCC Asia-Pacific Workshop on Integrated Assessment Moderls, Tokyo.
Van Vuuren, D.P., den Elzen, M.G.J., Berk, M.M., Lucas, P., Eickhout, B., Eerens, H. and Oostenrijk, R.: 2003. Regional costs and benefits of alternative post-Kyoto climate regimes. RIVM-report 728001025, www.mnp.nl/en, Netherlands Environmental Assessment Agency (MNP), Bilthoven, the Netherlands.
Van Vuuren, D.P., den Elzen, M.G.J., Eickhout, B., Lucas, P.L., Strengers, B.J. and Ruijven, B.: 2006a, 'Stabilising greenhouse gas concentrations. Assessment of different strategies and costs using an integrated assessment framework.' Climatic Change (accepted).
Van Vuuren, D.P., Eickhout, B., Lucas, P.L. and den Elzen, M.G.J.: 2005, 'Long-term multi-gas scenarios to stabilise radiative forcing', Energy Journal, in press.
Van Vuuren, D.P., Weyant, J.P. and de la Chesnaye, F.C.: 2006b, 'Mult-gas scenarios to stabilise radiative forcing', Energy Economics 28, 102-120.
Weyant, J.P., De la Chesnaye, F.C. and G., B.: 2005, 'Overview of EMF - 21: Multi-gas Mitigation and Climate Change', Energy Journal (In press).
White-House: 2002. Executive Summary of Bush Climate Change Initiative.
Wigley, T.M.L.: 2003a. MAGICC/SCENGEN 4.1: Technical Manual.UCAR - Climate and Global Dynamics Division, Boulder, CO.
Wigley, T.M.L.: 2003b. Modelling climate change under no-policy and policy emissions pathways, Benefits of climate policy: improving information for policy makers. Organisation for Economic Co-operation and Development (OECD), Paris, France.
Wigley, T.M.L. and Raper, S.C.B.: 2001, 'Interpretation of high projections for global-mean warming', Science 293(5529), 451-454.
Wigley, T.M.L. and Raper, S.C.B.: 2002, 'Reasons for larger warming projections in the IPCC Third Assessment Report', Journal of Climate 15(20), 2945-2952.
Wigley, T.M.L., Richels, R. and Edmonds, J.A.: 1996, 'Economic and environmental choices in the stabilisation of CO_2 concentrations: choosing the "right" emissions pathway', Nature 379, 240-243.
Yohe, G., Andronova, N. and Schlesinger, M.: 2004, 'To Hedge or Not Against an Uncertain Climate Future?' Science 306, 416-417.

Chapter 7:

Alcamo, J., E. Kreileman, M. Krol, R. Leemans, J. Bollen, J. van Minnen, M. Schaeffer, S. Toet and H. J. M. de Vries: 1998. 'Global modelling of environmental change: on overview of IMAGE 2.1'. in Global change scenarios of the 21st century. Results from the IMAGE 2.1 model. R. L. a. E. K. J. Alcamo. Elseviers Science, London.: 3-94.
Azar, C.: 1998. "The timing of CO_2 emissions reductions: the debate revisited.' International Journal of Environment and Pollution, 10: 508-521.
Azar, C. and H. Dowlatabadi: 1999. 'A review of technical change in assessment of climate policy,.' Annual Review of Energy and the Environment, 24: 513-544.
Azar, C., K. Lindgren, E. Larson and K. Möllersten: in press. 'Carbon capture and storage from fossil fuels and biomass - Costs and potential role in stabilizing the atmosphere.' Climatic Change.
Azar, C. and H. Rodhe: 1997. 'Targets for stabilisation of atmospheric CO_2.' Science, 276: 1818-1819.
Barker, T., H. Pan, J. Koehler, R. Warren and S. Winne: 2005. 'Induced technological change in the stabilisation of carbon dioxide concentrations in the atmosphere: scenario using a large-scale econometric model'. Avoiding Dangerous Climate Change, Exeter.
Berk, M., J. van Minnen, B. Metz, W. Moomaw, M. den Elzen, D. P. Van Vuuren and J. Gupta: 2002. Climate OptiOns for the Long term (COOL). Global Dialogue - Synthesis Report. MNP Netherlands Environmental Assessment Agency, Bilthoven. www.mnp.nl/en

Bruinsma, J.: 2003. World agriculture: towards 2015/2030. An FAO perspective. EarthScan, London.
Carpenter, S. and P. Pingali: 2005. Millennium Ecosystem Assessment - Scenarios Assessment. Island Press, Washington DC.
Corfee Morlot , J., J. Smith, S. Agrawala and T. Franck: 2005. 'Article 2, Long-Term Goals and Post-2012 Commitments: Where Do We Go From Here with Climate Policy?' Climate Policy, 5(3).
Criqui, P., A. Kitous, M. M. Berk, M. G. J. den Elzen, B. Eickhout, P. Lucas, D. P. van Vuuren, N. Kouvaritakis and D. Vanregemorter: 2003. Greenhouse gas reduction pathways in the UNFCCC Process upto 2025 - Technical Report. CNRS-IEPE, Grenoble, France.
de Beer, J.: 1998. Potential for industrial energy efficiency improvement in the long term. Department of Science, Technology and Society. Utrecht University.
de Vries, H. J. M., D. P. van Vuuren, M. G. J. den Elzen and M. A. Janssen: 2001. The Targets Image Energy model regional (TIMER) - Technical documentation.. MNP Netherlands Environmental Assessment Agency, Bilthoven, the Netherlands. www.mnp.nl/en
den Elzen, M., P. Lucas and D. P. Van Vuuren: 2006a. 'Regional abatement costs and options under allocation schemes for emission allowances for low CO_2-equivalent concentrations.' Submitted.
den Elzen, M. G. J. and P. Lucas: 2005. 'The FAIR model: a tool to analyse environmental and costs implications of climate regimes.' Environmental Modeling and Assessment, 10(2): 115-134.
den Elzen, M. G. J. and M. Meinshausen: 2005. Meeting the EU 2 degree target: Global and regional emission implications. MNP Netherlands Environmental Assessment Agency, Bilthoven, The Netherlands. www.mnp.nl/en
den Elzen, M. G. J., M. Meinshausen and D. P. Van Vuuren: 2006b. 'Multi-gas emissions corridors to meet long-term greenhouse gas concentration targets: trade-off between costs and climate risks.' Submitted.
ECF and PIK: 2004. What is dangerous climate change? Initial Results of a Symposium on Key Vulnerable Regions, Climate Change and Article 2 of the UNFCCC. European Climate Forum and Postdam Institute for Climate Impact Research. http://www.european-climate-forum.net/pdf/ECF_beijing_results.pdf
Edmonds, J. A., J. Clarke, J. Dooley, S. H. Kim and S. J. Smith: 2004. 'Modelling greenhouse gas energy technology responses to climate change.' Energy, 29: 1529-1536.
Eickhout, B., M. G. J. Den Elzen and G. J. J. Kreileman: 2004. The Atmosphere-Ocean System of IMAGE 2.2. A global model approach for atmospheric concentrations, and climate and sea level projections. MNP Netherlands Environmental Assessment Agency, Bilthoven. www.mnp.nl/en
EU: 1996. Communication of the Community Strategy on Climate Change. Council of the EU.
EU: 2005. Council of the European Union, Presidency conclusions, March 22-23. http://ue.eu.int/ueDocs/cms_Data/docs/pressData/en/ec/84335.pdf
Gitz, V. and P. Ciais: 2004. 'Future expansion of agriculture and pasture acts to amplify atmospheric CO_2 in response to fossil fuel and land-use change emissions.' Climatic Change, 67: 161-184.
Graveland, C., A. F. Bouwman, H. J. M. de Vries, B. Eickhout and B. J. Strengers: 2002. Projections of multi-gas emissions and carbon sinks, and marginal abatement cost functions modelling for land-use related sources. MNP Netherlands Environmental Assessment Agency, Bilthoven. www.mnp.nl/en
Ha-Duong, M., M. J. Grubb and J. C. Hourcade: 1997. 'Influence of socioeconomic inertia and uncertainty on optimal CO_2-emission abatement.' Nature, 390(6657): 270-273.
Hammitt, J. K., R. J. Lempert and M. E. Schlesinger: 1992. 'A sequential-decision strategy for abating climate change.' Nature, 357: 315.
Hansen, J., M. Sato, R. Ruedy, A. Lacis and V. Oinas: 2000. 'Global warming in the twenty-first century: an alternative scenario.' PNAS, 97(18): 9875-9880.
Hare, W. L. and M. Meinshausen: 2004. How much warming are we committed to and how much can be avoided?. Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany. http://www.pik-potsdam.de/publications/pik_reports
Hendriks, C., W. Graus and F. van Bergen: 2002. Global carbon dioxide storage potential and costs. Ecofys, Utrecht.

Hendriks, C., M. Harmelink , K. Burges and K. Ransel: 2004. Power and heat productions: plant developments and grid losses. Ecofys, Utrecht.
Hijioka, Y., T. Masui, K. Takahashi, Y. Matsuoka and H. Harasawa: in press. 'Development of a support tool for greenhouse gas emissions control policy to help mitigate the impact of global warming.' Environmental Economics and Policy Studies.
Hoogwijk, M.: 2004. On the global and regional potential of renewable energy sources. PhD-thesis. Science, Technology and Society. Utrecht University.
Hoogwijk, M., H.J.M. de Vries and W. C. Turkenburg: 2004. 'Assessment of the global and regional geographical, technical and economic potential of onshore wind energy.' Energy Economics, 26: 889-919.
Houghton, R. A.: 2003. 'Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850-2000.' Tellus, 55B: 378-390.
Hourcade, J. C. and P. Shukla: 2001. 'Global, Regional and National Costs and Ancillary Benefits of Mitigation'. in Climate Change 2001: Mitigation. B. Metz, O. Davidson, R. Swart and J. Pan. Cambridge University Press, Cambridge.
IEA: 2004a. CO_2 capture and storage. International Energy Agency, Paris.
IEA: 2004b. World Energy Outlook 2004. International Energy Agency, Paris.
IMAGE-team: 2001a. The IMAGE 2.2 implementation of the SRES scenarios. A comprehensive analysis of emissions, climate change and impacts in the 21st centuryBilthoven, the Netherlands.
IMAGE-team: 2001b. The IMAGE 2.2 implementation of the SRES scenarios. A comprehensive analysis of emissions, climate change and impacts in the 21st century.. Netherlands Environmental Asessment Agency (MNP), Bilthoven, the Netherlands.
IPCC: 2001. Climate Change 2001 - Synthesis Report. Cambridge University Press, Cambridge.
IPCC: 2005. Special Report on CO_2 capture and storage. Cambridge University Press, Cambridge.
Joos, F., M. Bruno, R. Fink, U. Siegenthaler, T. F. Stocker, C. Le Quéré and J. L. Sarmiento: 1996. 'An efficient and accurate representation of complex oceanic and biospheric models of anthropogeninic carbon uptake.' Tellus, 48B: 397-417.
Kaya: 1989. Impacts of carbon dioxide emissions on GWP: Interpretation of proposed scenarios. IPCC/Response Strategies Working Group, Geneva.
Leemans, R., B. Eickhout, B. J. Strengers, A. F. Bouwman and M. Schaefer: 2002. 'The consequences for the terrestrial carbon cycle of uncertainties in land use, climate and vegetation responses in the IPCC SRES scenarios.' Science in China. Series C., 45: 126-136.
Leemans, R. and B. E. Eickhout: 2004. 'Another reason for concern: regional and global impacts on ecosystems for different levels of climate change.' Global Environmental Change, 14: 219-228.
Lucas, P., D. P. Van Vuuren, M. G. J. Elzen, J. G. J. Olivier and A. Bouwman: in prep.. 'Long-term reduction potential of non-CO_2 greenhouse gases.'
Lucas, P. L., M. G. J. Den Elzen and D. P. Van Vuuren: 2005. A multi-gas abatement analysis of the Kyoto Protocol. Netherlands Environmental Assessment Agency (MNP), Bilthoven, The Netherlands.
MA: 2006. Ecosystems and human well-being: Scenarios. Findings of the Scenarios Working Group. Island Press, Washington.
Manne, A. S. and R. Richels: 2004. 'The impact of learning-by-doing on the timing and costs of CO_2 abatement.' Energy Economics, 26: 603-619.
Mastandrea, M. D. and S. H. Schneider: 2004. 'Probabilistic Integrated Assessment of dangerous climate change.' Science, 304: 571-574.
Matthews, B. J. H. and J. P. van Ypersele: 2003. UNFCCC Article 2, stabilisation and uncertainty: engaging citizens with a web-based climate model,
Meinshausen, M.: 2006. 'On the risk of overshooting 2oC'. in Avoiding Dangerous Climate Change. H. J. Schellnhuber, W. Cramer, N. Nakicenovic, T. Wigley and G. Yohe. Cambridge University Press, Cambridge, UK.
Meinshausen, M., B. Hare, T. M. L. Wigley, D. P. \van Vuuren, M. G. J. den Elzen and R. Swart: in press. 'Multi-gas emission pathways to meet climate targets.' Climatic Change.

Metz, B. and D. P. Van Vuuren: 2006. 'How, and at what costs, can low-level stabilisation be achieved? –An overview'. in Avoiding Dangerous Climate Change. H. J. Schellnhuber, W. Cramer, N. Nakicenovic, T. Wigley and G. Yohe. Cambridge University Press, Cambridge.
MIT: 2003. The future of nuclear power - an interdisciplinary MIT study. Massachusetts Institute of Technology, Cambridge, USA.
MNP: 2005. Limits to Global Warming. Netherlands Environmental Assessment Agency (MNP), Bilthoven,.
Morita, T., N. Nakicenovic and J. Robinson: 2000. 'Overview of mitigation scenarios for global climate stabilisation based on new IPCC emission scenarios (SRES).' Environmental Economics and Policy Studies, 3: 65-88.
Morita, T. and J. Robinson: 2001. 'Greenhouse gas emission mitigation scenarios and implications'. in Climate Change 2001: Mitigation. B. Metz, O. Davidson, R. Swart and J. Pan. Cambridge University Press, Cambridge.
Murphy, J.: 2004. 'Quantification of modelling uncertainties ina large ensemble of climate change simulations.' Nature, 430(768-772).
Nakicenovic et al.: 2000a. Special Report on Emissions Scenarios (SRES). Cambridge University Press, Cambridge, UK.
Nakicenovic, N., J. Alcamo, G. Davis, B. De Vries, J. Fenhamm, S. Gaffin, K. Gregory, A. Gruebler, T. Y. Jung, T. Kram, E. Lebre La Rovere, L. Michaelis, S. Mori, T. Morita, W. Pepper, H. Pitcher, L. Price, K. Riahi, A. Roehrl, H. H. Rogner, A. Sankovski, M. Schlesinger, P. Shukla, S. Smith, R. Swart, S. Van Rooyen, N. Victor and D. Zhou: 2000b. IPCC Special Report on Emissions Scenarios. Cambridge University Press, Cambridge.
Nakicenovic, N. and K. Riahi: 2003. Model runs with MESSAGE in the context of the further development of the Kyoto protocol. International Institute for Aplied Systems Analysis.
NIES: 2005. Emission scenario databaseNational Institute for Environmental Studies, Japan,
O'Neill, B. C. and M. Oppenheimer: 2002. 'Climate Change:Dangerous Climate Impacts and the Kyoto Protocol.' Science, 296: 1971-1972.
Prentice, I. C., W. Cramer, S. P. Harrison, R. Leemans, R. A. Monserud and A. M. Solomon: 1992. 'A global biome model based on plant physiology and dominance, soil properties and climate.' Journal of Biogeography, 19: 117-134.
Rao, S. and K. Riahi: 2006. 'The role of non-CO_2 greenhouse gases in climate change mitigation: long-term scenarios for the 21st century.' Energy Journal, in press.
Richels, R. G., A. S. Manne and T. M. L. Wigley: 2004. Moving Beyond Concentrations: The Challenge of Limiting Temperature Change. AEI-Brookings Joint Center, Washington D.C.
Rogner, H. H.: 1997. 'An assessment of World Hydrocarbon Resources.' Annual Review of Energy and the Environment, 22: 217-262.
Rosegrant, M. W., X. Cai and S. Cline: 2002. World water and food to 2025: Dealing with scarcity. International Food Policy Research Institute, Washington DC.
Ruijven, B., D. P. Van Vuuren and B. de Vries: in prep.. 'The potential role of hydrogen in energy systems with and without climate policy.'
Schlesinger, M. E., S. Malyshev, E. V. Rozanov, F. Yang, N. G. Andronova, H. J. M. de Vries, A. Grübler, K. Jiang, T. Masui, T. Morita, N. Nakicenovic, J. Penner, W. Pepper, A. Sankovski and Y. Zhang: 2000. 'Geographical distributions of temperature change for scenarios of greenhouse gas and sulphur dioxide emissions.' Technological Forecasting and Social Change, 65(167-193).
Sims, R. E. H., H. H. Rogner and K. Gregory: 2003. 'Carbon emission and mitigation cost comparisons between fossil fuel, nuclear and renewable energy resources for electricity generation.' Energy Policy, 31: 1315–1326.
Strengers, B. J., R. Leemans, B. Eickhout, B. de Vries and A. F. Bouwman: 2004. 'The land use projections in the IPCC SRES scenarios as simulated by the IMAGE 2.2 model.' Geojournal, 61(4): 381 - 393.
Strengers, B. J., J. Van Minnen and B. Eickhout: in prep.. 'Assessment of sinks potential.'
Swart, R., J. Mitchell, T. Morita and S. Raper: 2002. 'Stabilisation scenarios for climate impact assessment.' Global Environmental Change, 12(3): 155-165.
UN: 2004. World Population to 2300. United Nations, New York.

van Vuuren, D. P., J. Cofala, H. E. Eerens, R. Oostenrijk, C. Heyes, Z. Klimont, M. G. J. den Elzen and M. Amann: 2006a. 'Exploring the ancillary benefits of the Kyoto Protocol for air pollution in Europe.' Energy Policy, 34(4): 444-460.
van Vuuren, D. P., H. J. M. de Vries, B. Eickhout and T. Kram: 2004. 'Responses to technology and taxes in a simulated world.' Energy Economics, 26(4): 579-601.
van Vuuren, D. P., M. G. den Elzen, M. M. Berk, P. L. Lucas, B. Eickhout, H. Eerens and R. Oostenrijk: 2003. Regional costs and benefits of alternative post-Kyoto climate regimes. National Institute for Public Health and the Environment, Bilthoven, The Netherlands.
van Vuuren, D. P., B. Eickhout, P. Lucas and M. G. J. den Elzen: 2006b. 'Long-term multi-gas scenarios to stabilise radiative forcing - Exploring costs and benefits within an integrated assessment framework.' Energy Journal, in press.
Van Vuuren, D. P. and B. C. O'Neill: in press. 'The consistency of IPCC's SRES scenarios to 1990-2000 trends and recent projections.' Climatic Change.
van Vuuren, D. P., J. Weyant and F. De la Chesnaye: 2006c. 'Multigas scenarios to stabilise radiative forcing.' Energy Economics, 28(1): 102-120.
Weyant, J.P.(2000). An Introduction to the Economics of Climate Change Policy. Pew Center on Global Climate Change. Washington DC.
Weyant, J. P., F. C. De la Chesnaye and G. Blanford: in press. 'Overview of EMF - 21: Multigas Mitigation and Climate Change.' Energy Journal.
White-House: 2002. 'Executive Summary of Bush Climate Change Initiative.'
Wigley, T. M. L.: 1991. 'Coud reducing fossil-fuel emissions cause global warming.' Nature, 349: 503-506.
Wigley, T. M. L.: 2003. Modelling climate change under no-policy and policy emissions pathways. Organisation for Economic Co-operation and Development, Paris.
Wigley, T. M. L. and S. C. B. Raper: 2001. 'Interpretation of high projections for global-mean warming.' Science, 293: 451-454.
Wigley, T. M. L., R. Richels and J. A. Edmonds: 1996. 'Economic and environmental choices in stabilisation of atmospheric CO_2 concentrations.' Nature, 369: 240-243.
Yohe, G., N. Andronova and M. Schlesinger: 2004. 'To hedge or not to hedge against an uncertain climate future?' Science, 306: 416-417.

Chapter 8:

Azar, C., Lindgren, K., Larson, E. and Möllersten, K.: 2005, 'Carbon capture and storage from fossil fuels and biomass - Costs and potential role in stabilizing the atmosphere', Climatic Change (in press).
Berk, M.M. and den Elzen, M.G.J.: 2001, 'Options for differentiation of future commitments in climate policy: how to realise timely participation to meet stringent climate goals?' Climate Policy 1(4), 465-480.
Blanchard, O.: 2002. Scenarios for differentiating commitments. In: K.A. Baumert, O. Blanchard, Llose and J.F. Perkaus (eds.), Options for protecting the climate. WRI, Washington DC.
Böhringer, C. and Löschel, A., 2003. Climate Policy Beyond Kyoto: Quo Vadis? A Computable General Equilibrium Analysis Based on Expert Judgements. ZEW Discussion Paper No. 03-09, Centre for European Economic Research, Mannheim, Germany.

Böhringer, C. and Welsch, H., 1999. C&C - Contraction and Convergence of Carbon Emissions: The Economic Implications of Permit Trading,. ZEW Discussion Paper No. 99-13, Centre for European Economic Research, Mannheim, Germany.

Bollen, J., C , Manders, A.J.G. and Veenendaal, P.J.J., 2004. How much does a 30% emission reduction cost? Macroeconomic effects of post-Kyoto climate policy in 2020. CPB Document no 64, Netherlands Bureau for Economic Policy Analysis, The Hague.

Buchner, B. and Carraro, C., 2003. Emissions Trading Regimes and Incentives to Participate in International Climate Agreements. FEEM Working paper 104.03, Fondazione Eni Enrico Mattei (FEEM), Milan, Italy.

Criqui, P. et al.: 2003. Greenhouse gas reduction pathways in the UNFCCC Process up to 2025 - Technical Report. B4-3040/2001/325703/MAR/E.1 for the DG Environment, CNRS-IEPE, Grenoble, France.

de Vries, H.J.M., D.P. van Vuuren, den Elzen, M.G.J. and Janssen, M.A.: 2002. The Targets Image Energy model regional (TIMER) - Technical documentation. MNP-report 461502024, Netherlands Environmental Assessment Agency (MNP), Bilthoven, the Netherlands.

den Elzen, M.G.J.: 2002, 'Exploring climate regimes for differentiation of future commitments to stabilise greenhouse gas concentrations', Integrated Assessment 3(4), 343-359.

den Elzen, M.G.J. and Berk, M.M.: 2003. How can the Parties fairly and effectively establish future obligations under long-term objectives? In: D. Michel (ed.), Climate policy for the 21st century: meeting the long-term challenge of global warming. Center for Transatlantic Relations, Washington, D.C., pp. 79-112.

den Elzen, M.G.J., Berk, M.M. and Lucas, P.: 2004. Simplified Multi-Stage and Per Capita Convergence: an analysis of two climate regimes for differentiation of commitments. MNP-report 728001027, www.mnp.nl/en, Netherlands Environmental Assessment Agency (MNP), Bilthoven, the Netherlands.

den Elzen, M.G.J., Berk, M.M., Lucas, P., Criqui, C. and Kitous, A.: 2005a, 'Multi-Stage: a rule-based evolution of future commitments under the Climate Change Convention', International Environmental Agreements (in press).

den Elzen, M.G.J. and Lucas, P.: 2003. FAIR 2.0: a decision-support model to assess the environmental and economic consequences of future climate regimes. MNP-report 550015001, www.mnp.nl/fair, Netherlands Environmental Assessment Agency (MNP), Bilthoven, the Netherlands.

den Elzen, M.G.J. and Lucas, P.: 2005, 'The FAIR model: a tool to analyse environmental and costs implications of climate regimes', Environmental Modeling and Assessment 10(2), 115-134.

den Elzen, M.G.J., Lucas, P. and van Vuuren, D.P.: 2005b, 'Abatement costs of post-Kyoto climate regimes', Energy Policy 33(16), pp. 2138-2151.

den Elzen, M.G.J. and Meinshausen, M.: 2005. Meeting the EU 2°C climate target: global and regional emission implications. MNP-report 728001031 (www.mnp.nl/en), Netherlands Environmental Assessment Agency (MNP), Bilthoven, the Netherlands.

den Elzen, M.G.J. and Meinshausen, M.: 2006. Multi-gas emission pathways for meeting the EU 2°C climate target. In: H.J. Schellnhuber, W. Cramer, N. Nakicenovic, T. Wigley and G. Yohe (eds.), Avoiding Dangerous Climate Change. Cambridge University Press, Cambridge, UK.

den Elzen, M.G.J., Meinshausen, M. and van Vuuren, D.P.: 2005, in prep., 'Multi-gas emission corridors to meet long-term greenhouse gas concentration targets: trade-off between costs and climate risks', Climatic change.

ECF and PIK: 2004. What is dangerous climate change? Initial Results of a Symposium on Key Vulnerable Regions, Climate Change and Article 2 of the UNFCCC. European Climate Forum and Potsdam Institute for Climate Impact Research.

Eickhout, B., den Elzen, M.G.J. and van Vuuren, D.P.: 2003. Multi-gas emission profiles for stabilising greenhouse gas concentrations. MNP-report 728001026, Netherlands Environmental Assessment Agency (MNP), Bilthoven, the Netherlands.

European Council: 1996. Communication on Community Strategy on Climate Change, Council Conclusions. European Council, Brussels.

European Council: 2005. Presidency conclusions. European Council, Brussels.

Groenenberg, H., Blok, K. and van der Sluijs, J.P.: 2004, 'Global Triptych: a bottom-up approach for the differentiation of commitments under the Climate Convention', Climate Policy 4, 153–175.

Gupta, J.: 1998. Encouraging developing country participation in the climate change regime. Institute for Environmental Studies, Free University of Amsterdam, Amsterdam, the Netherlands.

Hare, W.L. and Meinshausen, M.: 2004. How much warming are we committed to and how much can be avoided?, Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany.

Höhne, N.: 2005. What is next after the Kyoto Protocol. Assessment of options for international climate policy post 2012, University of Utrecht, PhD thesis, Utrecht, the Netherlands.
Höhne, N., Galleguillos, C., Blok, K., Harnisch, J. and Phylipsen, D.: 2003. Evolution of commitments under the UNFCCC: Involving newly industrialized countries and developing countries. Research-report 20141255, UBA-FB 000412, ECOFYS Gmbh, Berlin.
Höhne, N., Phylipsen, D., Ullrich, S. and Blok, K.: 2005. Options for the second commitment period of the Kyoto Protocol, research report for the German Federal Environmental Agency. Climate Change 02/05, ISSN 1611-8855, available at www.umweltbundesamt.de, ECOFYS Gmbh, Berlin.
Hoogwijk, M., Faaij, A., Eickhout, B., de Vries, H.J. and Turkenburg, W.: 2005, 'Renewables', Biomass and Bioenergy 29, 225-257.
IEA: 2004. World Energy Outlook 2004. International Energy Agency, Paris.
IMAGE team: 2001. The IMAGE 2.2 implementation of the SRES scenarios. A comprehensive analysis of emissions, climate change and impacts in the 21st century. CD-ROM publication 481508018, Bilthoven, the Netherlands.
IPCC: 2001a. Climate Change 2001.The science of climate change. IPCC Assessment Reports. Cambridge University Press, Cambridge, UK, 1-18 pp.
IPCC: 2001b. Climate Change 2001: Mitigation. Cambridge University Press, Cambridge, UK.
Jacoby, H.D., Schmalensee, R. and Wing, I.S.: 1999. Toward a Useful Architecture for Climate Change Negotiations. Report No 49, MIT, Cambridge, MA.
Lucas, P., van Vuuren, D.P., den Elzen, M.G.J., Olivier, J.A. and Bouwman, A.: in prep, 'Long-term reduction potential of non-CO_2 greenhouse gases'.
Mastandrea, M.D. and Schneider, S.H.: 2004, 'Probabilistic Integrated Assessment of dangerous climate change', Science 304, 571-574.
Meinshausen, M.: 2006. What Does a 2°C Target Mean for Greenhouse Gas Concentrations? A Brief Analysis Based on Multi-Gas Emission Pathways and Several Climate Sensitivity Uncertainty Estimates. In: H.J. Schellnhuber, W. Cramer, N. Nakicenovic, T. Wigley and G. Yohe (eds.), Avoiding Dangerous Climate Change, Cambridge, UK.
Meyer, A.: 2000. Contraction and Convergence. The global solution to climate change. Schumacher Briefings, 5. Green Books, Bristol, UK.
Michaelowa, A., Butzengeiger, S., Jung, M. and Dutchke, M.: 2003. Beyond 2012. Evolution of the Kyoto Protocol Regime. An Environmental and Development Economics Analysis. Expertise for the WBGU Special Report „Climate Protection Strategies for the 21st Century: Kyoto and Beyond". WBGU website, http://www.wbgu.de/.
Murphy, J.M., Sexton, D.M.H., Barnett, D.N., Jones, G.S., Webb, M.J., Collins, M. and Stainforth, D.A.: 2004, 'Quantification of modelling uncertainties in a large ensemble of climate change simulations', Nature 430, 768-772.
Nakicenovic, N. et al.: 2000. Special Report on emissions scenarios. IPCC Special Reports. Cambridge University Press, Cambridge, UK.
Nakicenovic, N. and Riahi, K.: 2003. Model runs with MESSAGE in the Context of the Further Development of the Kyoto-Protocol. WBGU - German Advisory Council on Global Change, WBGU website, http://www.wbgu.de/, Berlin, Germany.
O'Neill, B.C. and Oppenheimer, M.: 2002, 'Climate Change: Dangerous Climate Impacts and the Kyoto Protocol', Science 296, 1971-1972.
Parry, M.L., Rosenzweig, C., Iglesias, A., Livermore, M.T.J. and Fischer, G.: 2004, 'Effects of climate change on global food production under SRES emissions and socio-economic scenarios', Global Environmental change-human and policy dimensions 14(1), 53-67.
Persson, T.A., Azar, C. and Lindgren, K.: 2006, 'Allocation of CO_2 emission permits – economic incentives for emission reductions in developing countries', Energy Policy In Press.
Strengers, B.J., van Minnen, J. and Eickhout, B.: in prep., 'Assessment of sinks potential'.
UN: 2004. World Population Prospects: the 2004 revision. United Nations Department for Economic and Social Information and Policy Analysis, New York, USA.
UNFCCC: 1992. United Nations General Assembly, United Nations Framework Convention on Climate Change, http://www.unfccc.int/resources.United Nations, New York.

UNFCCC: 1997. Kyoto Protocol to the United Nations Framework Convention on Climate Change. FCCC/CP/L7/Add.1, United Nations Framework Convention on Climate Change, Bonn, Germany.
van Vuuren, D.P., den Elzen, M.G.J., Eickhout, B., Lucas, P.L., Strengers, B.J. and Ruijven, B.: 2005, 'Stabilising greenhouse gas concentrations. Assessment of different strategies and costs using an integrated assessment framework.' Climatic Change (submitted).
WBGU: 2003. Climate Protection Strategies for the 21st Century. Kyoto and Beyond. German Advisory Council on Global Change, Berlin.
Weyant, J.P., De la Chesnaye, F.C. and G., B.: 2005, 'Overview of EMF - 21: Multi-gas Mitigation and Climate Change', Energy Journal (In press).
White House: 2002. Executive Summary of Bush Climate Change Initiative.
Winkler, H., Spalding-Fecher, R. and Tyani, L.: 2002, 'Comparing developing countries under potential carbon allocation schemes', Climate Policy 95, 1-16.
World Bank: 2001. World Development Report 2000/2001: Attacking Poverty. Oxford University Press, Oxford, UK.

Appendix A Main input parameters for the four scenarios

		A1	A2	B1	B2	Unit
	2000	2050	2050	2050	2050	
Wind						
Conversion efficiency	0.91	0.99	0.9	0.99	0.95	-
Array efficiency	0.9	0.97	0.9	0.97	0.95	-
Spec. investment costs[a]	935					$ kW^{-1}
System lifetime	20	30	30	30	30	year
Full load maximum hours	4000	5000	4500	5000	4750	hours
Nominal power	1100	2700	1450	2700	2000	MW
Solar-PV						
Conversion efficiency	0.14	0.3	0.2	0.3	0.25	-
Performance ratio	0.8	0.95	0.75	0.95	0.95	-
Module investment costs	3	0.75	1.75	0.75	1	$ Wp^{-1}
BOS investment costs	3	0.6	1.75	0.6	1	$ Wp^{-1}
System lifetime	25	30	30	30	30	year
Biomass Elec.						
Elec. conversion efficiency	0.38	0.53	0.49	0.53	0.51	%
Spec. investment costs	1400	1050	1225	1050	1110	$/MW
BSF Spec. invest costs[b] (1970=1)	0.9	0.53	0.81	0.53	0.63	-
MF woody	0.5	1.25	1.05	1.15	1.10	-
Biomass liquid						
BLF inv. costs (1970=1)[c]	0.87	0.56	0.73	0.56	0.66	-
MF sugar[d]	0.75	1.5	1.23	1.38	1.23	-
Conversion efficiency (woody)	0.45	0.55	0.50	0.55	0.50	-
Conversion efficiency (sugar)	0.40	0.53	0.47	0.53	0.47	-
General						
Interest rate	0.1	0.1	0.1	0.1	0.1	-
O&M costs	3	3	3	3	3	% of investment I

[a] The specific investment costs of 935 US$ kW^{-1} for the starting year is derived from an average 1000 US$ kW^{-1} for 800 kW turbines and a scaling coefficient of –0.3.

[b] BSF is an abbreviation for Bio Solid Fuel.

[c] BLF is an abbreviation for Bio Liquid Fuel.

[d] MF is an abbreviation for Management Factor.

Appendix B Key characteristics of the TIMER 2.0 model

The formula that allocates the market share among energy carriers in the sub-models of TIMER 2.0 is the *multinomial logit model*:

$$IMS_i = \frac{e^{-\lambda C_i}}{\sum e^{-\lambda C_i}}$$

IMS_i is the indicated share of total investments for energy carrier i, λ is the so-called logit parameter that determines the sensitivity of markets to price changes and C_i is the cost of energy carrier i. The latter may include other factors than the price of the energy carrier, such as premium factors and cost increases due to carbon taxes. In this analysis we used no premium factors on hydrogen. It should be noted that the multinomial logit is used to determine shares in new investment, which implies that the actual market shares respond much slower.

The concept of *learning-by-doing* describes the dynamics of decreasing cost with increasing cumulative production. The measure for technological learning is the progress ratio (PR), which is derived from the experience curve. This curve is generally described as:

$$y = y_0 * C^{-\pi}$$

In this equation y is the unit cost as a function of the output, y_0 is the cost of the first unit produced, C is the cumulative production over time and π is the learning coefficient. The factor 2^{π} is called the progress ratio (PR), which is mostly used to indicate the learning capacities of a technology.

Appendix C Key assumptions for the hydrogen scenarios

Table C1 Scenario assumptions on hydrogen production efficiency.

	Coal Gasification	**Oil (POX)**	**Gas (SMR)**	**Biomass Gasification**	**Electrolysis**	**Solar Thermal**	**Small-Scale SMR**
	Pessimistic						
2005–2100	60%	50%	75%	50%	75%	N/A	75%
	Intermediate						
2005	60%	50%	75%	50%	80%	N/A	75%
2050	62.5%	70%	82%	62.5%	82%	N/A	82%
2100	65%	75%	85%	65%	85%	N/A	85%
	Optimistic						
2005	60%	70%	75%	50%	80%	N/A	75%
2030	62.5%	72.5%	82.5%	62.5%	82%	N/A	82%
2100	67.5%	77.5%	87.5%	67.5%	85%	N/A	85%

Table C2 Scenario assumptions for hydrogen production investment cost parameters.

Variable	**Coal Gasification**	**Oil (POX)**	**Gas (SMR)**	**Biomass Gasification**	**Electrolysis**	**Solar Thermal**	**Small-Scale SMR**
	Pessimistic						
Initial Inv. Cost							
	1150 $/kW	700 $/kW	400 $/kW	1150 $/kW	575 $/kW	2875 $/kW	3000 $/kW
PR	0.88	0.88	0.88	0.88	0.88	0.88	0.88
	Intermediate						
Initial Inv.							

Cost							
	1000 $/kW	600 $/kW	350 $/kW	1000 $/kW	500 $/kW	2500 $/kW	3000 $/kW
PR	0.84	0.84	0.84	0.84	0.84	0.84	0.84
	Optimistic						
Initial Inv. Cost							
	900 $/kW	550 $/kW	300 $/kW	900 $/kW	450 $/kW	2250 $/kW	2700 $/kW
PR	0.785	0.785	0.785	0.785	0.785	0.785	0.785

Table C3 Assumptions on carbon capture and sequestration.

Technology	Capital Cost ($/kW)	Efficiency Loss (%)	CO_2 Capture (%)
Coal (Gasification)	197	3	95
Oil (POX)	185	2	95
Natural Gas (SMR)	76	2	88

Table C4 Scenario assumptions for hydrogen transport cost.

Hydrogen Demand	Pessimistic	Intermediate	Optimistic
0 (GJ/capita)	12 $/GJ	10 $/GJ	10 $/GJ
20 (GJ/capita)	10 $/GJ	6.5 $/GJ	5 $/GJ
50 (GJ/capita)	8 $/GJ	5 $/GJ	2 $/GJ
70 (GJ/capita)	6 $/GJ	3	
100 (GJ/capita)	6 $/GJ	3	

Table C5 Scenario assumptions for local hydrogen distribution cost.

t	Industry	Transport	Residential	Services	Other
	Pessimistic				
2005	2 $/GJ	6 $/GJ	3 $/GJ	2 $/GJ	3 $/GJ

2100	1 $/GJ	4 $/GJ	2 $/GJ	1 $/GJ	3 $/GJ
	Intermediate				
2005	2 $/GJ	5 $/GJ	3 $/GJ	2 $/GJ	3 $/GJ
2050	1 $/GJ	3 $/GJ	2 $/GJ	1 $/GJ	3 $/GJ
2100	0.75 $/GJ	2 $/GJ	1.5 $/GJ	0.75 $/GJ	3 $/GJ
	Optimistic				
2005	1 $/GJ	4.5 $/GJ	2 $/GJ	1 $/GJ	3 $/GJ
2030	0.75 $/GJ	3 $/GJ	1.5 $/GJ	0.75 $/GJ	3 $/GJ
2100	0.50 $/GJ	1 $/GJ	1 $/GJ	0.50 $/GJ	3 $/GJ

Table C6 Scenario assumptions for fuel cell investment cost and transport sector efficiency.

t	**Industry**	**Residential**	**Service**	**Other**	**Transport**	**FC η transport sector**
	Pessimistic					
2005	1500 $/kW	1400 $/kW	1400 $/kW	1500 $/kW	1200 $/kW	36 %
2100	800 $/kW	500 $/kW	500 $/kW	800 $/kW	250 $/kW	
	Intermediate					
2005	1500 $/kW	1400 $/kW	1400 $/kW	1500 $/kW	1200 $/kW	36 %
2050	800 $/kW	500 $/kW	500 $/kW	800 $/kW	250 $/kW	45 %
2100	500 $/kW	300 $/kW	300 $/kW	500 $/kW	200 $/kW	45 %
	Optimistic					
2005	1350 $/kW	1400 $/kW	1400 $/kW	1500 $/kW	1200 $/kW	40 %
2030	100 $/kW	100 $/kW	100 $/kW	100 $/kW	100 $/kW	50 %
2100	50 $/kW	50 $/kW	50 $/kW	100 $/kW	50 $/kW	60 %

Appendix D MAC curves

Different sets of MAC curves for different emission sources were used for the calculations and all updated conforming to our earlier study (Den Elzen and Meinshausen, 2005; 2006).

The MAC curves of *energy- and industry-related CO_2 emissions* were determined with the energy model TIMER 2.0. This energy model calculates regional energy consumption, energy-efficiency improvements, fuel substitution, and the supply and trade of fossil fuels and renewable energy technologies, as well as carbon capture and storage. The TIMER MAC curves were established by imposing a carbon tax and recording the induced reduction of CO_2 emissions, taking into account technological developments, learning effects and system inertia. The carbon tax leads to use of zero or less carbon-intensive fuels and technologies and efficiency. As a result, CO_2 emissions will be decreased. As discussed in the introduction, the costs of climate policy may depend strongly on the timing. To capture some of the important dynamics here, two different tax profiles were used to explore the level of emission reduction in TIMER (in the 'response year'): one that assumes a linear increase in the carbon tax value of 2010 in the response year (linear tax) and one that reaches the maximum value 30 years earlier (block tax). The second profile results in more CO_2 reductions in the response year because the energy system has a longer time period to respond to the higher prices of carbon-intensive fuels. The two sets of time- and path-dependent response curves for various carbon tax levels are used in the FAIR model as MAC curves. A combination of the linear-tax and block-tax MAC curves is made, depending on the trajectory of the calculated actual carbon tax (international permit price) associated with the emission pathway. The responses recorded on the linear tax profile are used for a rapidly increasing tax, while the responses recorded on the block tax are used if the carbon tax follows a more constant tax level. To do this, the FAIR model looks back 30 years. It constructs a linear combination of the two types of response curves by comparing the tax profile in that period to the one assumed in the block or linear tax profile used in TIMER. In this way, it is possible to take into account (as a first-order approximation) the time pathway of earlier abatement, which is a new element compared to our earlier work. The method results in dynamics similar to those observed for the TIMER model itself, as described by Van Vuuren et al. (2004).

The MAC curves for *carbon plantations* were derived using the IMAGE 2.3 model (Strengers et al., in prep.). In this model, the potential carbon sequestration of carbon plantations is estimated and compared, using a 0.5 x 0.5 grid, to the carbon sequestered by natural vegetation for land abandoned from agriculture. On the basis of grid cells that are potentially attractive for carbon plantations, carbon sequestration supply curves are established and converted into MAC curves by adding land and establishment costs. Besides these carbon credits from carbon plantations the model also includes carbon credits from forest management based on a conservative, low estimate from our earlier study.

An extended set of data from the Energy Modelling Forum-21 project (EMF-21) (Weyant et al., 2005) was used for the MAC curves for *non-CO_2 emission sources* (CH_4, N_2O and halocarbons). The original EMF-21 set, based on detailed abatement options, included abatement potential for a limited cost range of 0–200 US$ tC-eq^{-1} up to 2020, and did not include technological improvements over time. Lucas et al. (in prep.) extended this set on the basis of a literature survey and expert judgements about long-term abatement potential and costs. The long-term potential is significantly higher than current potential as a result of the technology development process and the removal of implementation barriers.

Appendix E Description of the emission envelopes calculation

The emission envelopes are calculated by systematically varying the parameters of the parameterised global CO_2-eq. emission pathway, that is, the yearly emission reductions (X_I, initial 2010 value, $X_1, \ldots, X_5$) and years ($t_1, \ldots, t_5$) at which the reduction rates change. Note that for each parameterised pathway we first calculated parameters X_1 and t_1 (assuming $X_2 = X_1$ and t_2) based on an iterative procedure to match the concentration with a concentration peaking profile, and secondly, we calculated the remaining parameters in the same way using the final concentration stabilisation profile (see den Elzen and Meinshausen, 2005).[88] The systematic procedure on the basis of four groups of emission pathways follows (see

Figure **6.**).

8) *Linear decrease to the maximum reduction rate at time t_1 (as early as possible)* stays at maximum level for at least 10 years (

9) Figure **6.**a). Repeat this for $t_1 + 5$, $t_1 + 10$, and so on. In this way, the first pathways are early action ones at the lower boundary of the envelope, but after many repetitions, the last pathways are delayed response pathways at the upper boundary.

10) *Decrease linearly as fast as possible to level X_1 (above maximum rate) at time t_1 (as early as possible)* stays at this level for at least 10 years (

11) Figure **6.**b). Repeat this for $X_1 + 0.2$, $X_1 + 0.4$, and so on. Similar to (i), we start with early action pathways and end with delayed response pathways.

12) *Follow the baseline rate as long as possible* (the concentration target can still be met) till time t_1, and then decrease as fast as possible to the maximum reduction rate (

13) Figure **6.**c). Repeat this for X – 5, X –10, …, 2015. Here we simulate from delayed response to early action pathways.

14) *Decrease first as fast as possible to time X_1 to intermediate level X_1* (between initial and maximum rate) for a certain period (defined by t_1 and t_2), and then decrease as fast as possible to the maximum reduction rate (

15) Figure **6.**d). Repeat this for variations in X_1, t_1 and t_2. The pathways belonging to group (iv) represent a large group of possible pathways (from early action to delayed response) in the envelope.

---

[88] Note that the effective emission reduction rates will be different from the preset rates due to (a) smoothing of emissions pathways and (b) lower bounds for some reductions of gases, which affect lower emission pathways. These lower bounds can result if a certain baseline and target emission path is chosen, the emission gap of which is not fully covered by the chosen MAC curves. As well, the non-reducible fractions for N_2O and CH_4 emissions are fixed after 2100 (see note 8), which can lead to a gap in pre-set and effective reduction paths after 2100 for lower concentration pathways.

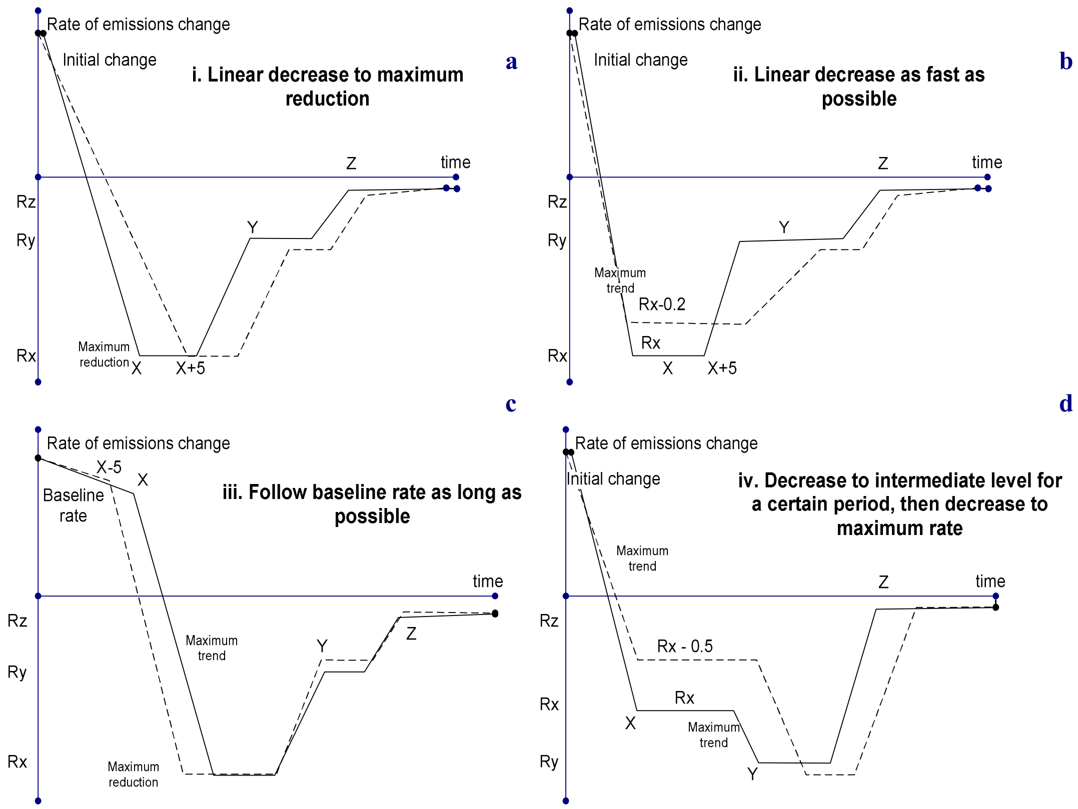


Figure 6.14 The methodology for the development of emission envelopes; the four groups of emission pathways and their sketched reduction rates.

Appendix F Model description

A brief description of the models is already included in the main text. This appendix provides additional information – for detailed model descriptions, the reader is referred to model documentation published elsewhere.

F.1 Description of the models used

The FAIR–SiMCaP 1.1 model

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 to design rule-based systems that simulate different proposals for differentiating future commitments ('burden sharing'). The model uses expert information from more complex models such as baseline emissions and marginal abatement cost curves (in particular, TIMER and IMAGE) to calculate the consequences of these proposals. The basic assumption of the model is that regions will reach their emission reduction commitments on the basis of least cost – that is, across different mitigation options (multi-gas) and across different regions (set by certain trading rules). Recently, the FAIR 2.1 has been integrated with the SiMCaP 1.0 model allowing 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 Den Elzen and Lucas (2005) and FAIR–SiMCaP 1.1 model in Den Elzen and Meinshausen (2005).

The TIMER model

The global energy system model TIMER (Targets IMage Energy Regional Model) has been developed to simulate (long-term) energy baseline and mitigation scenarios. The model describes the investments in, and the use of, different types of energy options influenced by technology development (learning-by-doing) and resource depletion. Inputs to the model are macro-economic scenarios and assumptions on technology development, preference levels and restrictions to fuel trade. The output of the model demonstrates how energy intensity, fuel costs and competing non-fossil supply technologies develop over time. In TIMER, implementation of mitigation is generally modelled on the basis of price signals (a tax on carbon dioxide). A carbon tax (used as a generic measure of climate policy) induces additional investments in energy efficiency, fossil fuel substitution, and investments in bioenergy, nuclear power, solar power, wind power and carbon capture and storage. Selection of options throughout the model is based on a multinomial logit model that assigns market shares on the basis of production costs and preferences (cheaper, more attractive options get a larger market share; but there is no full optimisation).

The TIMER model has been described in detail (de Vries et al., 2001). The model includes the following primary energy sources: coal, oil, natural gas, bioenergy, solar power, wind power, hydro power, and nuclear power. In terms of secondary energy carriers, it includes direct converted fuels based on the primary sources listed above and electricity, heat and hydrogen.

The IMAGE 2 model

The IMAGE 2 integrated assessment model describes important elements of the cause-response chain of global environmental change and has been described in detail elsewhere (Alcamo et al., 1998; IMAGE-team, 2001b). In the model, socio-economic processes are mostly modelled at the level of 17 world regions, while climate, land use and several environmental parameters are modelled at a 0.5 x 0.5 degree resolution. The models main model components are the Land-use and Land Cover Model, a climate model and several impact models (e.g., impacts on crops and soil degradation risk). The Land-use and Land Cover Model distinguishes 14 natural and forest land-cover types and five human-made land-cover types. A crop module based on the FAO agro-ecological zones approach computes yields of the different crops and pastures, estimating the areas used for their production as determined by climate and soil quality (Alcamo et al., 1998). In case expansion of agricultural land is required to satisfy growth of food demand, a rule-based ‘suitability map’ determines which grid cells are selected. IMAGE also includes a modified version of the BIOME model (Prentice et al., 1992) to compute changes in potential vegetation. The climate model of IMAGE (Eickhout et al., 2004) is an adapted version of the MAGICC model (Wigley and Raper, 2001); the carbon cycling modelling is integrated within the IMAGE model’s detailed description of the biosphere, and the ocean-carbon uptake is replaced by the Bern model (Joos et al., 1996). Pattern scaling methods are next used to calculate climate change at the level of a 0.5 x 0.5 grid. The modelling of land-use related greenhouse gas emissions in IMAGE is based on detailed descriptions of the physical drivers such as land-use change and animal production.

F.2 Specific assumptions on mitigation potential

In addition to the overall description of mitigation options in the main text, here we briefly indicate some of the quantitative assumptions and detailed references.

Energy

Table F.1 Assumptions within the TIMER model for various energy categories.

Option	Assumptions	References
Fossil Fuels	Regional resources and production costs for various qualities; global trade (coal, oil and natural gas resources equal 300, 45, and 117 ZJ respectively). Global average crude energy prices in 2050 are 1.4, 5.1 and 4.4 1995US$ GJ–1 for respectively coal, oil and natural gas. In 2000, these prices are 1.1, 3.0 and 2.3 1995US$ GJ–1.	(Rogner, 1997)
Carbon Capture and Storage	Regional reservoir availability and storage costs for various options (different categories of empty oil, natural gas and coal reservoirs, coal-bed methane recovery, aquifers). Total capacity equals 1500 GtC. Transport and storage costs range (depending op category and region) from 10–150 US$ tC–1.	(Hendriks et al., 2002)
Power Plant Efficiency and Investment Costs	Power plant efficiency and investment costs for 20 types of thermal power plants (coal, oil, natural gas, biomass) including carbon capture and storage defined over time.	(Hendriks et al., 2004)
Biomass	Potential and costs for primary biomass defined by region on the basis of IMAGE 2 maps (including abandoned agricultural land, natural grasslands and savannah). Primary biomass can be converted into liquid biofuels (for transport) and solid bioenergy (for electricity). Technology development is based on learning-by-doing. Maximum potential equals 230 EJ in 2050 and 600 EJ in 2100. Production costs for liquid fuels vary between 16 US$ GJ–1 and 10 US$ GJ–1 in 2000 (depending on scenario). Production costs for solid fuels vary around 4 US$ GJ–1.	(Hoogwijk, 2004)
Solar/Wind Power	Solar and wind power based on studies that assess global potential on the basis of 0.5 x 0.5 degree maps. Costs change over time as a result of depletion, learning-by-doing and grid penetration (declining capacity-credit and excess electricity production).	(Hoogwijk, 2004)
Nuclear Power	Investment costs of nuclear power based on available information in literature (most important references indicated). Investments costs are assumed to decrease over time. Fuel costs increase over time as result of depletion.	(MIT, 2003;Sims et al., 2003)
Hydrogen	Hydrogen modelled on the basis of production from fossil fuels, bioenergy, electricity and solar power (including carbon capture and storage). Selection on the basis of a multinomial logit model.	(Ruijven et al., in prep.)

Total marginal abatement curves

The total reduction potential per reduction category indicated in the main text is indicated in Table A.2. The table indicates the potential under our default assumptions (no BECS).

Table F.2 Overview of reduction potential under the main baseline (B2).

		2050			2100		
		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[a]	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**
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**	

[a] 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.