International Institute for
Applied Systems Analysis
Schlossplatz 1
A-2361 Laxenburg, Austria

Tel: +43 2236 807 342
Fax: +43 2236 71313
E-mail: publications@iiasa.ac.at
Web: www.iiasa.ac.at

Interim Report IR-08-020

IMAGE and MESSAGE Scenarios Limiting GHG Concentration to Low Levels

Shilpa Rao[1], Keywan Riahi[1], Elke Stehfest[2], Detlef van Vuuren[2], Cheolhung Cho[1], Michel den Elzen[2], Morna Isaac[2], Jasper van Vliet[2]

[1] International Institute for Applied Systems Analysis (IIASA), Austria
[2] Netherlands Environmental Assessment Agency (PBL), Netherlands

Approved by

Nebojsa Nakicenovic
Energy (ENE) Program

October 15, 2008

International Institute for Applied Systems Analysis
Registration number: ZVR 524808900

Contents

Abstract

This report discusses the attainability of low greenhouse gas concentrations levels based on an analysis using two integrated assessment models (MESSAGE and IMAGE). Model runs were preformed which explored the feasibility of reaching radiative forcing levels in 2100 between 2.6 to 2.9 W/m^2 above pre-industrial levels. Such low targets are necessary to limit global mean temperature increase to below 2^oC compared to pre-industrial levels with high probability. The analysis examines the attainability of low targets systematically with respect to key uncertainties, including alternative baseline development pathways, availability of different technologies, emissions of bio-energy, and impacts of forestry and land use assumptions. A number of sensitivity tests were carried out to test the robustness of achieving low GHG concentration targets. The results from the two models are discussed in detail comprising energy profiles and emission pathways consistent with such low stabilization targets.

Acknowledgments

Financial support from the European Commission is gratefully acknowledged. The paper reflects the personal opinion of the authors and does not necessarily reflect the opinion of the European Commission on the results obtained.

About the Authors

Shilpa Rao has been associated with IIASA since 2002 where she has been involved in modeling of large scale energy-economic systems, with a focus on environmental policy and technology adoption. She holds a degree in engineering from India followed by a M.S. in energy economics from Pennsylvania State University. She is currently completing her Phd at the Technical University of Vienna.

Keywan Riahi is a Senior Research Scholar in both IIASA's Energy and the Transitions to New Technologies Programs. He also holds a part-time position as Visiting Professor in the field of Energy Systems Analysis at the Graz University of Technology, Austria. His main research interests are the long-term patterns of technological change and economic development and, in particular, the evolution of the energy system.

Elke Stehfest is a research scientist at the Netherlands Environmental Assessment Agency since 2006, where she has been involved in global integrated assessment studies, and the further development of the IMAGE model. Her main research interests are land use change, crop and vegetation modelling, and integrated climate change mitigation strategies.

Detlef van Vuuren works as senior research scientist at the Netherlands Environmental Assessment Agency on the application and development of the IMAGE model, in particular with respect to scenario development and the energy system. His mean research interests include integrated assessment of global environmental change, integrated assessment of climate change response strategies and related long-term development in the energy system

Cheolhung Cho participated in IIASA's Young Scientists Summer Program (YSSP) in 2007, and joined the Energy Program in January 2008. Mr. Cho holds a master's degree in Environmental Sciences and Engineering from the University of North Carolina at Chapel Hill, USA, where he is at the moment aslo pursuing his Ph.D.

Michel den Elzen is a climate policy analyst at the Netherlands Environmental Assessment Agency on the application and development of the FAIR model, i.e. interactive policy-decision support tools to analyze post-2012 climate mitigation and adaptation strategies. He conducts research on climate policy issues, such as post-2012 climate policy regime, emission trading, adaptation, abatement costs and long-term emissions pathways to meet climate targets.

Morna Isaac joined the Netherlands Environmental Assessment Agency in 2005 to work on scenario development in the energy system using the IMAGE/TIMER model. She also works on supporting integrated assessment of both mitigation and adaptation strategies to climate change, including the development of low stabilization scenarios and assessment of potential feedbacks of climate impacts (such as changes in heating and cooling demand).

Jasper van Vliet works at the Netherlands Environmental Assessment Agency as climate policy analyst – using both the FAIR model to analyse climate policy strategies and the IMAGE/TIMER model to analyse the implications of these strategies for global energy use. He has been involved in several projects including the evaluation of different post-2012 climate regimes, the OECD Environmental Outlook and the assessment of global bio-energy potentials.

IMAGE and MESSAGE Scenarios Limiting GHG Concentration to Low Levels

Shilpa Rao, Keywan Riahi, Elke Stehfest, Detlef P. van Vuuren, Cheolhung Cho, Michel den Elzen, Morna Isaac, and Jasper van Vliet

Executive Summary

This report discusses the attainability of low greenhouse gas concentrations levels based on analysis using two integrated assessment models (MESSAGE and IMAGE). Model runs were preformed which explored the feasibility of reaching radiative forcing levels in 2100 between 2.6 to 2.9 W/m^2 above pre-industrial levels. Such low targets are necessary to limit the change of global mean temperature to below 2^{o}C compared to pre-industrial levels with high probability. Current scenario literature comprises only a very few comprehensive scenarios that achieve such low targets and some of the lowest scenarios developed so far are rather exploratory in nature (Fisher et al. 2007). The scenarios developed in this report assess the attainability of the targets systematically with respect to key uncertainties, including 1) alternative baseline development pathways, 2) availability of different technologies, 3) emissions of bio-energy, and 4) impacts of forestry and land use assumptions.

Main findings

Low targets such as the 2.6 and 2.9 W/m^2 forcing target are found attainable in the long term, but are conditional on a number of key technologies and other assumptions.

The attainability of low targets critically hinges on a number of key uncertainties including drastic, early and globally concerted mitigation initiatives; the rapid up-scaling and feasibility of large-scale bio-energy, availability of forest sinks, continued high rates of energy efficiency improvement, and carbon capture and storage technologies.

A very important assumption in the scenario analysis is that emission reductions will be implemented throughout the world from 2013 onwards – and that it is possible to peak global emissions around 2020. While both models find this to be technically feasible, it will require a clear strengthening of current climate policy.

Baselines assumptions are critical for attainability of low targets

The analysis with respect to different baseline scenarios indicates that the attainability of 2.6W/m^2 forcing target is dependent on the characteristics of the baseline scenario.

The MESSAGE analysis shows that the 2.6W/m^2 target is attainable (under specific conditions) from a B2 baseline scenario with intermediate emissions – but not from the fossil intensive and high energy demand A2r scenario. IMAGE results emphasize the importance of baseline land use assumptions for both land use emissions and the availability of bio-energy.

The low targets are achieved after an initial overshoot.

Another important characteristic of the low mitigation targets profiles is an overshoot in mid-century radiative forcing around 3W/m^2 (IMAGE) to 3.5 W/m^2 (MESSAGE). The level of overshoot does depend on the baseline emissions of non-CO_2 GHGs (in particular CH_4) and the ability to reduce these emissions, and on the availability and costs of negative emissions in the second half of the century.

Both the 2.9 and 2.6W/m^2 scenarios are consistent with the 2 degree target in the long term – but have different probabilities of achieving this target

Given the numbers presented in IPCC AR4, the probability of achieving the 2 degree target is estimated at around 50% for the 2.9 W/m^2 target and 50-95% for the 2.6 W/m^2 target. Specific probabilities were calculated for the MESSAGE scenario (see Chapter 3.9).

Both the 2.9 and 2.6W/m^2 targets require the application of a wide portfolio of abatement options and significant changes in the energy system.

Both targets (2.9 and 2.6) require the application of a wide portfolio of abatement options and fundamental changes in the energy system. Major contributors to emissions reductions comprise substantial energy efficiency improvements, substitution of fossil-fuels by renewable and/or nuclear energy, application of carbon capture and storage, forest sink enhancement, and reduction of non-CO_2 emissions. The MESSAGE analysis shows that achieving both targets is possible under alternate technological pathways of limited nuclear or bio-energy deployment. However, this leads to a corresponding increase in the deployment of fossil-fuel based technologies, especially in combination with carbon capture and sequestration.

Achieving the 2.6 target requires the transition to negative emissions from the energy sector by the end of the century. While not all technological options are equally crucial for low targets, reaching 2.6 W/m^2 is associated with larger uncertainties than 2.9 W/m^2 target.

In both the MESSAGE and IMAGE model, reaching 2.6 W/m^2 is conditional on the attainability of negative CO_2 emissions from the energy sector by the end of the century. This implies that the target is found to be unattainable in absence of negative emissions technologies (bio-energy in combination with CCS). In addition, the limited expansion of agricultural land for food production was found to be a precondition for achieving the 2.6 W/m^2 target. In other words, for the lowest target the mitigation portfolio with respect to bio-energy contributions is less flexible given the dependency on two options, CCS and bio-energy, and the associated uncertainty with respect to the realization of the required deployment schedule as well as the required technological up-scaling. The option of bio-energy and carbon capture and storage is not a precondition for the 2.9 W/m^2 target, but helps to reduce costs and limits the dependency on other mitigation options.

There is some flexibility for the emission pathway and the required mitigation over time

The IMAGE and MESSAGE results show somewhat different profiles over time. Still in both cases, the B2-2.6 scenario requires emissions to peak between 2010 and 2020 and decline thereafter. The results thus indicate that there is limited flexibility with regard to the timing of mitigation and the associated emissions pathway for 2.6. In the long term, the analysis leads to negative emissions in both models, indicating the importance of forest sinks and negative emissions technologies in the energy sector. Participation of developing countries will be key both in the short and long-term. In order to peak emissions around 2020, immediate participation of developing countries needs to be assumed.

Taking into account GHG emissions and energy feedbacks from bio-energy supply does make the targets more difficult – but does not play a key role

In both MESSAGE and IMAGE calculations it was found that additional indirect GHG emissions resulting from bio-energy production and use have a limited impact. This is because woody biomass, which has low nitrogen-fertilisation and conversion emissions, is assumed to become the dominant source of bio-energy in the scenarios. However, if woody biomass and second generation technologies do not emerge over the next decades, additional GHG-emissions associated from bio-energy may prevent achieving the low targets.

Land use related emissions decrease over time

In the IMAGE and MESSAGE scenarios, net emissions from deforestation and afforestation are decreasing over time. In MESSAGE, they become negative around 2040. As mentioned before, a complete reversal to net negative emissions from land use change and bio-energy use in the long term is found to be one of the preconditions for the attainability of the 2.6W/m^2 target in both MESSAGE and IMAGE

Additional abatement costs are in the order of 1-2% of GDP

MESSAGE and IMAGE show high carbon prices to achieve these low targets. Carbon prices are around 100 US$/tCO$_2$ in 2050, but increase rapidly to around 300 US$ (IMAGE) or even above 1000 US$/ tCO$_2$eq (MESSAGE) by the end of the century. In both models, the additional investments are in the order of 1-2% of GDP. In terms of GDP losses, the 2.6 target may lead to losses of 3% by 2050 and 5% by the end of the century (MESSAGE). The macroeconomic impact of the increased mitigation costs are lower for the 2.9 W/m^2 scenario (e.g., 2% GDP loss by 2050 and 4% loss by 2100). By comparison, global GDP is assumed to increase by about a factor of four between 2000 and 2050. Additional investments needed for mitigation in the 2.6 W/m^2 scenario range from 7-9 trillion US$ over the next 30 years compared to the B2 baseline scenario.

1. Introduction

1.1 Context, main questions and method

The long-term objective for EU climate policy is to limit global mean temperature increase to a maximum of 2°C over pre-industrial levels. The stringency of this target in terms of greenhouse gas emission reduction obviously strongly depends on the so-called climate sensitivity. Over the last few years, new studies have revised the range of likely values for the climate sensitivity upward. This implies that the number of mitigation scenarios published in the literature that can achieve the 2°C target with a probability of more than 50% are very low (see also Section 2). In order to explore what is needed to achieve the EU target further analysis of low mitigation scenarios is needed. Such analysis could provide insight into critical factors such as the trade-offs between the probability of achieving the target and the level of changes required in the energy system (and the rate at which these need to be implemented), the contribution of various mitigation options (including land-use related options) and the requirements for achieving these low targets.

At the same, IPCC is currently considering which scenarios – selected from existing literature – should be used to explore possible climate impacts during the next 100-300 years (IPCC 2008). A decision has been made that the set of scenarios should include a high and low scenario and 2 medium stabilization scenarios. While agreement has been reached on which published scenarios could serve as input for most IPCC scenarios, no decision was made on the lowest scenario – given questions on how robust current findings on very low scenarios are.

In this research project, the MESSAGE and IMAGE modeling teams perform model runs to explore the possibility to reach a radiative forcing level of around 2.6-3.0 W/m^2 by the end of the century. Such scenarios would be part of the very lowest category of the classification used by WG3 of IPCC (Fisher et al. 2007) (see Chapter 2). The two modeling groups explore key-uncertainties for achieving these low targets, in particular in relation to 1) baseline developments, 2) availability of different technologies, 3) emissions of bio-energy, 4) impacts of forestry and land use assumptions. Given the interest to test the robustness of achieving low GHG concentration targets, the quantitative analysis is restricted to sensitivity tests in which more pessimistic assumptions are made than in the default calculations. It should, however, be noted that the future may also develop in ways that would make achieving low concentration targets more easy (as indicated in the discussion section of Chapter 3 and Chapter 4). As start of the analysis also a literature review was made on the available information on low mitigation scenarios, and on the implications of this information.

The application of two alternative models, as proposed here, has the advantage that it permits a comparison of results obtained with different methodologies and alternative parameterizations. Such a comparison provides insight into the question how robust conclusions are against methodological uncertainties as well as scenario uncertainties. MESSAGE and IMAGE are particularly suited for this research as they are to date the only global multi-gas modeling frameworks with substantial experience in the development of low GHG concentration scenarios with forcing levels in the range of 3 W/m^2 and below by the end of the 21st century.[1] It should be noted that some of the lowest scenarios published in literature were exploratory in nature. In the meantime, new insights have emerged that need to be considered in the development of new scenarios. This includes for instance new information on the implications of wide-spread use of bio-energy.

The MESSAGE model (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) is a systems engineering optimization model used for medium- to long-term energy system planning, climate change policy analysis, and scenario development (Messner and Strubegger 1995; Riahi et al. 2007). The model's principal results comprise the estimation of global and regional, multi-sector mitigation strategies for specific climate stabilization targets (for details on MESSAGE see Appendix A). The Integrated Model to assess the Global environment (IMAGE) has initially been created to assess the impact of anthropocentric climate change, and has since then been further developed with respect to energy modeling, the assessment of mitigation options, international burden sharing, land-use (change) and biodiversity to provide a more comprehensive coverage of global change issues in an environmental perspective (IMAGE-team 2001; Bouwman et al. 2006). Recently, this modeling framework has been applied for analyzing mitigation scenarios (van Vuuren et al. 2007) (for details see Appendix A).

1.2 Structure of the report

Chapter 2 presents a review of the low GHG concentration scenarios in the literature, and summarizes the main findings with respect to presently available emissions pathways. Next, Chapter 3 and Chapter 4 present the MESSAGE and IMAGE modeling analyses, the underlying assumptions, and results with respect to the attainability of low targets. Finally, Chapter 5 compares the resulting emissions pathways of both models. The Appendix provides some technical background and a brief overview of the IMAGE and MESSAGE models respectively.

2. Low Mitigation Scenarios in the Literature

2.1 Current status of low mitigation scenarios

Because Article 2 of United Nations Framework Convention on Climate Change (UNFCCC) states as its objective the 'stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system' (UNFCCC 1992), most long-term mitigation studies have focused their efforts on GHG concentration stabilization scenarios. However, several other climate change targets may be chosen, e.g., rate of temperature change, radiative forcing, or climate change impacts (see e.g. (Richels et al. 2004; Corfee Morlot et al. 2005; van Vuuren et al. 2006). Recent literature has shown that a cost-effective way to

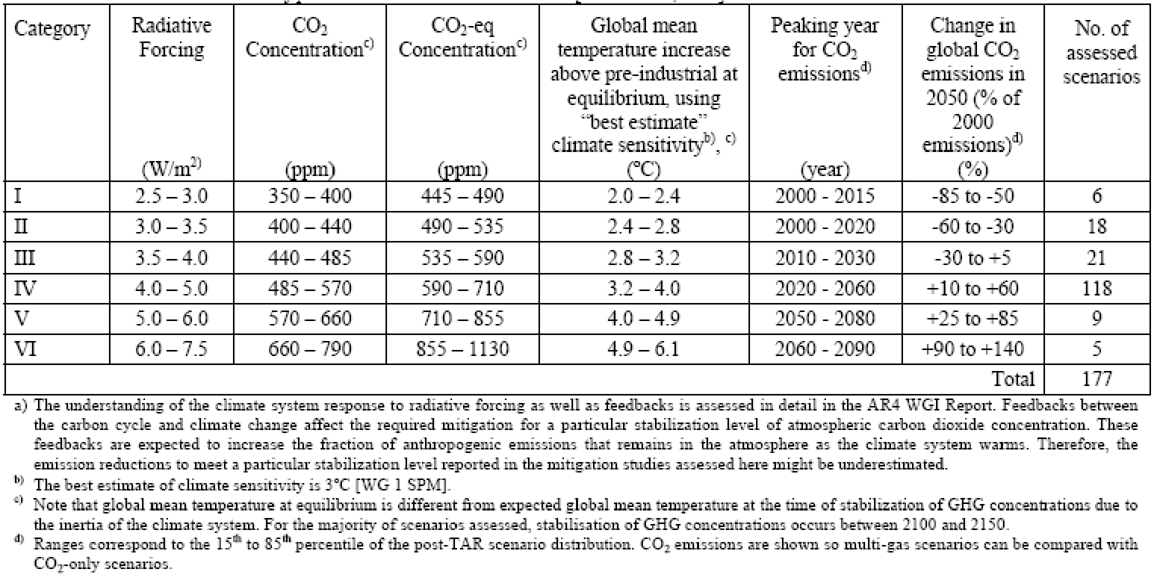
---

[1] Radiative forcing of the scenarios by 2100 differs from the long-term stabilization forcing level at equilibrium. For a comparison of radiative forcing levels by 2100 with the long-term equilibrium see Section 2.

limit temperature increase is not to stabilize GHG concentration, but rather to allow concentration (radiative forcing) to peak at a certain level, and then decrease with additional emissions reductions so as to avoid (delayed) further warming and stabilize global mean temperature (Meinshausen 2006; Den Elzen and Van Vuuren 2007). These types of scenarios are referred to as overshoot or peaking scenarios (in contrast to stabilization scenarios). It should be noted that the majority of the scenarios with very low targets tend to be overshoot scenarios. In order to avoid much confusion, in this report we tend to use the more general term "mitigation" scenarios.

The IPCC Working Group III (WGIII) of the AR4 assessed the literature on mitigation scenarios published since the SRES and the Third Assessment Report (TAR) (Fisher et al. 2007). A total of more than 300 scenarios were identified in AR4, 147 and 177 of which were baseline and mitigation scenarios, respectively. The result of the assessment of the mitigation scenarios is summarized in Table 2.1. Table 2.1 shows a grouping of mitigation scenarios in six different categories (based on either the CO_2 or CO_2-eq mitigation level reported by the study following column 3 or 4) in order to facilitate the comparison of different mitigation levels and their implications for the CO_2 emissions pathways. The six categories are labeled I for the lowest mitigation levels up to VI for the highest. The table also illustrates the rough relationship between radiative forcing, temperature change at equilibrium and concentration levels of CO_2 only and CO_2-equivalent.[2]

Table 2.1: Properties of mitigation scenarios assessed in AR4 (source: AR4, WGIII).



Category	Radiative Forcing (W/m^2)	CO_2 Concentration[c] (ppm)	CO_2-eq Concentration[c] (ppm)	Global mean temperature increase above pre-industrial at equilibrium, using "best estimate" climate sensitivity[b), c)] (°C)	Peaking year for CO_2 emissions[d)] (year)	Change in global CO_2 emissions in 2050 (% of 2000 emissions)[d)] (%)	No. of assessed scenarios
I	2.5 – 3.0	350 – 400	445 – 490	2.0 – 2.4	2000 - 2015	-85 to -50	6
II	3.0 – 3.5	400 – 440	490 – 535	2.4 – 2.8	2000 - 2020	-60 to -30	18
III	3.5 – 4.0	440 – 485	535 – 590	2.8 – 3.2	2010 - 2030	-30 to +5	21
IV	4.0 – 5.0	485 – 570	590 – 710	3.2 – 4.0	2020 - 2060	+10 to +60	118
V	5.0 – 6.0	570 – 660	710 – 855	4.0 – 4.9	2050 - 2080	+25 to +85	9
VI	6.0 – 7.5	660 – 790	855 – 1130	4.9 – 6.1	2060 - 2090	+90 to +140	5
						Total	177

a) The understanding of the climate system response to radiative forcing as well as feedbacks is assessed in detail in the AR4 WGI Report. Feedbacks between the carbon cycle and climate change affect the required mitigation for a particular stabilization level of atmospheric carbon dioxide concentration. These feedbacks are expected to increase the fraction of anthropogenic emissions that remains in the atmosphere as the climate system warms. Therefore, the emission reductions to meet a particular stabilization level reported in the mitigation studies assessed here might be underestimated.

b) The best estimate of climate sensitivity is 3°C [WG 1 SPM].

c) Note that global mean temperature at equilibrium is different from expected global mean temperature at the time of stabilization of GHG concentrations due to the inertia of the climate system. For the majority of scenarios assessed, stabilisation of GHG concentrations occurs between 2100 and 2150.

d) Ranges correspond to the 15th to 85th percentile of the post-TAR scenario distribution. CO_2 emissions are shown so multi-gas scenarios can be compared with CO_2-only scenarios.

(Note that the data in the last 3 columns are descriptive of the actual scenarios included in each category and cover only 15-85th percentile).

The lowest mitigation category (I: 2.5-3.0 W/m^2 – see Table 2.1) consists of 6 scenarios. Two scenarios were developed with the IMAGE model (van Vuuren et al.

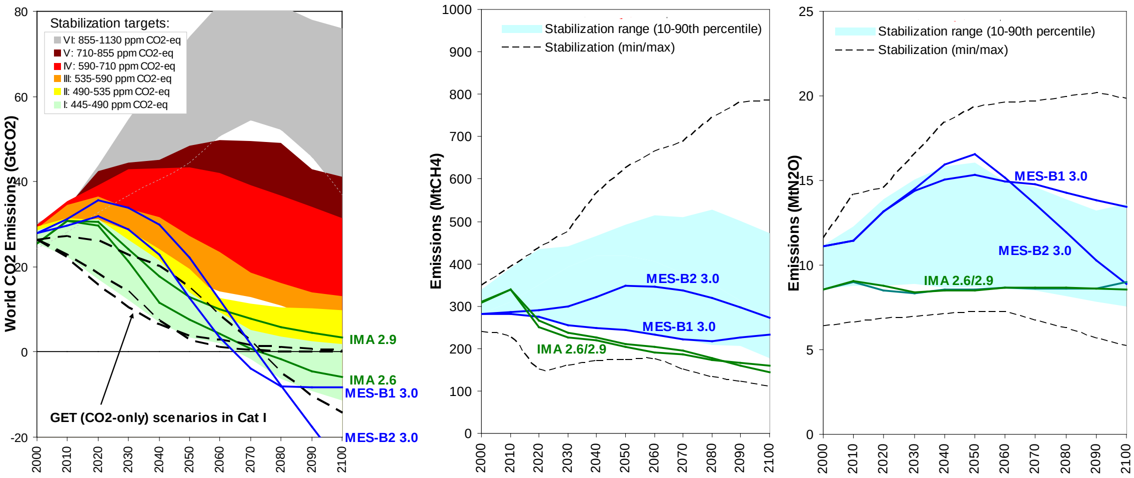
---

[2] Throughout this report CO_2-eq concentration refers to all major radiative forcing agents expressed in terms of the equivalent CO_2 concentration that would result in the same forcing level as all agents together.

2007), one with the MESSAGE model (Riahi et al. 2007) and three with the GET model (Azar et al. 2006). The IMAGE scenarios and MESSAGE runs are multigas scenarios. The IMAGE scenarios in this category aim lead to a 2100 radiative forcing of 2.6 and 2.9 W/m^2 respectively, while the lowest MESSAGE scenario aims at limiting forcing to about 3.0 W/m^2 (B1-3.0). An additional MESSAGE scenario (B2-3.0) exists that reduces forcing to slightly above 3 W/m^2 by 2100, and is hence part of category II of the IPCC assessment. These four scenarios are the lowest multi-gas scenarios including all GHGs and other radiatively active gases presently available in the literature. The other scenarios of the lowest mitigation category are CO_2-only scenarios developed by the GET model. These scenarios assume climate policies to start already around 2000, and aim at the stabilization of CO_2-only concentrations between 350 and 400 ppm. As the GET model provides half of the scenarios included in Category I, it has a significant influence on the statistical properties of this category summarized in Table 2.1.

A comparison between the specific emissions pathways of the low mitigation scenarios (for the main GHGs: CO_2, CH_4, and N_2O) and corresponding ranges from the scenario literature is shown in Figure 2.1. Note that a classification of the scenarios according to the mitigation targets does exist only for CO_2. Hence, for CH_4 and N_2O emissions pathways the full range as well as 10-90th percentiles of all mitigation scenarios assessed in table 2.1 are shown.

Figure 2.1: Development of main GHG emissions (CO_2, CH_4, and N_2O).



Note that CO_2 emissions are given in $GtCO_2$, while other figures in this report show CO_2 emissions in GtC.

2.2 Important characteristics of low mitigation scenarios

The comparison of emissions pathways reveals a number of important characteristics of the low mitigation scenarios:

1) While the CO_2 emissions pathway of the low MESSAGE and IMAGE scenarios are characterized by a further increase of global emissions after 2000 and peak of emissions by latest 2020, the lowest GET scenarios assume that emissions would be reduced instantly as of 2000. The latter category of scenarios is

obviously at odds with observed historic trends, and therefore overestimates feasibility of very low mitigation targets and cannot be compared to model runs that only start stringent climate policies after 2010. But even for the IMAGE and MESSAGE runs, the characteristics of steep emissions decline between 2010 and 2050 poses a challenge with respect to the feasibility of the short-term trajectory of these scenarios, particularly if regional distribution aspects and historic and present CO_2 emissions trends of developing countries are considered.

2) The IPCC classification denotes the 15-85th percentile of the scenario distribution for each mitigation category (see Table 1 and right hand panel shadings of Figure 1). Hence, it is important to note that full range of plausible CO_2 emissions pathways includes trajectories that are (temporarily) above or below the IPCC 15-85th percentile range (and that the 3 GET runs do strongly determine the range). See e.g., the emissions profiles of the low MESSAGE scenarios, which are initially exceeding the AR4 corridor for category I in the first half of the century, and are significantly below the range by the end of the century. Similarly, the IMAGE 2.9 scenario is above the category I range in the latter half of the century.

3) With regards to CO_2 emissions, the MESSAGE 3.0 and the low IMAGE 2.6 scenario show pronounced negative emissions due to carbon capture from bio-energy and forest sink enhancements. In this context, it is important to note that both models (consistent with the IAM literature as published so-far) assume bio-energy to be (nearly) carbon neutral. Recent literature (using life-cycle assessment (LCA) and other methods) raised serious concerns with respect to the greenhouse gas consequences of bio-energy – in particular due to associated emissions from N_2O and CO_2 (the latter due to deforestation or avoided reforestation).

4) It is important to note that for similar mitigation targets, the MESSAGE scenarios tend to have higher CO_2 emissions (compared to IMAGE) over the first half of the century, and significantly lower emissions in the long term (see MESSAGE 3.0 and IMAGE 2.9). This is primarily due to the more pronounced inertia of the energy system in MESSAGE over the short term as well as comparatively larger potential for negative emissions cut-backs over the long term.

5) For CH_4 and N_2O large variations of base year values are observed, which are primarily due to uncertainties of inventories. A direct comparison of the IMAGE and MESSAGE scenarios indicates that the baseline emissions and emissions reductions for these gases are higher in IMAGE compared to MESSAGE. Principal reasons for this are the underlying assumptions for the mitigation potential in the agricultural sector, particularly for CH_4 management from life stocks, which are assumed to be higher in IMAGE than in MESSAGE – and the lack of a vintage structure in the non-CO_2 modeling of IMAGE

As illustrated by our assessment, there is some degree of flexibility for the GHG emissions pathway even in the case of very low mitigation scenarios. Given the specific characteristics of the assessed scenarios, the low mitigation scenarios explored by the MESSAGE and IMAGE teams in this report comprise:

- short-term baseline and emissions reduction profiles consistent with present emissions trends;
- exploration of the feasibility of rapid CH_4 and N_2O emissions reductions, in order to explore the lowest attainable targets from this model;
- an assessment of potential trade-offs from biomass-based negative emissions technologies (for more details see next section); and
- the impact of deforestation and afforestation.

3. Low GHG Concentration Scenarios Using MESSAGE

3.1 Introduction

This section summarizes analysis done with the MESSAGE model, exploring the attainability and implications of a global climate regime that is directed towards limiting long-term increase of radiative forcing at 2.6 W/m^2 as compared to pre-industrial times. The scenario results for 2.6 W/m^2 are compared to scenarios with higher forcing levels, in particular to a target of about 2.9 W/m^2. Our analysis includes a detailed representation of the energy and GHG feedbacks. Particular highlights of this analysis include:

1. Inclusion of all six Kyoto GHGs as well as other radiatively active substances
2. A comprehensive treatment of fertilization induced N_2O emissions of large scale bioenergy (see appendix)
3. An assessment of the flexibility of the emissions pathway concerning alternative timing of mitigation in order to achieve the 2.6 W/m^2 target
4. A sensitivity analysis exploring the robustness of the target vis-à-vis mitigation portfolio uncertainties, identifying principal technology needs to attain the target
5. An analysis of the (potentially) necessary medium-term overshoot of the forcing target, given the short-term socio-economic and climate system inertia

3.2 Baseline and attainability

The choice of the baseline scenario is of critical relevance as it serves as the reference for the energy demand and GHG emissions based on which the stringency and attainability of the target can be considered. Two baseline scenarios were selected for this analysis-the A2r and B2 (for more details see (Riahi et al. 2007)). These span a relatively broad section of the scenario literature and thus provide a good basis for the analysis. Table 3.1 indicates the main features of these scenarios. The A2r scenario is fossil-intensive typified by an overall high energy demand combined with slow technological progress and results in high growth in GHG emissions by the end of the century. The B2 scenario is characterized by more moderate energy demand and higher rates of technological progress for both fossil and non-fossil technologies.

Table 3.1: Baseline scenarios.

	2000	B2		A2r	
		2030	2100	2030	2100
Population, 10^9	6	8.3	10	8.7	12
GDP, 10^{12}US$	27	65	238	60	189
Fossil PE, EJ	343	590	690	641	1184
Nuclear PE, EJ	9	23	140	25	257
Renewable PE, EJ	10	47	199	40	134
Biomass PE, EJ	43	74	256	78	169
GtC energy	7	11	14	13	28
GtC forests	1	1	-1	1	0
GtC-e all others	3	4	5	4	7
GtC-e total	11	17	19	19	35

The scenarios include a detailed representation of the six Kyoto GHGs and the corresponding mitigation technologies. This approach endogenizes energy feedback effects from mitigation and takes into account interactions between GHGs (Rao and Riahi 2006).The scenarios also account for trends like increased agricultural productivity that may lead to lower emissions of CH_4 and N_2O from agriculture sources in the future. The scenarios also include representation of policies that could affect non-CO_2 GHG's emission growth, for example, the World Semiconductor Council's mandate on SF6 and the Montreal Protocol that calls for a complete phase-out of HCFCs in developed countries by 2030 and in developing ones by 2040 (for more details see (Schaefer et al. 2006)). However, the scenarios do not reflect recent directives that limit the use of high HFC gases that have higher global warming potentials (GWP) in the future(EC 2006a; EC 2006b). While this would have a significant impact on the MESSAGE baseline scenarios which show a relatively high growth of HFCs in the future, the effect on the mitigation scenarios themselves is likely to be small in terms of emission reductions, but may have some impact on costs. The reason for this is that the penetration of a number of HFC mitigation technologies implies a rapid decline in HFCs for the 2.9 and 2.6 scenarios, with the result that their contribution to the total radiative forcing is only about 0.1 W/m^2 by the end of the century (see Figure 3.4 below).

One of the major refinements in this analysis is a more in-depth representation of bio-energy feedbacks. Potential bio-energy supplies in MESSAGE can be divided into two broad categories: (i) agricultural residue and (ii) dedicated energy plantations, which are mainly short rotation woody crops. The amount of biomass for energy purposes depends on income, population and how people's preferences for meat, nature and landscapes develop over time. It also depends on how climate change will affect forestry and agriculture. While previous studies with the model have included updated land-use models that account for issues of competition of land (see Riahi et al. 2007), recent literature (see Crutzen et al. 2007) suggests that N_2O emissions from fertilizer use might be an important factor that has so far been neglected in the consideration of large-scale bio-energy plantations. For this analysis we have included a detailed representation of the energy and GHG emission feedbacks from fertilizer production and application, employing similar assumptions as the IMAGE team[3] (see Appendix A). However the impact on the B2 baseline scenario is found to be relatively small (around 5% change in primary energy), since woody or second generation biomass, which forms the bulk of the bio-energy stock in our analysis has comparatively limited fossil energy and GHG impacts of producing them. As the right-hand panel of Figure 3.1 indicates, the contribution to total N_2O emissions from energy-related fertilizer use is limited because of the dominance of soil related N_2O emissions from other agricultural practices.[4] In terms of energy-related N_2O emissions, however, there is a long-term increase of almost a factor three compared to the case without the N_2O feedbacks. As the share of energy-related N_2O in total emissions is relatively small, this is effect is found not to be of major concern also in the low GHG concentration scenarios discussed further below.

Figure 3.1: Increase in N_2O emissions due to bioenergy feedbacks.

Employing climate constraints on both baseline scenarios (A2r and B2) to limit radiative forcing change to 2.9 W/m^2 and 2.6 W/m^2 we find that the targets would be – under certain conditions (see sensitivity analysis further below) - attainable from the intermediate ‘B2’ baseline scenario, but not from the fossil intensive and high-demand A2r scenario. Unfavorable socio-economic conditions, including high population growth and the lack of economic and technological convergence between the industrialized and developing world, combined with relatively modest assumptions concerning technology improvements and slow improvements for energy intensity/efficiency leading to high demand are the main factors that limit the feasibility of attaining very low forcing targets in an A2r world. The feasibility of the mitigation scenarios thus also indicates the importance of the presence of appropriate socio-economic conditions and a favorable climate for technological development for stringent targets.

It should be noted that while we do not include in this analysis the ‘sustainable development’ B1 scenario, the lower energy demand (due to lower population growth) and faster rates of technological progress associated with this scenario will imply that attaining the 2.6W/m^2 target is also possible under this scenario. Earlier analysis (Riahi

---

[3] This includes an accounting of the energy use and GHG emissions associated with fertilizer production for bio-energy crops as well as increase in energy use in farming.

[4] As illustrated, total N_2O emissions increase in the first half of the century due to relatively rapid increase in population and agricultural production, which is the primary source of global N_2O emissions. The decrease of total N_2O emissions after 2050 is primarily due to slow-down of population growth in combination with increasing productivity in the agricultural sector, including more efficient fertilizer use and widespread mechanization (resulting in declining N_2O emissions coefficients per unit of agricultural production).

et al. 2007) shows also that in general costs under the B1 scenario would – for comparable forcing targets – be lower as compared to the B2 scenario.

Table 3.2 indicates the climate outcomes of various GHG scenarios by 2100, including the B2_2.6 results in CO_2-equivalent concentrations of 450 ppm and a global mean temperature change of around 1.7 (assuming a climate sensitivity of 3^oC). Both the B2_2.9 and the B2_2.6 are found to achieve temperature changes below 2 degrees at climate sensitivity of 3^oC per doubling of CO_2. However, given the uncertainty in climate sensitivity and other parameters, we will provide at a detailed probabilistic assessment of the scenarios with regards to their temperature consequences later in this report.

Table 3.2: Climate indicators.

Scenario Category	Radiative Forcing in 2100 (W/m^2)	CO_2-Concentration in 2100 (ppm)	CO_2-eq Concentration in 2100 (ppm)**	Global mean temperature increase above pre-industrial in 2100 (^oC)*
A2r Baseline	8.6	900	1430	4.5
B2 Baseline	6.6	640	970	3.6
A2r-4.8	4.6	490	680	2.7
B2-4.8	4.6	510	680	2.8
B2-2.9	2.9	370	490	1.9
B2-2.6	2.5	340	450	1.7

*All results are reported at 3 degree C climate sensitivity

** CO_2-equivalent concentration takes into account radiative forcing of all GHGs, and other radiatively active gases.

3.3 Timing of mitigation

Our results indicate that for both the B2_2.9 and the B2_2.6 scenarios, emissions would need to peak latest by 2020 and decline thereafter. This indicates that the attainability of low GHG concentration scenarios will critically depend on the ability to mobilize mitigation technologies in the short-term in order to achieve the levels of emissions reductions necessary. While, as seen in Figure 3.2 in general, early action is seen to be necessary even for higher stabilization levels like the B2_4.5, the urgency and magnitude of immediate action is intensified with the stringency of the target. This emphasizes that delaying action is not an option for achieving emissions pathways consistent with very low GHG concentrations.

The choice of discount rate will play an important role in determining the justification for costly emissions mitigation in the near term as the benefits of such reductions are likely to occur only in the distant future due to the long residence times of some of the greenhouse gases. Our results are based on a social planner modeling framework (minimizing mitigation costs while excluding damage and adaptation costs) with a uniform rate of time preference of five percent. In order to determine how the timing of mitigation actions would change with different assumptions on the discount rate, additional runs for the 2.6 W/m^2 target have been performed with discount rates of 1% and 10% respectively. The results indicate that an altered rate of time preference is unlikely to affect the need for immediate mitigation, with the peak in emissions occurring in the 2010-2020 period. We find that even under very high discounting of

10%, emissions will need to peak around 2020, although at a bit higher levels, thus indicating that there is limited flexibility with regards to the timing of mitigation (see Figure 3.3).

Figure 3.2: GHG emissions.

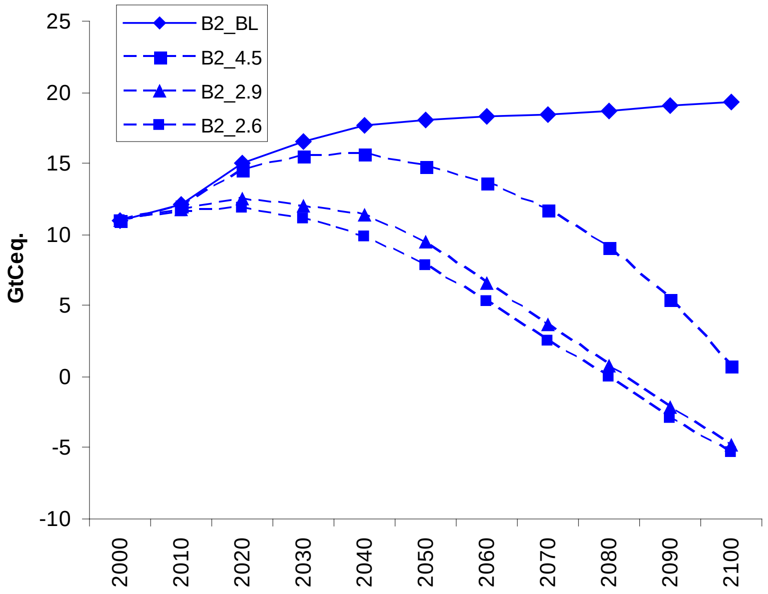
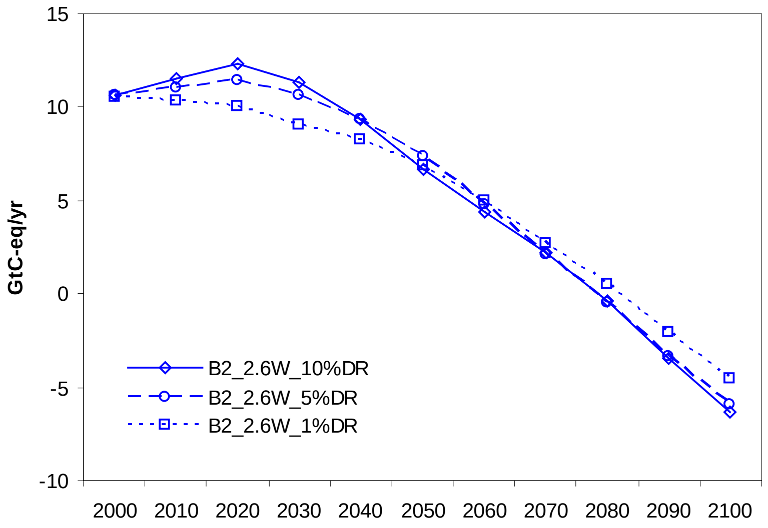


Figure 3.3: Implications of alternative discount rates.



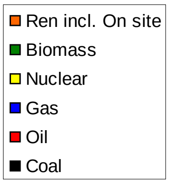
3.4 Mitigation profile

The multigas nature of our modeling framework (Rao and Riahi 2006) and the complete when and where flexibility imply that emission reductions will occur across different greenhouse gases and sectors, as indicated in Figure 3.4. In general, applying default assumptions of the modeling framework (Riahi et al. 2007) and the B2 baseline scenario, including the updates for bio-energy feedbacks discussed earlier, more than 80 percent of total emissions reduction occurs in the energy and industrial sectors, primarily from CO_2 but also from non-CO_2 GHGs with similar trends observed in the B2_2.9 W scenario. Thus, the primary focus of any cost-effective mitigation strategy has to target the full basket of energy-related and industrial sources of CO_2, CH_4, and F-gases.

Figure 3.4: Shares by GHG in cumulative emissions reductions in B2-2.6.

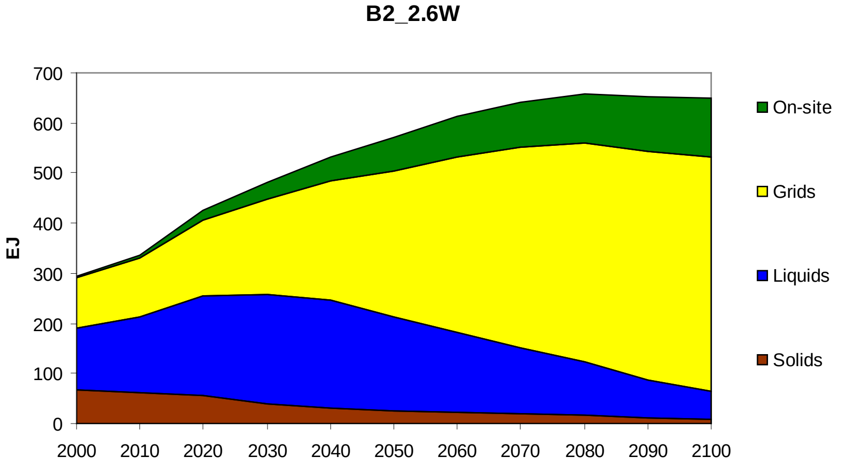
In spite of significant technological change that is already a part of the B2 baseline scenario; fundamental shifts will be required in the energy system in order to make both the 2.9W/m^2 and the 2.6W/m^2 target feasible. As Figure 3.5 indicates, a significant restructuring of the energy system will be needed with a move towards clean fossil electricity and increased share of non-fossil technologies.

Figure 3.5: Primary energy by fuel in B2_2.6 (numbers in shaded areas indicate the % change compared to the baseline, cumulative 2000-2100).



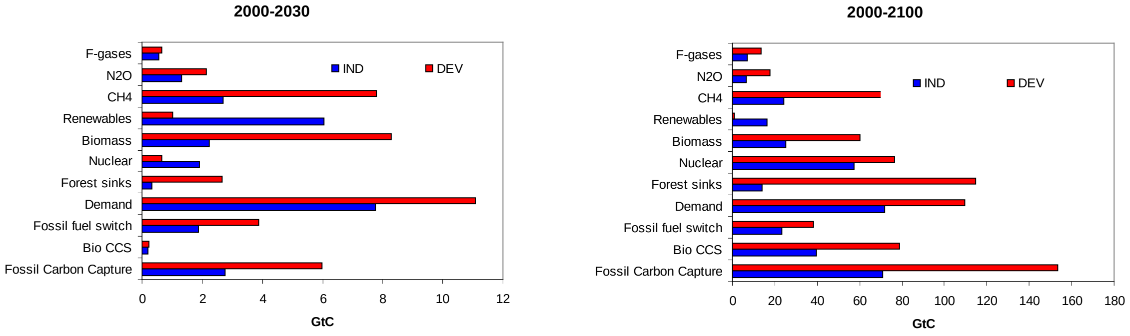
In terms of final energy, while the B2 baseline already assumes a high penetration of liquid fuels like ethanol in the transportation sector, low forcing targets will further accelerate the drive for oil substitutes in the medium term as Figure 3.6 shows. In the longer-term, electricity and hydrogen based systems (both from fossil sources like gas as well as biomass) will be dominant, thus bringing with it an obvious need for new production facilities and large scale infrastructure.

Figure 3.6: Final energy by form.



Results for the 2.6 case indicate the need for deployment of a host of mitigation technologies. As Figure 3.7 indicates, main mitigation options in the short-term include demand reductions and non-CO_2 mitigation. In the medium to long-term, fundamental restructuring of the energy system will become necessary, including in particular biomass and fossil based carbon capture. In addition, forest sinks will become an important part of the overall solution. Also visible in Figure 3.7 is the importance of developing countries' contribution to the mitigation efforts both in the short and long-term. While our modeling framework is based on a least-cost approach that does not address the issue of who pays for the mitigation, in general it is found to be more cost-effective to carry out mitigation in developing countries, which not only have in the long run a larger share of baseline emissions but also a number of cheaper mitigation alternatives. While energy investment needs in developing and transition countries will form a higher share of the overall economy as compared to industrialized countries, our results indicate that the investment requirements associated with the energy sector over this century will still be less than 10 percent of GDP. Assuming that capital markets will grow relative to GDP, this indicates that future economic growth will make the investment requirements for new technologies and fuels attainable. However, these investments will have to compete with other priorities in many countries and hence may not necessarily be available where they are needed and thus there will be an urgent need to prioritize investments into advanced, low-emissions technologies. This would bring with it a need for appropriate mechanisms and incentives that can facilitate financial or technological transfers (e.g., through mechanisms such as the CDM) to realize environmentally benign investments in developing countries.

Figure 3.7: Mitigation by technology, B2_2.6.



Reductions in energy demand are seen to be major contributors to emissions mitigation, particularly in the short-term, with a 7% cumulative reduction below the B2 baseline for the B2_2.6 scenario. An important point to be kept in mind is thus that the B2 baseline already assumes a number of energy efficiency and conservation measures. If these intensity improvements do not come about, the actual magnitude of demand reductions will have to be three times higher. The attainability of the 2.6 W scenario is thus conditional on the technological development in the baseline scenario, which already includes significant improvements in energy efficiency and conservation. Efficiency improvements will be especially important because many of the advanced mitigation technologies are still in the early stage of commercialization (e.g., solar) or demonstration (e.g., carbon capture and storage) and will thus require time to be able contribute significantly to mitigation efforts over the next 30 years. Another notable source of reductions in the short-term is CH_4 reductions from mining, landfills and other energy related sources with an almost 20% reduction.

In the medium and longer-term, there will be a need for both replacing existing electric capacity, particularly in developed countries where many fossil-based power plants are aging as well as towards installation of new capacity, both in developing and industrialized countries. A comparative analysis of the up-scaling effort for both the B2_2.6 and the B2_2.9 scenarios is given in Table 3.3. In both scenarios, the new capacity can be expected to be a mix of diverse technologies including advanced coal power (including CCS), [5] combined natural gas plants, nuclear and renewable electricity. By the end of the century, around 95% of the fossil electricity generation capacity will need to include carbon capture and sequestration. The importance of biomass as a fuel in the electric sector will be especially enhanced because of its potential for negative emissions if combined with CCS and around 75% of new biomass based power plants will be based on such systems. Nuclear power will need to increase to more than double that in the baseline by the end of the century. Renewable energy technologies already constitute a large part of electricity generation in the B2 baseline and we find that limiting forcing to both 2.9 W/m^2 and 2.6 W/m^2 lead to an accelerated deployment of such technologies in the first half of the century.

---

[5] Note that we consider the possibility of adding CCS to existing power plants and the corresponding higher costs of carbon capture technologies due to application of pre-combustion technology combined with low efficient power generation capacities.

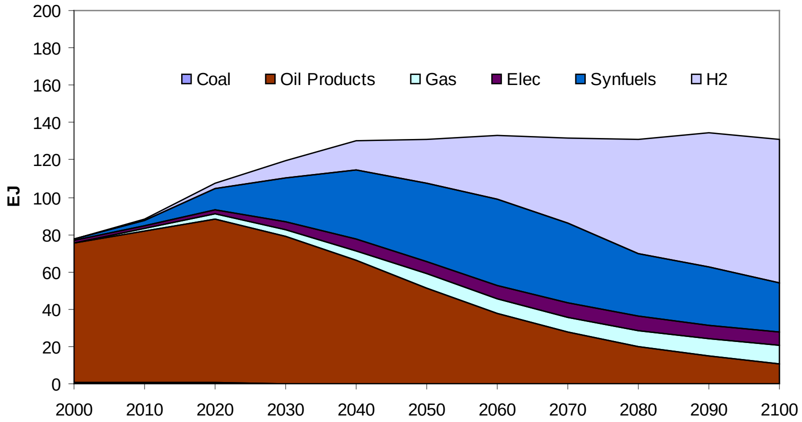
The scale of deployment suggested by the scenarios indicates that there will need to be a massive restructuring of the electricity systems globally. Table 3.3 shows a sharp increase of electricity generation capacity from nuclear (a factor of 3), biomass (a factor of 10), and other renewables (a factor of 4) by 2030. This not only highlights that the feasibility of such low forcing levels is highly dependent on technological shifts at large scales but also that policy changes will be needed if ambitious targets are the goal.

Table 3.3: Total installed electric generation capacity, GW(e).

	2000	2030			2100		
		B2_BL	B2_2.9	B2_2.6	B2_BL	B2_2.9	B2_2.6
Fossil electricity	2884	3865	2771	2622	5558	3213	2737
of which CCS share	0%	0%	6%	14%	0%	96%	96%
Nuclear	400	984	1194	1231	6024	14303	15776
Biomass electricity	45	215	466	458	333	3636	3877
of which BECS share	0%	0%	1%	1%	0%	75%	75%
Other renewables	793	1991	3049	2513	10205	10907	10922

Both targets require also a major shift on the demand side with the transportation sector experiencing a large-scale increase in use of synthetic fuels and hydrogen, as Figure 3.8 indicates (for the 2.6 scenario). The magnitude of this shift will require a major up-scaling of current synthetic fuel and hydrogen production facilities and an expansion in the imports of such fuels, especially in industrialized countries, thus reiterating that attaining such mitigation scenarios will be a major technological challenge.

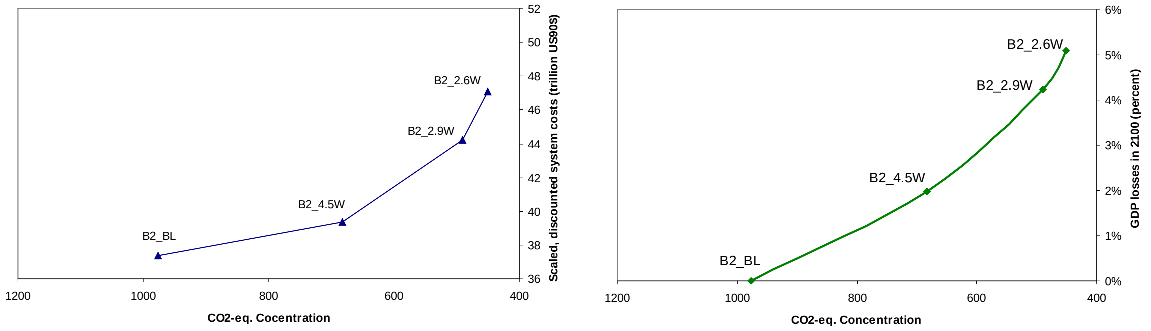
Figure 3.8: Final energy in transportation sector, B2_2.6.



3.5 Costs of Mitigation

We find that the macroeconomic costs of the 2.6 W/m^2 target are in the range of around 3% by 2050 and 5% of GDP by the end of the century (Figure 3.9). The economic losses of the 2.9 scenarios are with 2% by 2050 and 4% by 2100, modestly below the ones of the 2.6 scenario. Both scenarios indicate that even for ambitious targets the costs are relatively modest, particularly compared to the scenario's underlying economic growth assumptions.

Figure 3.9: Costs of climate mitigation in 2100.



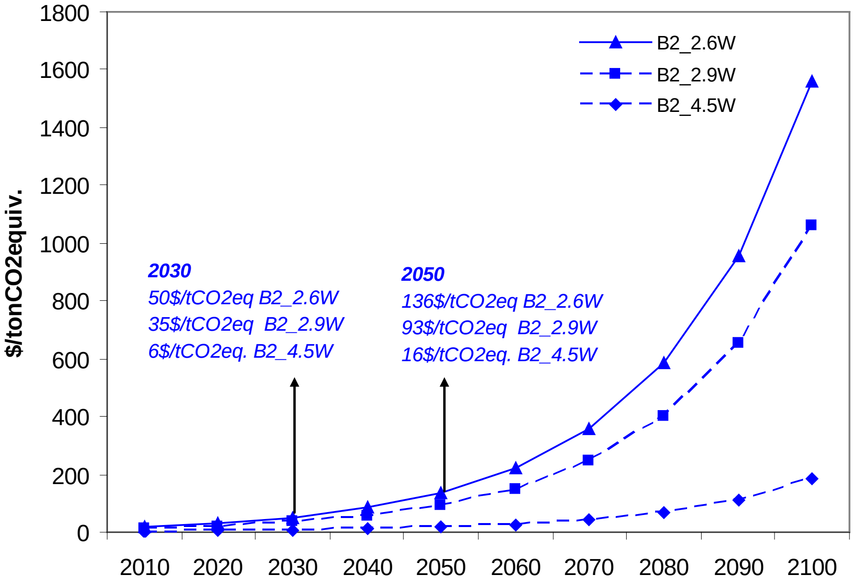
Achieving low forcing levels do not only require an increase in global investments to keep pace with growing energy demand, but more importantly a shift in paradigm from mainly large-scale infrastructure investments like fossil-based electricity towards a more balanced portfolio of investments that includes renewable and other energy sources as Figure 3.10 indicates. An additional 4 trillion dollars will be needed (corresponding to about 0.3% of GDP or 7% of total energy system costs) already in the next 30 years as compared to the B2 2.9 case, thus indicating that an enormous extent of up scaling efforts will be needed in a short-period of time. The exact costs of reaching a specific target will of course critically depend on the choice of the baseline scenario. While we do not specifically explore the 2.6W/m^2 target for the B1 scenario, earlier results (Riahi et al., 2007) indicate that there can be large differences in the costs of meeting identical climate targets, depending on the chosen baseline. Generally, more favorable conditions as in the B1 scenario (better socio-economic conditions, higher rates of technological change, lower population growth and decreased land-use change etc.) will imply that the 2.6W/m^2 scenario could be achieved at lower costs.

Figure 3.10: Additional investments for climate mitigation.

B2_4.5 B2_2.9 B2_2.6

The shadow prices of the B2_2.6 scenario, as seen in Figure 3.11, indicate a sharp increase in the marginal costs of abatement for stringent mitigation efforts as required in this scenario with 2020 carbon prices of more than 30 US$/ton CO_2 equivalent that increase to more than 1500 US$/ton CO_2-eq. by the end of the century .On comparing to the B2 2.9 scenario, we observe not so much difference in the short-term prices but more significant increases in prices by the end of the century. The results thus indicate that even a relatively small change in the target may result in relatively large increases in GHG prices necessary to drive further technological change within an energy system, which is already close to its limits (see also Figure 3.9 for the increase of total system costs and associated GDP losses).

Figure 3.11: GHG shadow prices, US$/ton CO_2 equivalent (in 2000 US$).



3.6 Flexibility analysis assessing the robustness of the targets vis-a-vis technology uncertainties:

The scenarios discussed so far assume the availability of large potentials for mitigation from all sources. Given the uncertainties with respect to the large-scale deployment of advanced technologies, we now address the specific question of whether it is possible to reach 2.9 W/m^2 and 2.6W/m^2 under alternate assumptions of technological availability. In other words, we perform a feasibility analysis by constraining individual mitigation options of the mitigation portfolio and examining the effect this has on the mitigation profile and costs. By doing so, we aim to assess the flexibility vis-à-vis the possibility of achieving the target through the deployment of alternative technology portfolios. We concentrate on the main contributors to mitigation, namely fossil and biomass carbon capture, nuclear energy, bio-energy, demand side reductions and forest sinks. Table 3 shows the various sensitivities we performed and indicates the feasibility of the model runs.

We find that while the attainability of the 2.9W/m^2 target is conditional on particularly the viability of large-scale efficiency and conservation measures, the 2.6 W/m^2 target is conditional on the successful deployment and development of a number of additional mitigation options, including:

- fossil carbon capture and storage systems, (FCCS) (particularly to limit the rate of emissions increase in the short term)
- biomass-based carbon capture, (BECS) (permitting negative emissions in the long term)
- and forest sink enhancement (avoided deforestation and afforestation leading to negative emissions in the order of 3GtC/yr in the long term)

Table 3.4: Scenario attainability matrix for B2_2.6 and B2_2.9 scenarios.
(Numbers in parenthesis indicate results of B2_2.9 scenario)

Low forcing scenarios	Reference case (all options)	w/ Biomass constraint at baseline	w/ Nuclear constraint at baseline	w/o Fossil CCS	w/o Biomass CCS	w/o Forest Sinks	w/o Demand reduction
Attainability	Wide portfolio of options including all alternatives	lack of biomass mitigation potential is substituted by nuclear and other renewables	lack of nuclear mitigation potential is substituted by fossil CCS and demand savings	not feasible (feasible)	not feasible (feasible)	not feasible (feasible)	not feasible (not feasible)
GDP loss in 2050, 2100 (relative to baseline)	3%, 5% (2%, 4%)	3.25%, 5% (2.3%, 4%)	3.6%, 7% (3%, 6%)	n/a (2.5%, 5.6%)	n/a (4%, 5%)	n/a (4%, 5%)	n/a
Shadow Price of Carbon in 2050, 2100 (US\$/tonCO_2)	135, 1596 (92, 1061)	146,1676 (101,1152)	172, 1985 (108,1350)	n/a (116,1252)	n/a (229,2626)	n/a (197,2263)	n/a

We find that the B2_2.9W scenario is feasible in the absence of individual technological options like fossil carbon capture, BECS and forest sinks. In contrast, the 2.6W/m^2 target is seen to be not possible if any one of these options is unavailable. The results from the sensitivity analysis thus suggests that the B2_2.9 scenario is found to be more robust as compared to the B2_2.6 with respect to technological uncertainties and the corresponding risk that the large-scale deployment of individual mitigation technologies may be found to be unattainable. It is important though to recall that the results are conditional on the baseline assumptions of the B2 scenario as implemented in the MESSAGE model (Riahi et al. 2007). Similarly, it is important to note that this is not to suggest that the B2_2.9W scenario is easy to achieve. Both targets will require very ambitious deployment schedules for many of the mitigation technologies, which are still in their infancy stage. Achieving 2.6 W/m^2 is placing though a comparatively higher pressure on the energy system and requires more technological options to be deployed close to their fullest extent compared to 2.9 W/m^2.

We also find that reaching both 2.9 W/m^2 and 2.6 W/m^2 is possible under assumptions of limited nuclear and bio-energy (i.e., if these options are available only at their baseline levels), thus indicating that here is some modest flexibility of the mitigation portfolio to reach the respective target. However, this leads to a corresponding increase in the deployment of fossil-based options, including carbon capture and sequestration, with higher costs (see Table 3.4).

For a comparison of the contributions of individual mitigation options in the alternative 2.6 W/m^2 scenarios see Figure 3.12. As shown all scenarios require a portfolio of mitigation measures, with increasing contributions of all options towards lower targets. Limitation of the mitigation potential from a particular option implies higher costs and a skewed response with alternative technology being deployed at large scales. For example, limiting nuclear power in the 2.6W/m^2 scenario to the baseline values leads to large penetration of fossil carbon capture with cumulative contributions to mitigation almost close to 250 GtC.[6] While this is well within the range of storage estimates (IPCC 2005) of around 150-500 GtC just from depleted oil fields and enhanced oil recovery, the deployment of this technology at such a large scale will require that safety issues as well as legal and institutional barriers be addressed

Figure 3.12: Contribution to mitigation, 2000-2030 and 2000-2100.

Note that Bio_Lim and Nuc_Lim denote the feasible 2.6 W/m^2 scenarios with limited nuclear and biomass deployment (Table 3.4).

The above analysis is specifically directed towards analyzing the feasibility of attaining the low targets under conditions of limited availability of certain technologies. It may of course also be possible to consider that technological development might be more rapid than currently assumed, especially for technologies still in their developmental stages like solar PV cells. While the B2 scenario already assumes technological learning for a range of fossil and non-fossil technologies resulting in consequent cost declines and efficiency improvements, a more rapid technology development pathway may lead to an increased deployment of some of these options and could impact the timing of emissions reductions for the low GHG concentration scenarios.[7] As discussed earlier,

---

[6] Note that renewables cannot completely substitute nuclear due to differences in load characteristics.

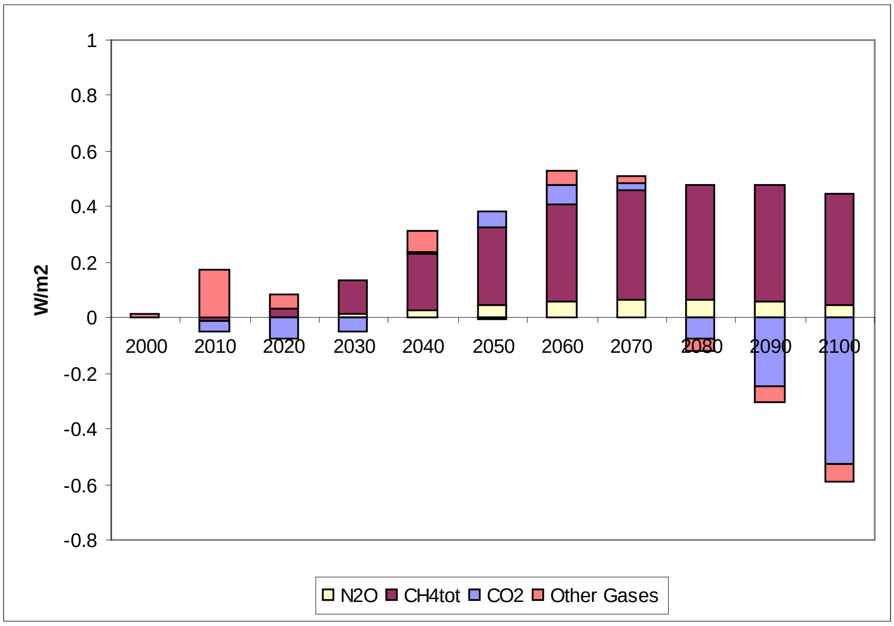
[7] Learning rates assumed in the range of 3-5%, in the B2 scenario.

the choice of baseline scenario will also have a significant impact on the mitigation technology portfolio and the mitigation response under the B1 scenario, for instance, is likely to be different. An additional point to note is that the B2 baseline scenario assumes a relative continuity of past dynamics of change and, due to accumulated inertia, and does not include the impacts that instantaneous shifts in the energy system (e.g., sudden hikes in fossil fuel prices or technological breakthroughs) may have on the energy system. However, concerns about economic recoverability of fossil fuels and environmental quality as well as a balanced technological development imply that declines in energy and emissions intensity (decarbonization) already form a significant part of the B2 scenario, thus making the attainability of low targets relatively easier than if for instance these intensity improvements were not taken into account. On the other hand, faster decline in energy and emissions intensities in the B1 baseline could make the attainability of the target easier, and thus also less costly.

3.7. Importance of overshoot

An important characteristic of the MESSAGE mitigation profiles is an overshoot in mid-century radiative forcing of significantly above 3W/m^2, with the extent of the overshoot depending on the stringency of the target. In order to look closer into the overshoot, we compare the B2_2.6W with the (original) IMAGE 2.6 scenario reported in the literature and find that one of the main contributors to the difference in forcing is the contribution of CH_4 as seen in Figure 3.13.

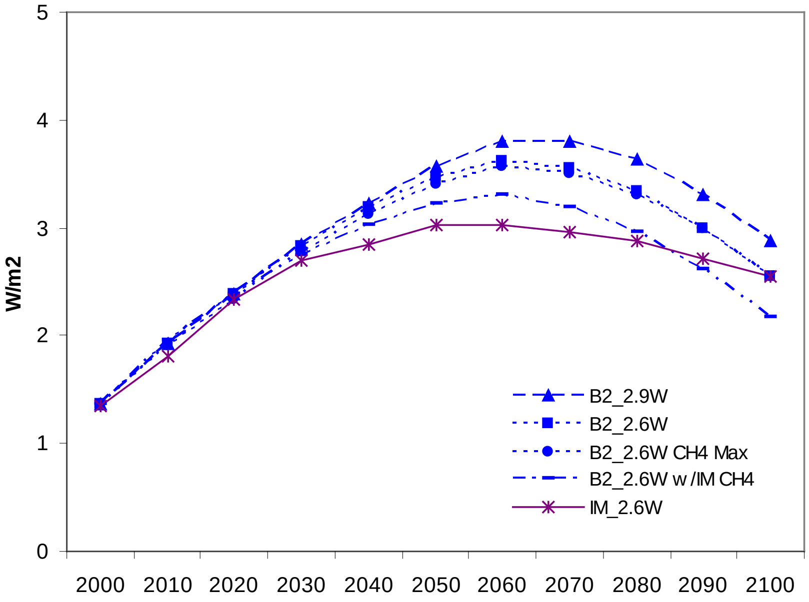
Figure 3.13: RF Difference between B2_2.6W and IM_2.6W.



The main cause of limited CH_4 reductions in the B2_2.6W case is relatively low mitigation potentials in the agricultural sector (for details see (Rao and Riahi 2006)). Under a multi-gas strategy, the contribution of the non- CO_2 GHGs in total reductions is relatively large early in the scenario period, (around 20%). However, if the overshoot in radiative forcing is to be reduced (as comparable to IM_2.6), more reductions in CH_4

will be needed. We performed a sensitivity run that attempts to force the maximum CH4 reductions from the B2_2.6 scenario. However, the overshoot in this scenario (CH_4 Max) is still seen to be higher than that of the IM_2.6 scenario, although the extent of overshoot decreases slightly. It appears that identified CH_4 emission reduction potentials become exhausted if substantial emission reductions (i.e., more than 30% CH_4 emission reduction compared with baseline emissions) is required. As an experiment, we also impose the identical CH_4 pathway of IM_2.6W/m^2 on the MESSAGE B2_2.6W/m^2 scenario and find that while the overshoot declines substantially, it does not disappear as seen in Figure 3.14.[8] The results indicate an important conclusion that an overshoot of the forcing target during the transition phase is inevitable to reach the 2.6W/m^2 target in the long term in the MESSAGE framework.

Figure 3.14: Overshoot in radiative forcing.



3.8 The forest sector

The development of global CO_2 emissions from the forest sector is presented in Figure 3.15. Already in the B2 baseline, emissions from the forest sector are assumed to decrease over time, leading at the end of the century to net negative emissions from afforestation and deforestation. This trend is mainly due to increasing affluence in the developing world, where higher productivity in the agricultural sector combined with slow-down of population growth is leading to less pressure for deforestation. Similar dynamics have been observed in the past for many of today's industrialized countries, where forest land-cover is presently growing.

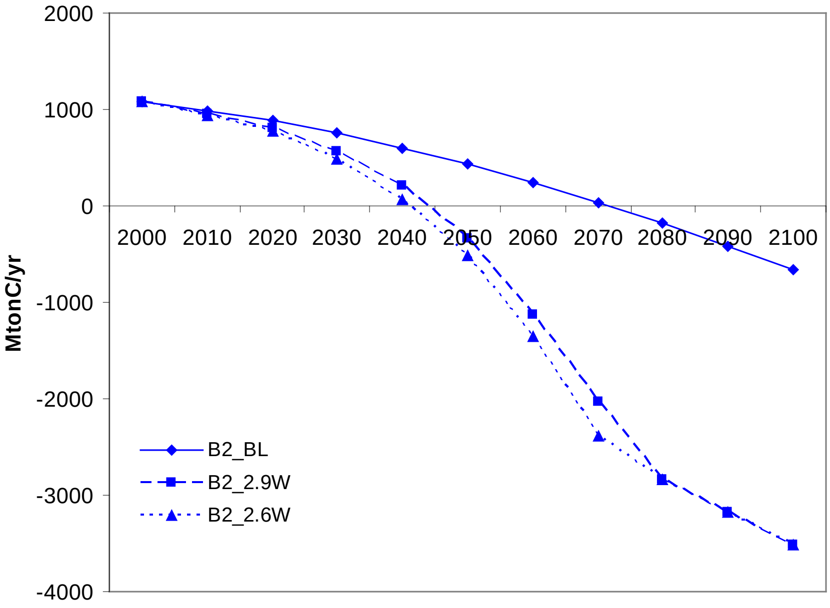
The decline of emissions from the forest sector is accelerated significantly in the mitigation scenarios. The carbon price of the climate policy represents an additional

---

[8] Note that the combination of modeling results from the two models is a mind experiment for illustrative purposes only, and does not correspond to an internally consistent and plausible scenario.

incentive for reducing deforestation as well as accelerating afforestation to reduce emissions. In both, the 2.6 and the 2.9 W/m2 scenarios, the cost-optimal emissions pathways lead to net zero emissions by 2040, where on aggregate deforestation is offset by additional afforestation. After that point the global forests act as a net sink, reaching at the end of the century net negative emissions of more than 3 GtC/yr. The forest sector is thus seen to be one of the principal contributors for the attainability of the 2.6W/m2 target (see flexibility analysis of section 3.6 above). At the same time land-use emissions are subject to large uncertainties. Further research and the development of refined modeling tools to better understand uncertainties as well as competition over land between bio-energy, food, and climate-related forest sink enhancements will thus remain an important area for the future research.

Figure 3.15: Forest CO_2 emissions.



3.9 Probabilistic assessment of temperature change

Global average temperature change outcomes resulting from specific emissions and forcing pathways are subject to considerable uncertainty. Given in particular the major uncertainty of climate sensitivity per doubling of CO_2 concentrations (CS), the temperature outcome of emissions scenarios can thus only be assessed within relatively wide margins. Numerous studies have explored probability distribution functions of climate sensitivity to help to understand the likelihood of this parameter and its implication for global climate change projections. These are summarized in Meinshausen (2006). Building upon the wide range of probability distribution of CS in the literature, we employ a probabilistic analysis to assess the likelihood of the 2.6

W/m^2 and 2.9 W/m^2 scenarios for a range of temperature targets. Our results build also upon methodologies presented in Meinshausen (2006) and Keppo et al. (2007).[9]

The results of the probabilistic assessment are summarized in Figure 3.16. The figure illustrates the cumulative probability distribution for staying below a range of temperature thresholds for the B2_2.6 (left-hand panel) and the B2_2.9 scenarios (right-hand panel). Individual lines correspond to the results from our calculations using different climate sensitivity probability distributions from the literature. We find that the probability of the scenario for staying below e.g., 2^{o}C is very much dependent on the shape of the underlying climate sensitivity PDF (i.e. probability distribution function). Based on the PDFs from Knutti et al. (Knutti et al. 2003) and Murphy et al. (Murphy et al. 2004) probabilities for staying below 2^{o}C are found to be lowest at about 30%. Employing, on the other hand, the same probabilistic calculus based on the Forest et al. (2002) PDF, results in the highest probability estimates for the 2.6 W/m^2 scenario of about 80% likelihood. A similar wide range is observed for the probability of staying below 2^{o}C for the 2.9W/m^2 scenario, with a full range from about 15 to 67% percent likelihood.

Comparing the results from individual PDFs, we find that the probability of 2.9 for staying below 2C is about 5 to 18 % below that for the 2.6 scenario. For the full range across all results from individual climate sensitivity PDFs (analyzed here) this translates into a likelihood between 30 and 80 % for the 2.6 W/m^2 scenario, compared to 15 to 67 % for the 2.9 W/m^2 scenario. The results thus indicate that both scenarios could be consistent with a target of 2^{o}C with the likelihood being modestly higher in the case of 2.6 W/m^2.

Figure 3.16: Probabilities of staying below specific temperature thresholds (B2-2.6 left-hand panel; and B2-2.9 right-hand panel).*

2.6 W/m2

2.9 W/m2

*Figure based on climate sensitivity PDFs from (Andronova and Schlesinger 2001; Wigley and Raper 2001; Forest et al. 2002; Gregory et al. 2002; Knutti et al. 2003; Murphy et al. 2004; Frame et al. 2005; Piani et al. 2005; Knutti and Meehl 2006)

---

[9] Note that we use the same probabilistic framework presented in Keppo et al. (2007) with the addition that for the specific purpose of this report, we take also the correlation of ocean diffusivity and aerosol forcing of alternative CS parameters into account. The resulting methodology is thus almost identical to the one used by Meinshausen 2006. For the climate calculations we use MAGICC version 4.0, a climate model of intermediate complexity.

3.10 Summary of results using MESSAGE

Implications of different baseline assumptions

The analysis, with respect to different baseline scenarios, indicates that the attainability of both the 2.9 W/m^2 and 2.6 W/m^2 forcing target is dependent on the characteristics of the baseline scenario. We found both the targets to be – under certain conditions (see further) - attainable under an intermediate emission B2 baseline scenario – but not from the fossil-intensive and high-demand scenario of A2r. The latter scenario is characterized by an overall slow energy efficiency/intensity improvements combined with slow technological progress, high dependency of fossil fuels, and a high demand for food due to rapid population growth. All factors together imply that low stabilization levels cannot be met under this baseline scenario. In the B2 scenario, a more moderate energy demand growth and higher rates of technological progress allow achieving these low targets.

Emissions pathways to 2.6 W/m^2

Based on a series of sensitivity runs for alternative discount rates we explore the timing of mitigation in the B2_2.6 scenario. We find that in all cases the B2_2.6 scenario requires emissions to peak between 2010 and 2020 and decline thereafter. This is even the case under a high discount rate of 10%, which tends to postpone mitigation later in time, although the emission peak takes place in 2020.The result thus indicates that there is little flexibility with regards to the timing of mitigation and the associated emissions pathway for 2.6 W/m^2 scenario. In the long term, the analysis leads to negative emissions in all cases, indicating the importance of forest sinks and negative emissions technologies in the energy sector.

Mitigation options in the short-term include demand reduction and non-CO_2 GHG reductions. In the medium to long-term, fundamental restructuring of the energy system will become necessary, especially by application of biomass- and fossil-based carbon capture. The use of forest sinks is also an important part of the overall solution. Participation of developing countries will be crucial both in the short -and long-term. In order to peak emissions between 2010 and 2020, immediate participation of developing countries needs to be assumed.

Flexibility analysis assessing the robustness of the targets vis-à-vis technology uncertainties

The attainability of both the 2.9W/m^2 and the 2.6 W/m^2 scenarios critically hinges on a number of key uncertainties including the feasibility of a wide range of technological options.

We find that while the attainability of the 2.9 W target is conditional on particularly the viability of large-scale efficiency and conservation measures, the 2.6 W/m^2 target is conditional on the successful deployment and development of a number of additional mitigation options, including 1) fossil carbon capture and storage systems both in the short and long-term 2) biomass-based carbon capture (permitting negative emissions in the long term), and 3) forest sink enhancement (avoided deforestation and afforestation leading to negative emissions in the order of 3 GtC/yr in the long term). The results from the sensitivity analysis thus suggests that the feasibility of the 2.9 W scenario is found to be more robust as compared to the 2.6 W with respect to technological uncertainties and the corresponding risk that the large-scale deployment of individual mitigation technologies may be found to be unattainable. Both targets will require ambitious deployment schedules for many of the mitigation technologies, which are still in their infancy stage. Achieving the 2.6 W/m^2 target is placing a higher pressure on the energy system and requires more technological options to be deployed close to their fullest extents compared to the 2.9 W/m^2 target.

We find that achieving 2.6 W/m^2 and 2.9 W/m^2 is possible under alternate technological pathways of limited nuclear and bio-energy deployment. However, this leads to a corresponding increase in the deployment of particularly fossil-based mitigation options, including carbon capture and sequestration. The costs of such constrained technological pathways are also higher. This suggests that there could be some flexibility with regards to the technological portfolio needed to meet very low forcing targets. This flexibility is however limited as emissions would still need to decline to zero over the medium term and become negative in the longer-term.

Costs

Costs of reaching 2.6 W/m^2 target are around 3% of GDP by 2050 and 5% by the end of the century, compared to 2% and 4% of GDP for 2050 and 2100 respectively for the 2.9 W/m^2 target. Carbon prices are about 100 US\$/tCO$_2$ for the first half of the century for both the 2.6 W/m^2 and 2.9 W/m^2 target. In the long term the carbon price is increasing to about 1000 US\$/tCO$_2$ by the end of the century for the 2.9 W/m2 target, compared to about 1600 US\$/tCO$_2$ in the case of 2.6 W/m2 target. Additional investments needed for mitigation range from 7-9 trillion US\$ over the next 30 years for 2.6 W/m^2 and 3.5 -6 trillion US\$ for 2.9W/m^2, compared to the B2 baseline scenario.

Overshoot

Another important characteristic of our mitigation profile is an overshoot in mid-century radiative forcing of about 3.5 W/m^2. Reductions in non-CO$_2$ GHGs in particular CH$_4$ are seen to largely determine the extent of overshoot and the feasibility of attaining even lower radiative forcing levels by the end of the century. While the contribution of CH$_4$ in total reductions is relatively large especially early in the century, further reductions are limited by scenario assumptions with respect to the mitigation potentials in the agriculture sector. An ex-post sensitivity analysis using alternative CH$_4$ emissions pathways from the IMAGE 2.6 scenario (considering more rapid reductions of CH$_4$) indicates that it may be possible to reduce the extent of overshoot, but not to completely avoid it.

The forest sector

The importance of mitigation in the forest sector is illustrated by the fact that a complete reversal of the sector (afforestation as well as avoided deforestation) to net negative emissions by around 2040 is found to be one of the *preconditions* for the attainability of the 2.6 W/m^2 target.

The probabilistic assessment of the MESSAGE B2_2.9W and B2_2.6W scenarios suggests that both RF levels would be consistent with the 2 degree target in the long term – but have different probabilities of staying below this temperature level

The likelihood of achieving 2^oC global mean temperature change target compared to pre-industrial times is found to be 30 to 80 % for the 2.6 W/m^2 scenario, compared to 15 to 67 % for the 2.9.0 W/m^2 scenario. The results thus indicate that both scenarios could be consistent with a target of 2^oC, with the likelihood being on average about 5-18% higher in the case of 2.6 W/m^2.

4. Low Stabilization Scenarios Using IMAGE

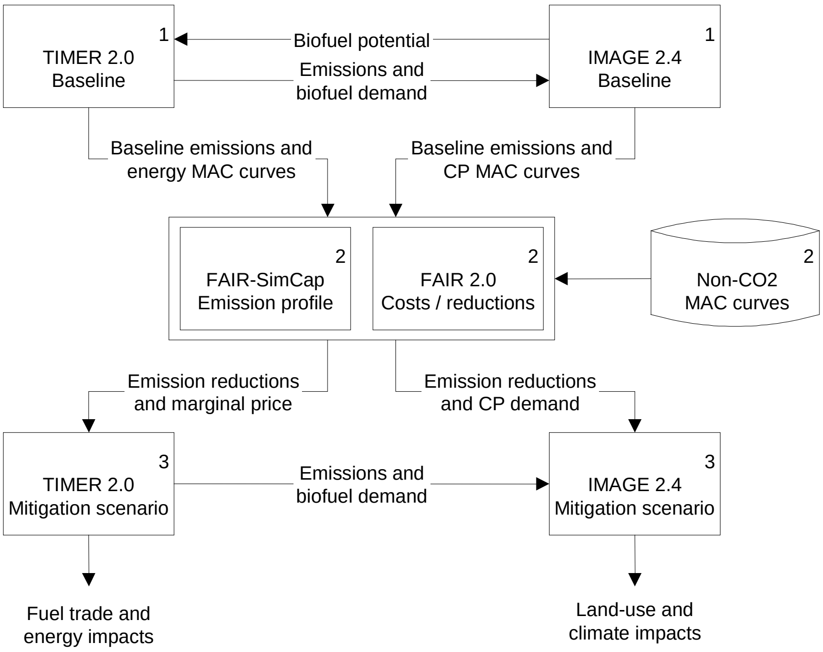
4.1 Overall methodology

For the construction of the stabilization scenarios, we use the Integrated Assessment modeling framework IMAGE 2.4 Integrated Assessment model (Bouwman et al. 2006), which includes the TIMER 2 energy model (Van Vuuren 2007), coupled to the climate policy model FAIR–SiMCaP (den Elzen and Meinshausen 2005). The IMAGE 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. The global energy model, TIMER 2.1, as part of the IMAGE model, describes the primary and secondary demand and production of energy and the related emissions of GHG and regional air pollutants. The FAIR-SiMCaP 1.0 model is a combination of the abatement costs model of FAIR and the SiMCaP model. The FAIR cost model distributes the difference between baseline and global emission pathway following a least-cost approach using regional MAC curves for the different emissions sources (den Elzen and Lucas 2005). The land and climate modules of IMAGE describe the dynamics of agriculture and natural vegetation, and, together with input from TIMER and FAIR, calculate total emissions, atmospheric concentrations, radiative forcing, and resulting climate change.

The overall analysis consists of three major steps (Figure 4.1):

1. Both the IMAGE and the TIMER model are used to construct the baseline emission scenario. These models also provide information on the potentials and abatement costs of reducing emissions from the energy and land use systems.
2. The FAIR-SiMCaP model is used to develop global emission pathways that lead to a stabilization of the atmospheric GHG concentration. As part of this step, the FAIR model distributes the global emission reduction from baseline over the different regions, gases and sources, using the marginal abatement costs, and using a constant discount rate of 5%.
3. The IMAGE/TIMER model implements the changes in emission levels resulting from the abatement action (emission reductions) and the permit price, as determined in the previous step, to develop the final mitigation scenario (emissions, land use, energy system).

Figure 4.1: Linkage and information flows of the applied modeling framework (note CP = Carbon plantations). Numbers in figure are explained in the text.



Compared to the publication of the IMAGE 2.3 version used to create the earlier 2.9/2.6 scenarios (van Vuuren et al. 2007), the following changes were made:

- The number of regions was extended from 17 to 26 regions;
- The bio-energy model was recalibrated and extended by including N_2O emissions and indirect energy use (see Appendix);
- The carbon fertilisation of natural vegetation was reduced in order to better comply with existing literature. The NPP under optimal conditions is now assumed to increase by 35% under doubled CO_2 concentration (before: plus 60%).
- The land use scenario was re-implemented to bring it closer to the original scenarios from the IMPACT, which were developed in the Millennium ecosystem assessment; for B2, the “adaptive mosaic” scenario had been used, and for A2, the “global orchestration” scenario (Alcamo et al. 2006; van Vuuren et al. 2007).

A more detailed description of the IMAGE 2.4 methodology is found in Appendix A.

Associated emissions from bio-energy application

Bio-energy is a significant contributor to the overall mitigation profile in both the earlier MESSAGE B2-3.0 and the IMAGE-2.9/2.6 scenarios. An important factor associated with large scale biomass plantations will be the use of nitrogenous fertilizers and this can be expected to have major implications for the direct emissions of nitrous oxide (N_2O). Crutzen et al. (2007) have recently completed a study that concludes that the use of agricultural crops for energy production can lead to N_2O emissions large enough to cause increased climate warming. Similar finding were obtained by Smeets et al. (2008). This could be an important factor in offsetting some of the positive effects of hitherto assumed GHG neutral bioenergy and has so far not been adequately taken into account in the scenarios. Next to fertilizer induced N_2O emissions, the production, transport, processing and conversion of biomass for bio-energy causes additional greenhouse gas emission, which have been assessed in life cycle analysis (LCA) studies (JRC et al. 2004; Harmelink and Hoogwijk 2008). The updated IMAGE model versions includes these potentially important emissions and examines what implications this may have for achieving low stabilization levels. The assumptions were based on the work of Smeets et al (2008) for N_2O emissions biofuel crops (choosing natural vegetation as a reference), new estimates for woody biofuel N_2O, and the ECOFYS report for all other emissions (Harmelink and Hoogwijk 2008). The assumptions on emissions from bioenergy production are documented in the Appendix.

4.2 Baseline

4.2.1. General assumptions

The baseline scenarios used in this study are based on the original set of SRES scenarios (Nakicenovic et al. 2000). The SRES scenarios have been reviewed several times with respect to their consistency with current trends. Van Vuuren and O’Neill (2006) found that the SRES scenarios were mostly consistent with trends and expected trends around that time. More recently, Pielke et al. (2008) and Raupach et al. (2007) raised questions whether rapid increase in emissions would make the SRES scenarios unlikely. Van Vuuren and Riahi (2008) assessed available evidence to conclude that emissions are currently increasing rapidly – but are still within the wide range of IPCC scenarios. Moreover, they did not see reasons to assume that current rapid increase would lead to higher emissions in the long-term. Finally, the recent surge in energy prices and the financial crisis of late 2008 might limit demand increases.

However, with respect to some factors, the SRES scenarios needed updates (e.g. population projections and short-term assumptions on GDP). Here, we follow the updates that were made to the IPCC scenarios by Van Vuuren et al. (2007) and have implemented these for the new IMAGE model (24/26 world regions).

The SRES B2 scenario explicitly focuses on exploring possible developments under medium assumptions for the most important drivers (population, economy, technology development and lifestyle). In terms of its quantification in IMAGE 2.4, the B2 scenario follows the earlier IMAGE 2.3 scenario. In first the 30 years it is based on the reference scenario of the World Energy Outlook 2004. After 2030, economic growth converges to the IPCC B2 trajectory. For population, the long-term UN medium population projection is used. Trends in agricultural production (production levels and yields) are based on the Millennium Ecosystem Scenarios (Alcamo et al. 2006) which were elaborated for these parameters by the IMPACT model (Rosegrant et al. 2002). For B2, the “adaptive music” scenario had been chosen, as it comes closest to medium assumptions. However, it has to be noted that it is very optimistic with respect to agricultural technology development, and has low land-use change. Therefore it resembles more a true B2 world vision of regional and environmental orientation than the “middle of the road” definition of the B2-SRES scenario. All other assumptions are based on the earlier implementation of the SRES scenarios in IMAGE (IMAGE-team 2001).

Table 4.1: Baseline scenario.

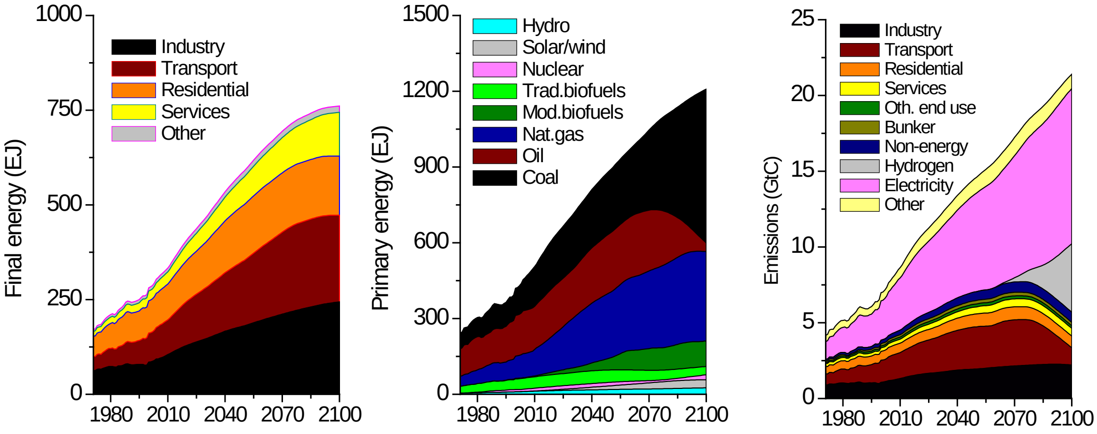
	2000	B2	
		2030	2100
Population, 10^9	6.1	8.2	9.1
GDP, 10^{12}US\$ [a]	34.1	83.9	329.0
Fossil PE, EJ	356.6	607.0	998.8
Nuclear PE, EJ	9.1	14.2	19.6
Renewable PE, EJ	10.3	22.6	57.6
Biomass PE, EJ	43.6	66.9	132
GtC energy (CO_2-only)	7.0	11.6	20.3
GtC-e total	10	16.5	26.5

[a] expressed in 1995-US$.

4.2.2. Energy system in the baseline

Under the central baseline, B2, worldwide primary energy use increases by 70% between 2000 and 2030 and by another 70% between 2030 and 2100. Most of this growth occurs in non-Annex I regions (about 80%). During most of the 21st century, oil consumption is more-or-less constant, with high oil prices stabilizing demand (55 US$/bbl in 2020 and 65 US$/bbl in 2050). In transport, oil is challenged by bio-energy and natural gas and by the end of the century hydrogen. In the power sector, natural gas continues to have a high share – but by the end of the century it looses market share to coal. Coal use expands significantly mostly for power and hydrogen production. As a result, energy-sector CO_2 emissions continue to rise for most of the century, going to around 20 GtC by the end of the century. By the end of the century, depletion of oil and natural gas resources – and a consequently rapid increase in coal use (for both electricity and H_2 production) contribute to a further increase in emissions – despite a stabilising population and a slowing-down of growth in energy use.

Figure 4.2: Energy consumption and associated CO_2 emissions.



4.2.3 Land in the baseline

Land is an important element in the climate system, and crucial for achieving low stabilization scenarios. Not only does expansion of agricultural area contribute to GHG emissions, but the area needed for food production also determines the remaining area available for biofuel production. Furthermore, the terrestrial biosphere has until now been a large carbon sink, and its future behavior under a changing climate is crucial for the GHG concentration resulting from a certain emission pathway, and thereby for the required emission reduction to achieve a certain GHG stabilization level.

Figure 4.3 shows the crop area under the A2 and the B2 land use baselines. Under these scenarios, the crop area expands gradually over the first part of the 21st century, with a much stronger increase in the A2 scenario. These changes are a result of yield increases on the one hand and an even faster increase in food demand on the other. The total increase over the period 2000-2050 (22% under A2 and 6% under B2) lies within the range of cropland projections made by other studies. Pasture land shows much less change (Figure 4.3, right panel), despite a rapid increase in meat demand. This is partly a consequence of shifts from extensive (grazing) to more intensive (use of feed) forms of animal husbandry. As pasture dominates total agriculture land use, the changes in the total are substantially smaller than the crop land changes (note: across a wide range of scenarios, including many IMAGE scenarios, the total agriculture area in the 2000-2030 period increases on average by 11% (with a likely range from 2-22%).

Figure 4.4 shows the land-related CO_2 fluxes for the B2 baseline. In 2000, the total emissions from deforestation amount to around 1.5 GtC, and stay above 1 GtC throughout the century. However, uptake by regrowing vegetation is increasing, and therefore net land use emissions decrease over time (Figure 4.4, right panel). The decrease is mainly caused by the slow increase in global agricultural area in the B2 land use baseline until 2030, and thereafter even a net decrease of agricultural area (Figure 4.3). Therefore the emissions from deforestation for agriculture (“biomass burning” in Figure 4.4, right panel) decrease strongly, and after 2030 total land use CO_2 emissions are largely caused by the demand for modern and traditional biofuels and timber (Figure 4.4, right panel). Although vegetation regrowth is assumed after harvest of timber and traditional biofuels, the uptake of CO_2 by the regrowing vegetation is slower than the emission, and is only accounted for during a limited amount of time. Therefore net emissions stay slightly positive for some more decades, and only become negative around 2080. The uptake of CO_2 by natural vegetation also increases, mainly as a result of carbon fertilization (Figure 4.4, left panel).

The B2 land use baseline of the IMAGE model (based on the “adaptive mosaic” scenario of the Millennium Ecosystem Assessment) is very optimistic about agricultural technology, and is characterized by a global net stabilization of agricultural area after 2030. Therefore, and as the 2.6 target is attainable with “conventional” mitigation options (see below), no specific scenario of avoided deforestation was calculated.

Agriculture related emissions for the non-CO_2 gases grow over time – but at a much slower rate than CO_2 emissions from energy. Around 2050, the increase is in the order of 40% for CH_4 (reaching a level of 2 GtC-eq) and 15% for N_2O (reaching a level of 0.7 GtC-eq) compared to 2000.

Figure 4.3: Food crop and pasture area in the B2 and A2 baseline.

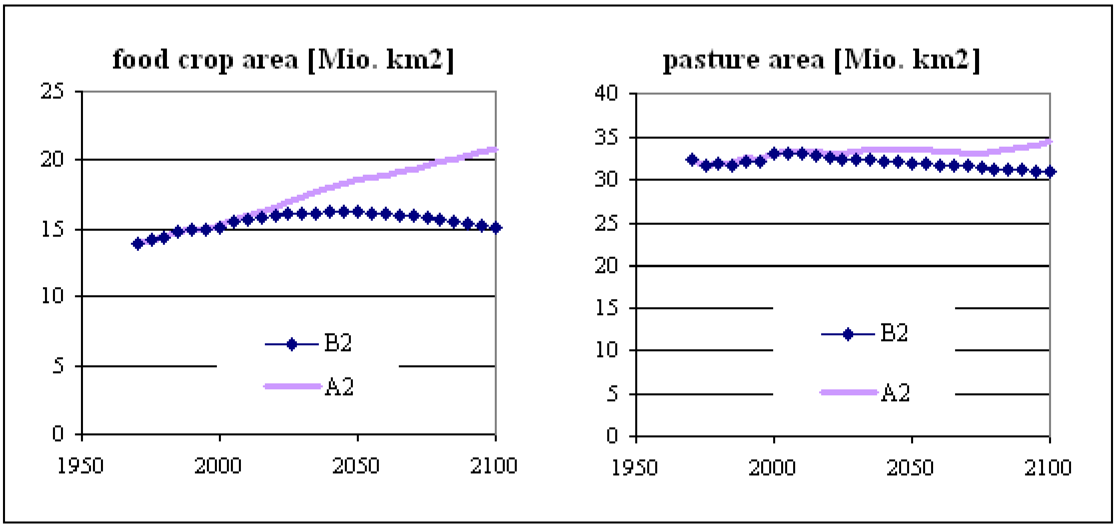
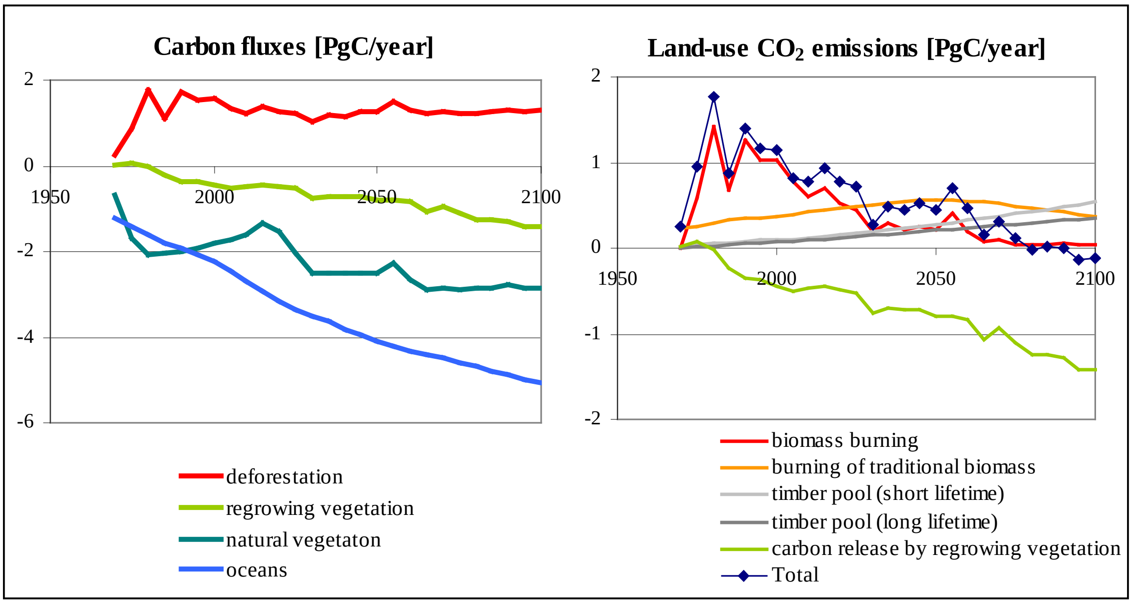


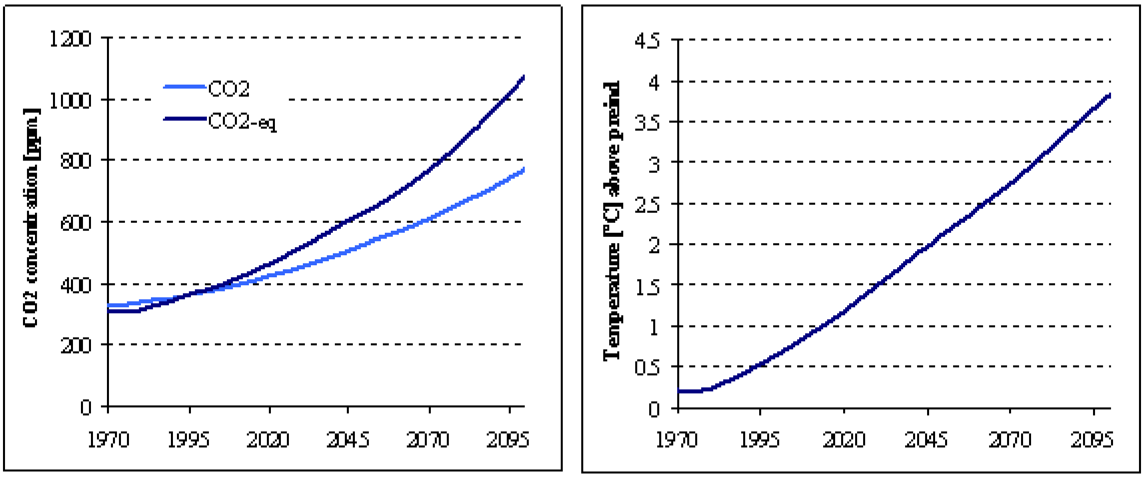
Figure 4.4: Carbon fluxes in the B2 baseline.



4.2.4 GHG concentration and climate in the baseline

Total GHG emissions increase significantly in the B2 scenario, i.e. from about 10 GtC-eq. today to 25 GtC-eq. in 2100. Compared to existing scenario literature the B2 baseline should be regarded as a medium emission baseline. Driven by the increases in emissions of greenhouse gases, also the CO_2-eq concentration rises significantly over time. Under the B2 scenario, the CO_2 eq concentration over all gases therefore reaches about 1000 ppm in 2100 (Figure 4.5). This is slightly higher than the MESSAGE B2 scenario discussed in the previous chapter, which reaches a level of 970 ppm; the difference is a net result of lower non-CO_2 gas emissions in IMAGE, but higher CO_2 emissions.

Figure 4.5: CO_2 and CO_2 equivalent concentrations and temperature in the B2 baseline. CO_2 equivalent concentration calculated over all radiative forcing agents.



The global mean temperature increase of the B2 scenario reaches nearly 4°C above pre-industrial levels in 2100, assuming a climate sensitivity of 3°C. In other words, the probability of remaining below the 2°C target by following the baseline scenario is (virtually) non-existent.

4.3 Implementation of low stabilization scenarios

4.3.1 Overall emission reductions

On the basis of the B2 baseline, different scenarios were explored to reach a 2.9 and 2.6 W/m^2 target by the end of the century. Emissions reductions for these targets are substantial. For the 2.9 target cumulative emissions in the 2000-2100 period need to be reduced by more than 65% (and current emissions in 2100 by 90%) – for the 2.6 target this even amounts to more than 75% (and to nearly 100% compared to current emissions). With the updated IMAGE 2.4 model framework used in this analysis, the both targets (2.6 and 2.9 W/m^2) can be reached by the end of the century given the assumptions on the baseline and mitigation options used here (see also below).

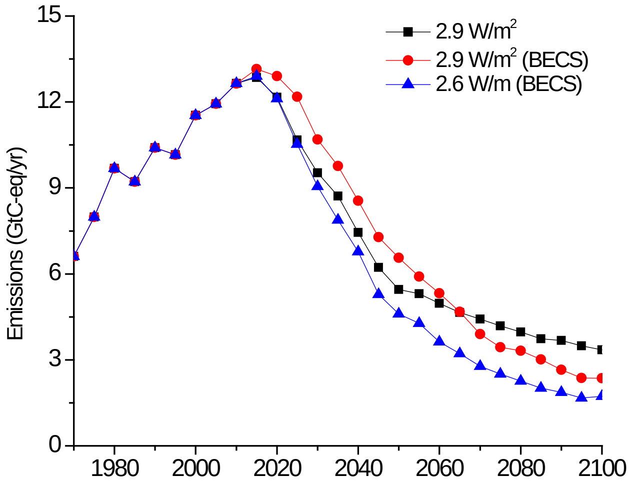
Participation in emission reductions

In our analysis, we assume that emissions can be reduced world-wide from 2013 onwards. As participation may occur in different forms, the fact that emission will be reduced throughout the world does not say anything on who will bear the costs of these reductions. It is important to realize that for low emission scenarios access to emission reduction potential in almost all countries is required. As shown in the uncertainty analysis of both the MESSAGE (see previous chapter) and IMAGE model (see further in this chapter) global emissions need to peak around 2020 – and flexibility in timing of emission reductions is relatively low. Without going into detail here, the need for participation of all major emitters can be illustrated by rather simple calculations. In our cost optimal calculations, emission reductions outside Annex-I countries are somewhat higher than the world average given the lower abatement costs. Just assuming that all emission would need to be reduced in Annex-I countries would result in emission reduction that can not be met (for instance, if the emissions in the non-Annex I countries do not deviate from the baseline until 2020, the theoretical emission cut of Annex I countries would amount to 80% in 2020 compared to 1990 to achieve the same emissions as shown here for the 2.6 W/m^2 emission profile). Financial mechanisms like emission trading and CDM could provide incentives for early emissions reductions in non-Annex 1 countries.

Timing of mitigation action

The timing of emission reductions is determined by minimizing the net present value of abatement costs in the period 2000-2100 (using a 5% constant discount rate). The scenarios, however, are close to the maximum achievable reduction potential and rate of change in the model, so very limited flexibility exists. The flexibility obviously is dependent on the available reduction potential. While we concentrate on the 2.9 W/m^2 without bio-energy and carbon capture and the 2.6 W/m^2 with bio-energy and carbon capture, also other variants have been tested (see also the section on uncertainty). Adding the option of bio-energy and carbon capture to the 2.9 W/m^2 scenario obviously increases flexibility in timing and leads to a situation in which emission reductions are partly postponed in the period 2020-2060 compared to a scenario without this technology. This is offset by stronger reductions after 2070 (but leading to a lower net present value of abatement costs).

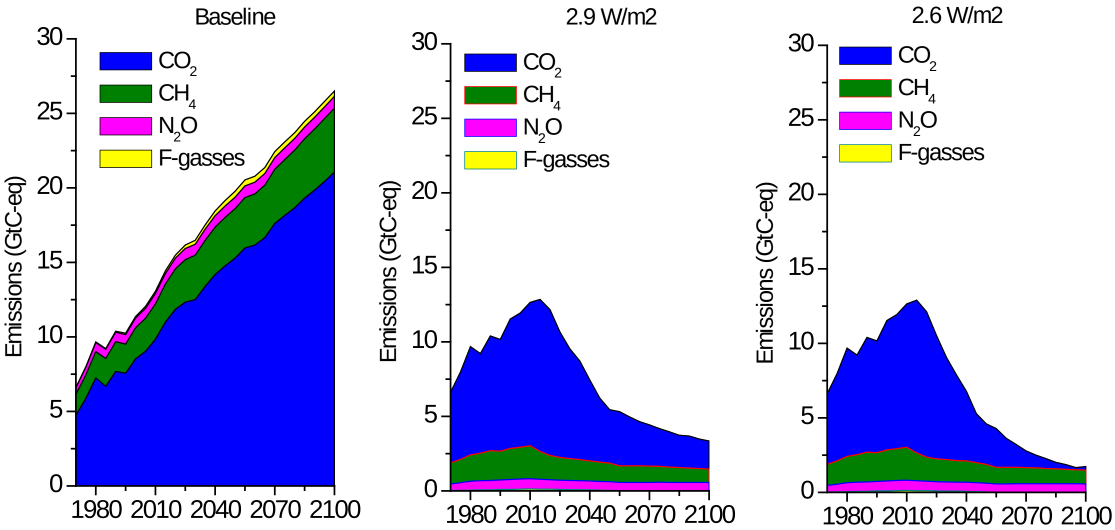
Figure 4.6 Emissions in 2.6 and 2.9 W/m2 scenarios.



Emission reduction by source

Figure 4.7 shows the emissions under the different scenarios. In the short term, a substantial share of the reduction is achieved by reducing non-CO$_2$ gases in all stabilization scenarios, while only a small part of the reductions come from reducing energy-related CO$_2$ emissions. This is consistent with earlier finding (Lucas et al. 2007). The disproportionate contribution of non-CO$_2$ abatement is mainly caused 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$_2$O emissions from adipic and acidic acid industries). It should be noted that this effect is related to the fact that we use global warming potentials (GWPs) to determine the cost-effective mix of reductions among the different GHGs (see method section). Alternative approaches, e.g. long-term costs optimization under a radiative forcing target, may result in a different mix (van Vuuren et al. 2006). After 2015, more and more reductions need to come from CO_2 in the energy system. This shift simply reflects that non-CO_2 gases represent about 20% of total GHG emissions, and that some of them only have a limited reduction potential.

Figure 4.7 Emissions in baseline and 2.9 and 2.6 scenario.

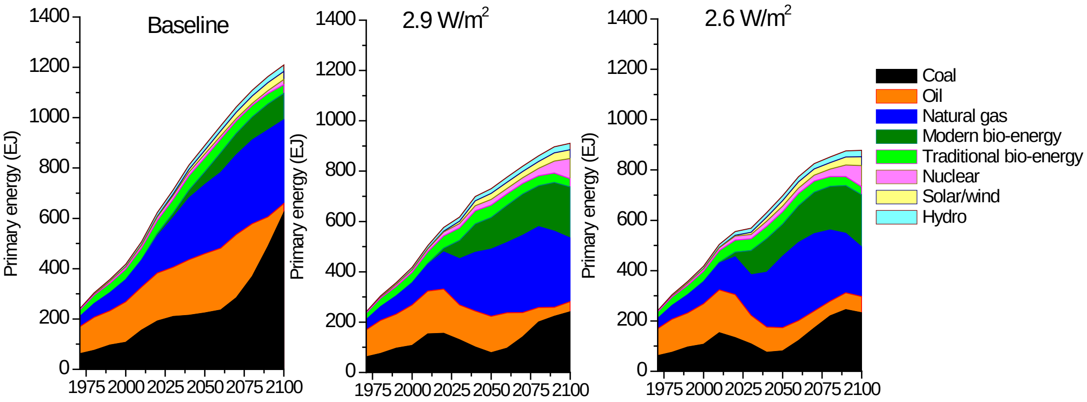


The energy-related CO_2 emissions are at around 2 GtC by the end of the century for the 2.9 scenario, and negative (-0.7 GtC) for the 2.6 scenario. The overall CO_2 emissions are not negative as both process emissions and land use related emissions offset the negative emissions from energy.

4.3.2 Energy system

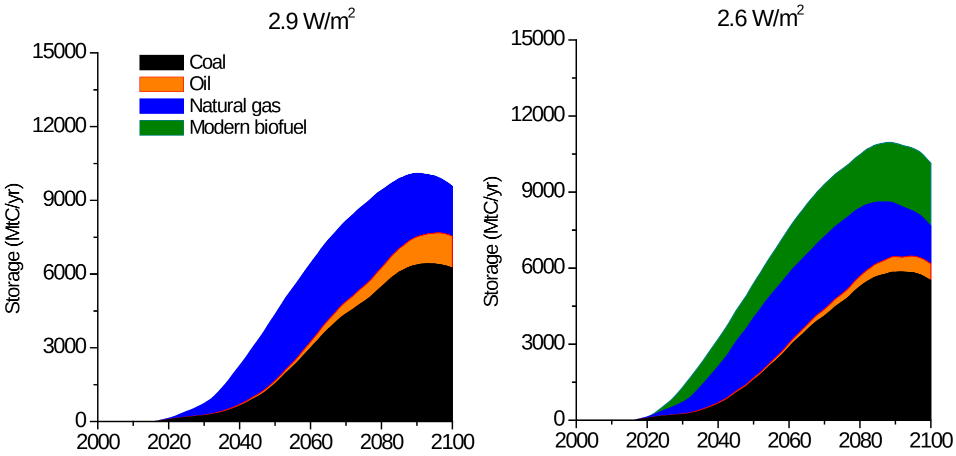
Figure 4.8 shows that the climate policies required to reach the stabilization pathways lead to substantial changes in the energy system compared to the baseline scenario. Global primary energy use is reduced by around 25% compared to the baseline. The reductions are different for the different energy carriers. The largest reductions occur in the short-term for coal, with the remaining coal consumption being primarily used in electric power stations using CCS. Interestingly, coal regains market share in the second half of the century, as it is used to power both hydrogen and electricity plants in combination with CCS. There is a very substantial reduction for oil. Interestingly, by the end of the century the “postponed” oil depletion makes that oil production is even slightly higher than in the baseline. Reductions for natural gas are less substantial, while other energy carriers – in particular solar, wind, nuclear-based electricity and modern biomass – gain market share in the mitigation scenarios.

Figure 4.8: Energy use in the baseline and the 2.9 and 2.6 W/m2 scenarios (SW=Solar and wind).



The largest reduction in the energy sector results from changes in the energy supply. 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 (Figure 4.9). Using medium estimates of storage capacity (around 1000 GtC), it seems that this is achievable, but it should be noted that 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 near the end of the century so that these regions will also use aquifers as a storage option[2]. It should be noted that CCS technology still has to be proven in large scale application and that aquifer capacity is uncertain.

Figure 4.9: Annual rate of carbon capture and origin by fuel type (2.9 and 2.6 scenario).



Bio-energy use also accounts for a large proportion of the emission reductions. In the baseline scenario of this study about 20 EJ of modern bio-energy is used 2050 and slightly more than 100 EJ in 2100. In the most stringent stabilization scenario, bio-energy use increases to 113 EJ in 2050 and 240 EJ in 2100. In terms of crops, the bio-energy is initially produced mostly from sugar cane and after 2030 mostly from wood (2nd generation). The bio-energy use replaces fossil fuels and its related emissions, but also leads to some specific emissions for production and processing. However, the impact of these emissions is relatively small.

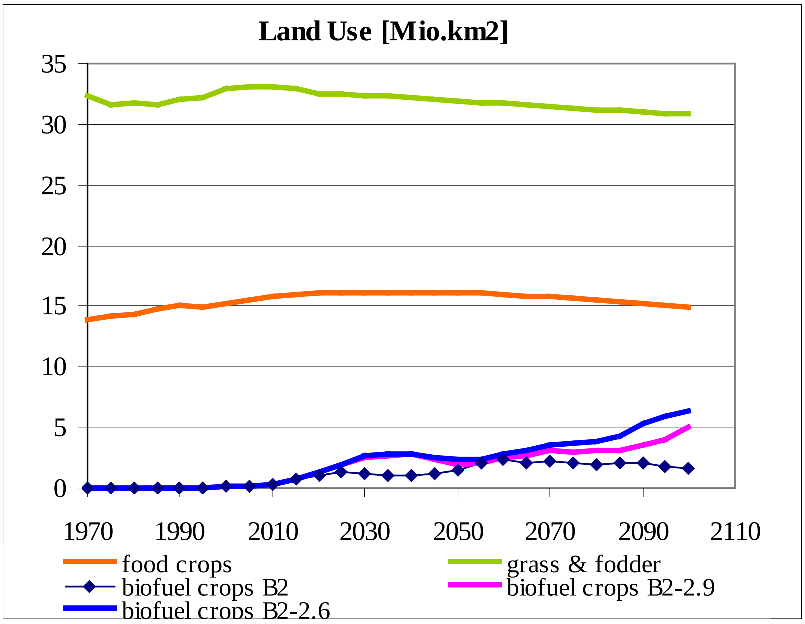
Solar, wind, hydro and nuclear power also account for a considerable proportion of the required reductions. In our baseline scenario, the application of hydro, wind and solar power is considerably larger than that of nuclear power (based on current policies and costs). In the mitigation scenarios both categories increase their market share (Figure 4.8).

Energy efficiency represents a relatively important part of the portfolio early on in the century – but a much smaller share compared to baseline later on. The main reason for the decreasing impact is that costs reductions of zero carbon energy supply options reduces the both the effectiveness and attractiveness of energy efficiency measures. The contribution of efficiency does vary strongly by region and over time.

4.3.3 Land use

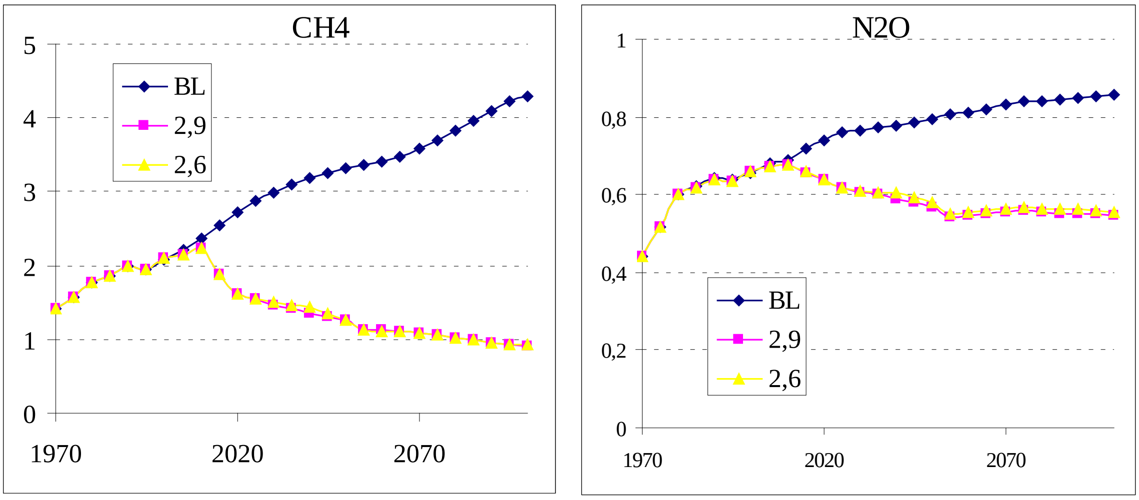
Under the B2-2.9 mitigation scenarios, up to 5 Mio km^2 are used for energy crop production, mainly woody crops (Figure 4.10), and provide up to 240 EJ/y primary energy (Figure 4.8). For the B2-2.6, the numbers are comparable, but bio-energy is used in different way. Instead of being almost exclusively used to create biofuels for transport, in the 2.6 scenario part of the bio-energy is also used in power plants in combination with carbon capture and storage.

Figure 4.10: Land use in the B2 baseline, the B2-2.9 and B2-2.6 scenario (only biofuel crops are different between the scenarios).



In all mitigation scenarios N_2O emissions from land use are reduced in most regions by their (time-dependent) maximum levels, which reach about 40% after 2050. CH_4 emission reduction in land use is also close to its maximum level in the entire scenario period. After 2050, emissions of these two gases stay constant at about 1 and 0.6 $GtCO_2$-C equivalents for CH_4 and N_2O, respectively (Figure 4.11).

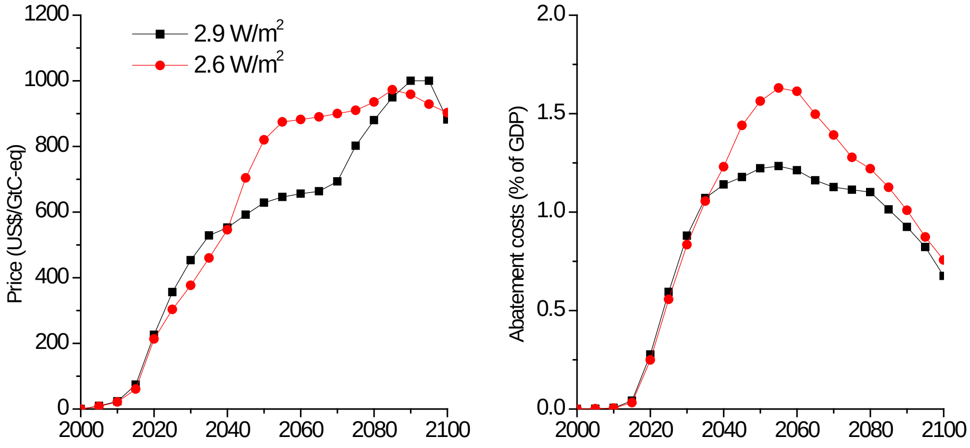
Figure 4.11: Trends in methane and nitrous oxide emissions (GtC-eq.)



4.3.4 Costs

For measures of mitigation costs, we 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 and adaptation costs of climate change). The carbon taxes that are required to induce the changes described above rise rapidly in the first decades of the simulation from around 25 US\$/tC (or 7 US\$/tCO_2) in 2010 to 225 US\$/tCO_2 (or 60 US\$/tCO_2) in 2020, nearly 380-450 US\$/tC (or 100-120 US\$/tCO_2) in 2030 and nearly 650-820 US\$/tC (or 170-220 US\$/tCO_2) in 2050 (Figure 4.12). All costs are expressed in 1995 prices. It should be noted that the high marginal price is particularly necessary to reduce emissions from the less-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 carbon prices of ‘only’ 200-300 US\$/tC-eq. From 2050 onwards, both in the 2.6 and 2.9 simulation prices stay at high levels around 800-1000 US\$/tC (220-270 US\$/tCO_2). Despite its stronger emission reductions, the 2.6 simulation, with the option to use bio-energy carbon capture and storage, has a comparable price level as the 2.9 simulation throughout most of the century as a result of this additional technology. The overall costs are higher for the 2.6 simulation (given the larger reduction requirement). In the 2.6 W/m^2 case, abatement costs reach a level of around 1.7% of GDP in 2050. The direct abatement costs can be compared to the total expenditures on the energy sector (which, worldwide, are about 7.5% of GDP today and expected to remain nearly constant under our baseline) or to the expenditures on environmental policy (in the EU around 2.0-2.8%, mostly for waste and wastewater management).

Figure 4.12: Carbon price and abatements costs of the 2.6 and 2.9 scenario.



4.3.5 Emission profile, concentration and climate response

The total emission profile of the scenarios has been presented above (Figure 4.6). Figure 4.13 shows the trajectory of radiative forcing and carbon dioxide concentration over time. Both the 2.9 and 2.6 scenario are so-called overshoot or peaking scenarios, that first have a forcing slightly above 3 W/m^2 in mid-21st century and return to lower radiative forcing levels in 2100. The corresponding 2100 CO_2 concentration levels are 435 and 410 ppm (compared to 770 ppm in the baseline).

The radiative forcing of the different scenarios reflects the changes in terms of emission reductions. However, a few other important observations can be made. First, halocarbons become a considerable forcing agent in the baseline by the end of the century (7% of total radiative forcing), surpassing as a group the contribution of N_2O. Secondly, N_2O itself only represents a relatively small contribution to forcing, but given the relatively low availability of reduction options, its contribution is hardly decreased in the mitigation scenarios. Third, in addition to the contributions of the Kyoto gases, there are also a number of other forcing agents, including tropospheric ozone, sculpture aerosols (negative forcing) and other aerosols. The contribution of the latter is very uncertain and only causes a small net negative forcing in the current IMAGE model. The forcing of tropospheric ozone and sculpture aerosols, however, might still be in the order of a third of the N_2O forcing. Interestingly, both ozone and sculpture aerosols are coupled to the reduction of CO_2 emissions. While reducing the net cooling effect of SO_2 leads to higher temperatures of about 0.1 degree in 2100, the net reduction of ozone-forcing, in turn, leads to lower temperatures and offsets the sculpture impact on this time scale

In the baseline, emissions of CFCs were assumed to follow the Montreal Protocol – while emissions of HFCs, PFCs and SF6 were assumed to increase (consistent with IPCC scenarios). In the mitigation scenarios, the emissions of these gases are reduced by over 80% due to their relatively low abatements costs. Newly negotiated emission reductions for halogenated gases in the Nairobi protocol can be regarded as consistent with these emission reductions.

Figure 4.13: Radiative forcing and carbon dioxide concentration.

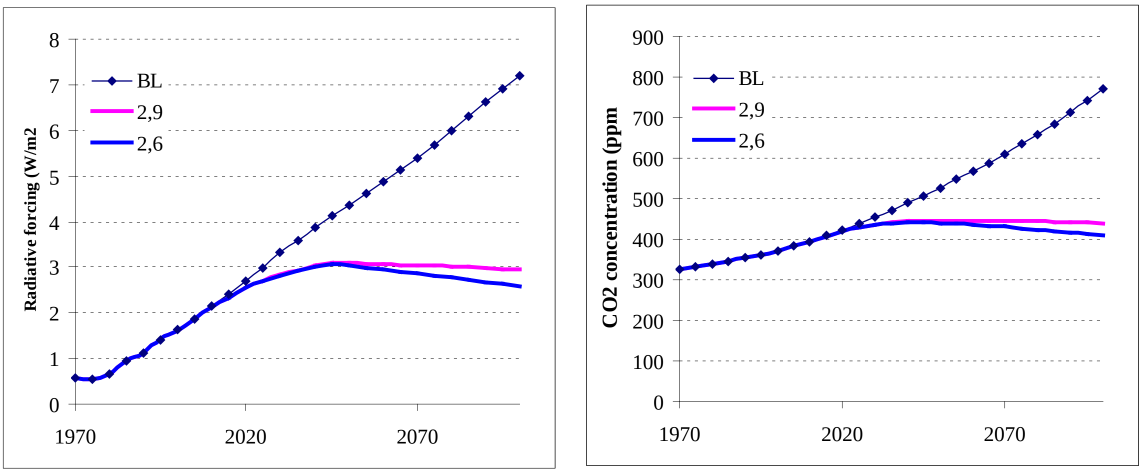
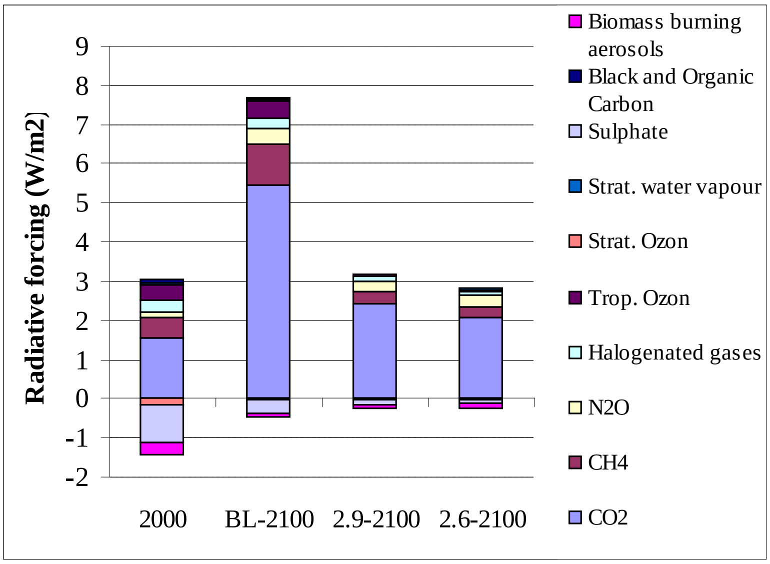


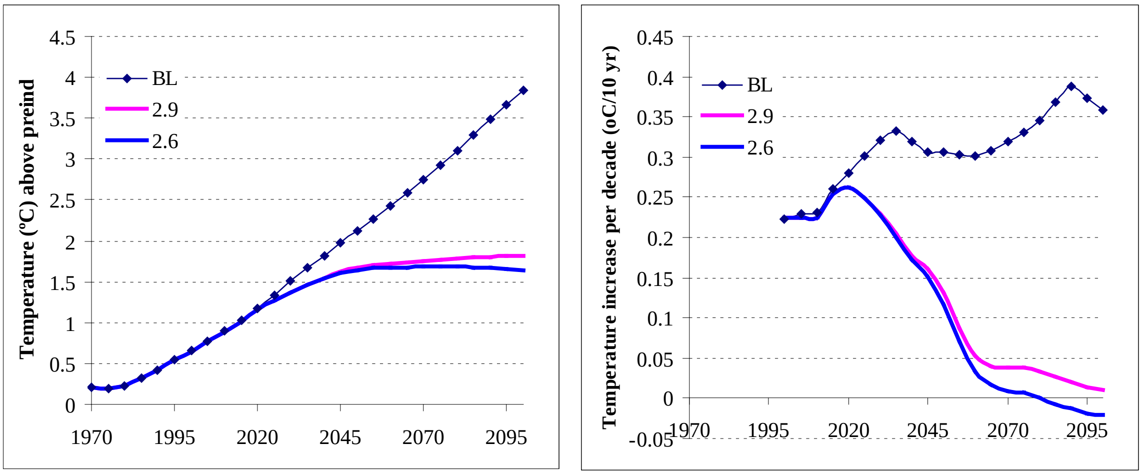
Figure 4.14: Contribution to radiative forcing by different forcing agents.



The scenarios analyzed here lead to clearly different temperature increases, both during this century and in the long run. It should be noted, however, that the temperature results of the different stabilization scenarios do depend to a considerable extent on the uncertain relationship between the GHG concentration and temperature increase. This implies that impacts on temperature can better be expressed in probabilistic terms as done for the MESSAGE analysis in the previous chapter. The results shown in that chapter can also be interpreted for the IMAGE scenarios. Using previously published numbers by Meinshausen et al. (2007) the 2.9 scenario results in a probability of 20-70% to stay below the 2°C target, while this probability increases to about 50-95% under the 2.6 scenario. Figure 4.14 shows the evolution of temperature in the IMAGE model, using a climate sensitivity of 2.5°C.

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 4.15). In the baseline scenario, the rate of temperature change is around 0.25°-0.3°C per decade. In the mitigation scenarios, the rate of temperature increase drops significantly and actually falls below zero in 2100 for the 2.6 scenario. In the early decades, however, the mitigation scenarios show a temperature that is only slightly lower than in the baseline. One reason is the slow temperature response of the climate system. Another reason is that changes in the energy system to mitigate CO_2 emissions also lead to a reduction in SO_2 emissions, and therefore to lower sulphur cooling (as already emphasized by Wigley (1991)). However, as mitigation in the beginning focuses on non-CO_2 GHGs like CH_4, which is much less coupled to sulphur, the impact of reduced sulphur cooling is limited.

Figure 4.15: Development of temperature in the baseline and 2.9/2.6 cases.



4.4 Major uncertainties

There are major uncertainties associated with the scenario runs. We have performed an uncertainty analysis to explore the impacts of some of these factors. Moreover, we discuss other uncertainties in qualitative terms below.

For the sensitivity analysis, we used the 2.6 scenarios as a basis. As this scenario reaches nearly the maximum feasible reduction levels (the IMAGE model uses a maximum of 1000 US$/tC) it can be regarded an indication of the maximum feasible emission reductions in IMAGE. By using exactly the same carbon tax profile, we have tested the sensitivity of the emission reductions for the following factors: 1) availability of bio-energy carbon capture and storage, 2) availability of carbon capture and storage, 3) availability of energy efficiency improvement (in combination with and without bio-energy and carbon capture and storage and 4) land use (by using the A2 land use pattern as an alternative, see Figure 4.3). Table 4.2 shows the results obtained. It should be noted that there also could be developments that would make achieving the 2.6 W/m^2 target easier. Some of these are discussed qualitatively further in this section.

Table 4.2: Sensitivity analysis.

	Radiative forcing level in 2100 (W/m^2)
Default	2.6
No BECS	3.0
No CCS	3.5
No energy efficiency (compared to bl)	3.2
No energy efficiency (compared to bl) + No BECS	3.4
A2 land use	3.0

These results indicate that the 2.6 target can only be obtained if the technologies tested above are in place, i.e., CCS, bio-energy and CCS, and energy efficiency improvement beyond the baseline, and if land-use change is not much stronger than in the B2 scenario.

In the energy system, important uncertainties are associated with the technology development of the different energy options, and for some options even their availability is uncertain. Key uncertainties include the development of second generation biofuels and the availability of carbon capture and storage. Without the availability of these options low mitigation target is not attainable.

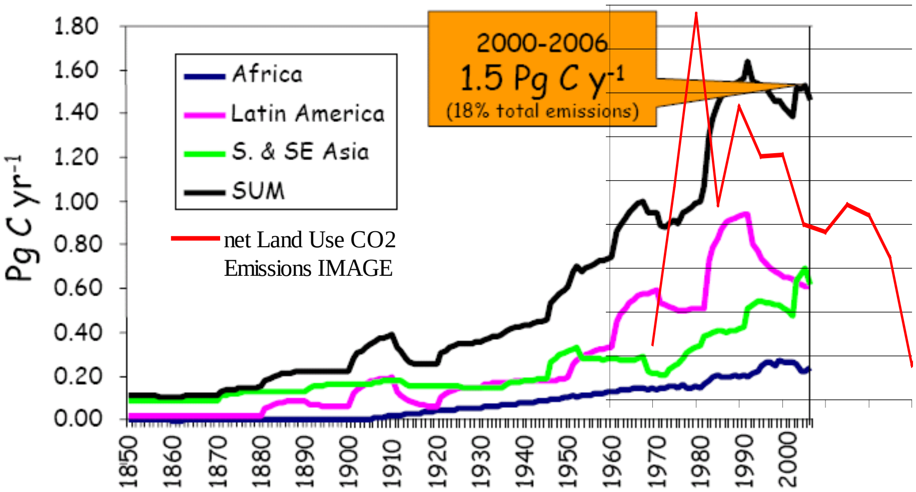
Bio-energy plays a key role in achieving low mitigation targets. In order to fulfill this role, emissions from bio-energy production and processing need to be low. Our assessment shows that these emissions depend on various factors, including uncertainty in N_2O emissions after fertilizer application, and the impact of bio-energy use on land use change. The latter depends among others on (i) whether it is possible to steer feedstock production (so that forests are protected), (ii) the impact biofuel cropping on soil carbon in grasslands and (iii) yield improvements. So-far, emissions seem to be only very low for woody crops used as a second-generation bio-energy technology. In other words, the results depend critically for this technology to be available (in our analysis it is assumed that it is available from 2010 onwards, but at initially high costs which decreases over time).

In land-use scenarios, a key uncertainty is the development of yields for food crops, and the food demand. If yield improvement is slow, little room is available for bio-energy production and/or reforestation. For non-CO_2 emissions from agriculture, not only technology change itself, but also its implementation in different word regions is crucial. At the moment, all kind of implementation barriers (such as the question how to spread technologies among large amounts of small-holder farmers) prevent non-CO_2 emission reduction to be implemented. We have assumed that such barriers (partly as a result of climate policy) disappear over time.

As described above, land use emissions of CO_2 are very important for the feasibility of the 2.6 and 2.9 mitigation scenario. In the B2 baseline, agricultural area increases rather slowly, and decreases after 2030. In the IMAGE model, land use CO_2 emissions are caused by expansion of agriculture, and deforestation for timber and traditional biofuel. On harvested and unused area, regrowth of natural vegetation is assumed, therefore reducing net CO_2 emissions. Additionally, no shifting cultivation is assumed, and also high emissions from deforestation and draining on peat lands are not included.

Therefore, historical land use CO_2 emissions are lower than reported by other sources, but still within the uncertainty range (Figure 4.16)

Figure 4.16: IMAGE land use CO_2 emissions compared to Houghton (unpublished) and Canadell et al. PNAS (as shown in an ESSP presentation).



On the other hand, some of the uncertainties might also result in a higher feasibility of the stabilization scenarios. The most important factor here would be the development of baseline emissions, which could be lower than the baseline assumed here. Low emissions baseline have been proposed in the literature (e.g., the B1 scenario), but it should be noted that the baseline in this report is more-or-less comparable to a median emission scenario in literature. Other factors may include more rapid costs reductions for PV and/or nuclear and rapid development of electricity storage technologies (allowing for easier penetration of intermittent power supply options). Also, in the current settings, no forest area is allowed to be used for additional bioenergy production, thereby limiting the bioenergy potential to abandoned agricultural land, sparsely forested areas like shrub land and savannas. While some forests might potentially be used to produce biomass for energy it is questionable whether their use would lead to a serious net contribution to lower greenhouse gas emissions during this century. An important contribution may come from lifestyle changes, such as substantial changes in modal shift (reduction of work-home travel; more use of bikes) and diets (e.g. less meat consumption (Stehfest et al. 2009)). These options have not been explored.

In addition, there are important uncertainties in the biophysical earth system, which have implications for the scenario results. First of all, the relationship between emissions and greenhouse gas concentrations is uncertain. The most important factors here (given the dominance in radiative forcing) are the uncertainties related to the carbon cycle and in particular the uptake of the biosphere of carbon dioxide (depending among other on the carbon fertilization and the response of the biosphere to temperature change). While complex carbon cycle and climate models have been run for high emissions scenarios, such work has not been done for low mitigation scenarios. It is therefore unknown whether the simple climate/carbon cycle models used in integrated assessment models are correct in terms of their response. A critical factor here might also be thresholds that would make overshoot scenarios less effective or even impossible. An example of such a threshold could be impacts on the carbon storage in the Amazon. Obviously, a crucial uncertainty that determines the effectiveness of the emission reductions in terms of temperature impacts is the uncertainty in climate sensitivity.

We conclude that given the sensitivity analysis achieving a stabilization target of 2.9 W/m^2 is more robust than a 2.6 W/m^2 target. While there are developments that could make the feasibility of low stabilization targets more likely, there are also serious risks of developments that reduce the feasibility. Overall, one of the most critical factors is the assumption that all parties participate in emission reductions from 2013 onwards and that, based on this, global emissions can be peaked in 2020.

Box 1. The difference with our earlier study of van Vuuren et al. (2007). The emission pathways, CO_2-eq concentration and radiative forcing for the old and new 2.9 and 2.6 W/m2 can also be seen in Figure 5.1.

In general the differences in the emission pathways come from the following factors:

1. *higher baseline emissions* ─ more reductions are necessary if baseline emissions are higher. The present baseline emissions in the first 1-2 decades are higher than before consistent with recent emission trends between 2000 and 2007.
2. *higher non-Annex I emissions in 2010* (the middle of the first commitment period) ─ For the short term it is important whether the pathways assume that the Kyoto protocol targets are implemented or not. Here we assume all Annex I countries (excluding the USA) meeting the Kyoto targets and the non-Annex I countries follow their baseline emissions. For the Annex I countries, similar assumptions were made, except that we now assume that Australia meets the Kyoto target and the former Soviet Union starts at their baseline emissions in 2010 in stead of their Kyoto target. The non-Annex I emissions are higher than before due to revised, higher economic growth projections.
3. *Lower marginal abatement costs and reduction potentials* ─ More pessimistic assumptions on the costs and reduction potential of biofuels affect the possible reduction rates for the emission pathways.
4. *Higher CO_2 concentrations (now about 1050 ppm, before 950ppm).* This is not only caused by higher emissions in the baseline, but also by a lower CO_2 uptake by natural vegetation in the second half of the century due to a decreased CO_2 fertilization factor (now +35% NPP under doubled CO_2 concentration, before +60%). Higher temperature generally decreases the uptake of CO_2 into the biosphere.
5. *Land use.* Land use in the new and the old scenarios is not identical, as the land use parameters were re-implemented to come closer to the original IMPACT model results. In total, this results in slightly lower land-use CO_2 emissions, less decrease in pasture area, and less land availability for energy-crops.
6. *Non-CO_2 land-use emissions.* CH_4 emissions from land use in the baseline are similar to the old baseline, but mitigation is much stronger in the new mitigation scenarios. Land use N_2O emissions are lower in the new baseline, and therefore

also in the new mitigation runs. This related to a) less agricultural area and less emissions from agricultural waste burning and crop residues, and b) to fertilizer application emissions. For the latter, the IPCC emission factor had been reduced from 1.25 to 1.0.

7. *Bio-energy*. The use of biomass for energy in the new scenario is about 50% lower in the new scenario, which is caused by both changes in the energy system and changes in land availability for biofuels.

4.5 Main findings

From the analysis of the IMAGE scenarios, the following findings are obtained:

- Reaching a radiative forcing level of 2.9 W/m^2 in 2100 seems achievable from a B2 baseline but requires a very wide portfolio of reduction options that are implemented at rates near their maximum potential in the model. A key technology in achieving the 2.9 W/m^2 in 2100 in the IMAGE model is large-scale application of bio-energy.
- Also reaching a level of 2.6 W/m^2 seems achievable in the IMAGE model by additionally using bio-energy CCS. Again, wide-scale application of bio-energy is necessary. 2.6 W/m^2 is less robust than 2.9, as it needs during most of the century the maximum available mitigation and as it thereby strongly depends on large scale deployment of the two options CCS and bio-energy.
- Additional GHG emissions for bio-energy have a low impact as most of the bio-energy comes from wood, which has low nitrogen-fertilisation and conversion emissions. However, if second generation bio-energy does not become available fast enough, associated GHG-emissions from first-generation bio-energy would prevent achieving the low targets.
- Other key requirements for making the 2.6 target achievable include:
    - Only limited expansion of agricultural land for food production. A too large expansion would lead to high emissions from land use change and reduce the potential for bio-fuel and reforestation, thereby making low mitigation targets unattainable.
    - Sufficient technologies to reduce greenhouse gases from electricity use (nuclear power and carbon capture and storage).
    - Peak in global emissions around 2020, requiring global participation in emission reductions from 2013 onwards.
    - The option to combine carbon capture and storage and bio-energy.

Some of the requirements also hold for the 2.9 target. However, the sensitivity analysis shows that some technologies as e.g. bio-energy CCS are not an absolute requirement for 2.9. Both the 2.9 and the 2.6 scenario could be consistent with the 2 degree target. Given the numbers presented in IPCC AR4 for relationships between CO_2 equivalent concentrations and the temperature (Meinshausen et al. 2007), the probability of staying below 2 degree is 30-70% for the 2.9 and 50-95% for the 2.6 scenario.

5. A Brief Comparison of the IMAGE and MESSAGE Pathways

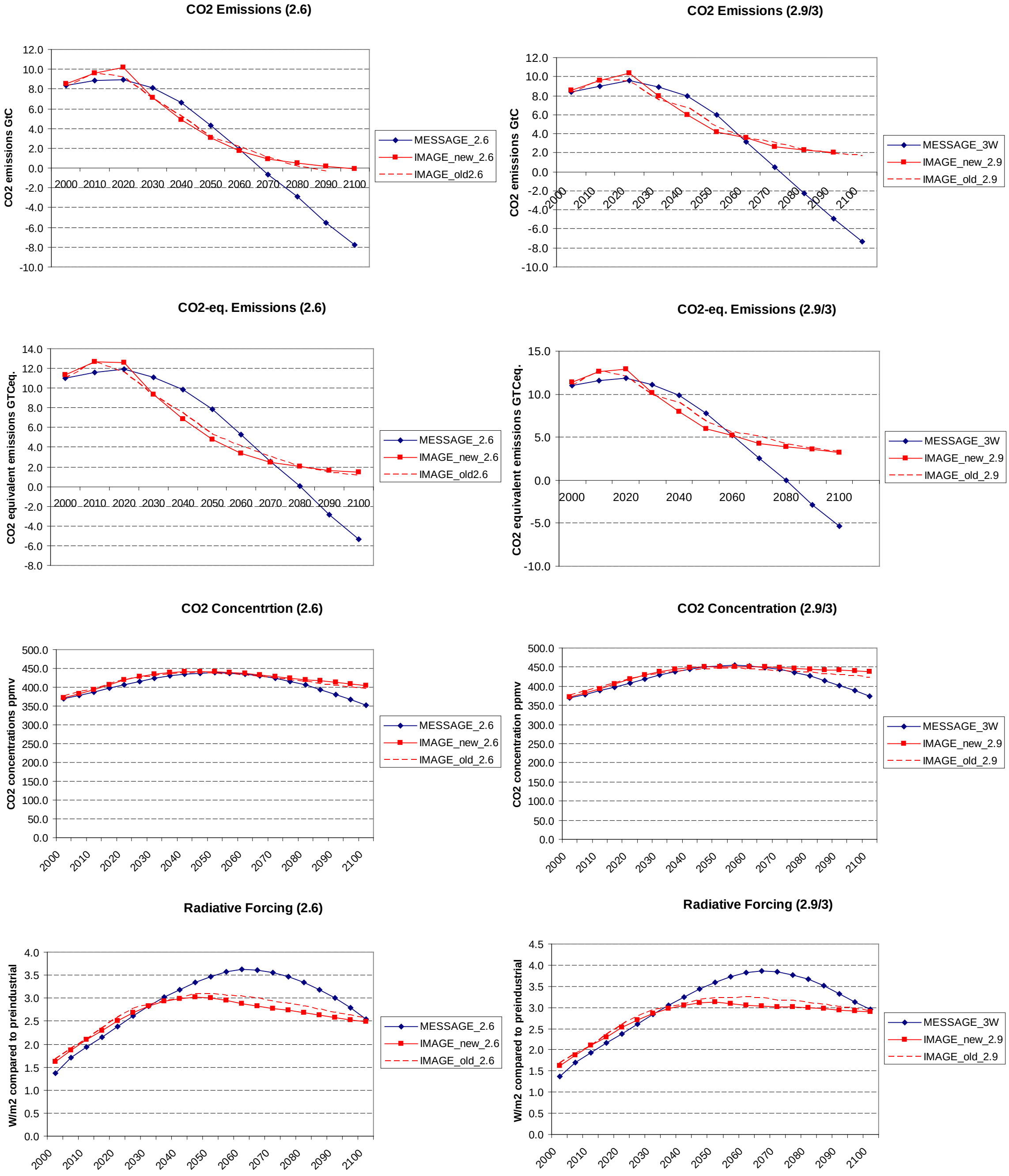
This section presents a brief comparison between the low scenarios from the IMAGE and MESSAGE models. We focus in particular on climate relevant outcomes, and the development of emissions, concentrations, and radiative forcing pathways. In addition to the new 2.6 and 2.9/3.0 W/m^2 scenarios, which were developed for this report, we compare the results also to earlier 2.6 and 2.9 IMAGE scenarios published in Van Vuuren et al., (2007).

The upper two panels of Figure 5.1 show the development of CO_2 and CO_2-equivalent emissions including all GHGs and other gases contributing to radiative forcing. We observe some significant differences between the IMAGE and MESSAGE emissions pathways, in particular with respect the timing of emissions reductions. While the IMAGE model shows more rapid reductions over the first half of the century, the MESSAGE scenarios indicate the need of significant reductions in the latter part of the century, including net negative CO_2 emissions by almost 8 GtC. A bit less than half of the negative emissions by the end of the century stem from forest sink enhancements, and the rest is due to large-scale application of bioenergy in combination with carbon capture (in the order of 2.8 TWe). With respect to the emissions pathways, the differences between the earlier IMAGE scenarios and the new ones are relatively modest.

The resulting CO_2 concentration pathways as well as the aggregated effect for the development of radiative forcing are illustrated in the two lower panels of Figure 5.1. The CO_2 concentrations are similar across the scenarios until about 2050, and become lower in the MESSAGE scenarios due to the net negative CO_2 emissions in the latter half of the century (compared to IMAGE). The perhaps most significant difference between the IMAGE and MESSAGE scenarios is, however, the development of radiative forcing, particularly with respect to overshoot. The IMAGE scenarios show a more modest overshoot of the long-term target, primarily due to the attainability of more rapid reductions of short-lived CH_4 emissions in the first half of the century (and the relatively smaller potential for negative emissions compared to the MESSAGE model in the long tem).[2] It should also be noted that the non-CO_2 greenhouse gas emissions are already significantly lower in the IMAGE baseline than in the MESSAGE baseline. Consequently, radiative forcing is peaking at slightly above 3.5 W/m^2 in the MESSAGE 2.6, and somewhat below 4 W/m^2 in the MESSAGE 3.0 scenario. By contrast, both IMAGE 2.6 and 2.9 show a peak around 3 W/m^2.

In summary, we find that while scenarios that reach low forcing targets can be generated in both modeling frameworks, the specific pathways to get there differ significantly.

Figure 5.1: Comparison of CO_2 emissions, CO_2-eq. emissions, CO_2 concentrations, and radiative forcing pathways (left-had panels show 2.6 W/m^2 scenarios; and right-hand panel the 2.9/3 W/m^2 scenarios).



References

Alcamo, J. A., D. P. Van Vuuren and W. Cramer (2006). Changes in Provisioning and Regulating Ecosystem Goods and Services and their Drivers Across the Scenarios. Millennium Ecosystem Assessment - Scenarios Assessment. S. Carpenter and P. Pingali. Washington DC, Island Press.

Azar, C., K. Lindgren, E. Larson and K. Möllersten (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.

Bouwman, L., T. Kram and K. Klein-Goldewijk (2006). Integrated modelling of global environmental change. An overview of IMAGE 2.4. Bilthoven, Netherlands Environmental Assessment Agency.

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 Special Issue **Accepted for publication**.

Crutzen, P. J., A. R. Mosier, K. A. Smith and W. Winiwarter (2007). "N2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels." Atmos. Chem. Phys. Discuss **7**: 11191-11205.

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. Bilthoven, The Netherlands, RIVM.

Den Elzen, M. G. J. and D. P. Van Vuuren (2007). "Peaking profiles for achieving long-term temperature targets with more likelihood at lower costs." PNAS **104**(46): 17931-17936.

EC (2006a). Directive 2006/40 of the European Parliament and of the Council relating to emissions from air conditioning systems in motor vehicles and amending, European Commission.

EC (2006b). Regulation (EC) No. 842/2006 of the European Parliament and of the Council of May 17th, 2006 on certain fluorinated greenhouse gases, European Commission.

Fischer, G., F. N. Tubiello, H. van Velthuizen and D. A. Wiberg (2007). "Climate change impacts on irrigation water requirements: Effects of mitigation, 1990–2080." Technological Forecasting and Social Change **74**(7): 1083–1107.

Fisher, B., N. Nakicenovic, K. Alfsen, J. Corfee Morlot, F. De la Chesnaye, J.-C. Hourcade, K. Jiang, M. Kainuma, E. La Rovere, A. Matysek, A. Rana, K. Riahi, R. Richels, S. Rose, D. P. Van Vuuren and R. Warren (2007). Issues related to mitigation in the long-term context. Climate Change 2007 - Mitigation. B. Metz, O. Davidson, P. Bosch, R. Dave and L. Meyer. Cambridge, Cambridge University Press.

Harmelink, C. and M. Hoogwijk (2008). Future scenarios for first and second generation biofuels. Utrecht, Ecofys.

Hendriks, C., W. Graus and F. van Bergen (2002). Global carbon dioxide storage potential and costs. Utrecht, Ecofys.

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. Bilthoven, the Netherlands, National Institute for Public Health and the Environment.

IPCC (2005). Special Report on CO2 capture and storage. Cambridge, Cambridge University Press.

IPCC (2008). Towards new scenarios for analysis of emissions, climate change, impacts, and response strategies. IPCC Expert Meeting Report on New Scenarios, Noordwijkerhout, Intergovernmental Panel on Climate Change.

JRC, EUCAR and CONCAWE (2004). Well-to-wheel analysis of future automotive fuels and powertrains in the European context. , European Council for Automotive R&D (EUCAR), European association for environment, health and safety in oil refining and distribution (CONCAWE), the Institute for Environment and Sustainability of the EU Commission's Joint Research Centre (JRC/IES).

Keppo, I., B. C. O'Neill and K. Riahia (2007). "Probabilistic temperature change projections and energy system implications of greenhouse gas emission scenarios." Technological Forecasting and Social Change **74**(7): 936-961.

Knutti, R., T. F. Stocker, F. Joos and G. K. Plattner (2003). "Probabilistic climate change projections using neural networks." Climate Dynamics **21**(3-4): 257-272.

Lucas, P., D. P. Van Vuuren, M. G. J. Elzen, J. G. J. Olivier and A. Bouwman (2005). "Long-term multigas scenarios."

Lucas, P. L., D. P. Van Vuuren, J. G. J. Olivier and M. G. J. Den Elzen (2007). "Long-term reduction potential of non-CO2 greenhouse gases." Environmental Science & Policy **10**(2): 85-103.

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. Avoiding Dangerous Climate Change. H. J. Schellnhuber, W. Cramer, N. Nakicenovic, T. Wigley and G. Yohe. Cambridge, UK. **Chapter 28**.

Meinshausen, M., B. Hare, T. M. L. Wigley, D. P. \van Vuuren, M. G. J. den Elzen and R. Swart (2007). "Multi-gas emission pathways to meet climate targets." Climatic Change.

Messner, S. and L. Schrattenholzer (2000). "MESSAGE-MACRO: Linking an Energy Supply Model with a Macroeconomic Model and Solving It Interactively." Energy **25**: 267-282.

Messner, S. and M. Strubegger (1995). User's Guide for MESSAGE III. Laxenburg, Austria, International Institute for Applied Systems Analysis.

Murphy, J. M., D. M. H. Sexton, D. N. Barnett, G. S. Jones, M. J. Webb, M. Collins and D. A. Stainforth (2004). "Quantification of modelling uncertainties in a large ensemble of climate change simulations." Nature **430**: 768-772.

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 (2000). IPCC Special Report on Emissions Scenarios. Cambridge, Cambridge University Press.

Pielke, R., T. Wigley and C. Green (2008). "Dangerous assumptions." Nature **452**: 531-532.

Rao, S. and K. Riahi (2006). "The Role of Non-CO2 Greenhouse Gases in Climate Change Mitigation: Long-term Scenarios for the 21st Century." The Energy Journal **Special Issue #3**: 177-200.

Raupach, M. R., G. Marland, P. Ciais, C. Le Quére, C. G. Canadell, G. Klepper and C. B. Field (2007). "Global and regional drivers of accelerating CO2 emissions." PNAS **104**(24): 10288–10293.

Riahi, K., A. Gruebler and N. Nakicenovic (2007). "Scenarios of long-term socio-economic and environmental development under climate stabilization." Technological Forecasting and Social Change **74**(7): 887–935.

Richels, R., A. Manne and T. M. L. Wigley (2004). Moving beyond concentrations: the challenge of limiting temperature change, AEI-Brookings Joint Center for Regulatory Studies.

Rokityanskiy, D., P. C. Benítez, F. Kraxner, I. McCallum, M. Obersteiner, E. Rametsteiner and Y. Yamagata (2007). "Geographically explicit global modeling of land-use change, carbon sequestration, and biomass supply." Technological Forecasting and Social Change **74**(7): 1057–1082.

Rosegrant, M. W., X. Cai, S. Cline and W. D.C. (2002). World water and food to 2025: Dealing with scarcity. Washington DC, International Food Policy Research Institute.

Schaefer, D. O., D. Godwin and J. Harnisch (2006). "Estimating future emissions and potential reductions of HFCs, PFCs and SF6." Energy Journal **Special Issue #3**.

Smeets, E. M. W., A. F. Bouwman, E. Stehfest, D. P. Van Vuuren and A. Posthuma (2008). "The contribution of n2o to the greenhouse gas balance of first-generation biofuels." submitted.

Stehfest, E., L. Bouwman, D. P. Van Vuuren, M. G. J. den Elzen, B. Eickhout and P. Kabat (2009). "Climate benefits of changing diet." Climatic change **forthcoming**.

UNFCCC (1992). United Nations Framework Convention on Climate Change, http://www.unfccc.int/resources.

Van Vuuren, D. P. (2007). Energy systems and climate change. Scenarios for an uncertain future. Science, Technology and Society. Utrecht, Utrecht University.

van Vuuren, D. P., M. G. J. Den Elzen, P. Lucas, B. E. Eickhout, B. J. Strengers, B. Van Ruijven, S. Wonink and R. Van Houdt (2007). "Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs." Climatic Change **81**(2): 119-159.

van Vuuren, D. P. and B. C. O'Neill (2006). "The consistency of IPCC's SRES scenarios to 1990-2000 trends and recent projections." Climatic Change **75**(1-2): 9-46.

Van Vuuren, D. P. and K. Riahi (2008). "Will current emission trends imply for-ever higher emissions?" Climatic Change **accepted**.

van Vuuren, D. P., J. Weyant and F. De la Chesnaye (2006). "Multigas scenarios to stabilise radiative forcing." Energy Economics **28**(1): 102-120.

Weyant, J. P., F. C. De la Chesnaye and B. G. (2005). "Overview of EMF - 21: Multigas Mitigation and Climate Change." Energy Journal.

Wigley, T. M. L. (1991). "Coud reducing fossil-fuel emissions cause global warming." Nature **349**: 503-506.

Wigley, T. M. L. and S. C. B. Raper (2001). "Interpretation of high projections for global-mean warming." Science **293**: 451-454.

Appendix A: Brief Description of Modeling Frameworks

A.1 IMAGE Model

A.1.1: General description

IMAGE 2 is an integrated assessment modeling framework describing global environmental change in terms of cause–response chains (Bouwman et al. 2006). It represents interactions between society, the biosphere and the climate system to assess sustainability issues like climate change, biodiversity and human well-being. The objective of the version of IMAGE model is to explore the long-term dynamics of global change as the result of interacting demographic, technological, economic, social, cultural and political factors.

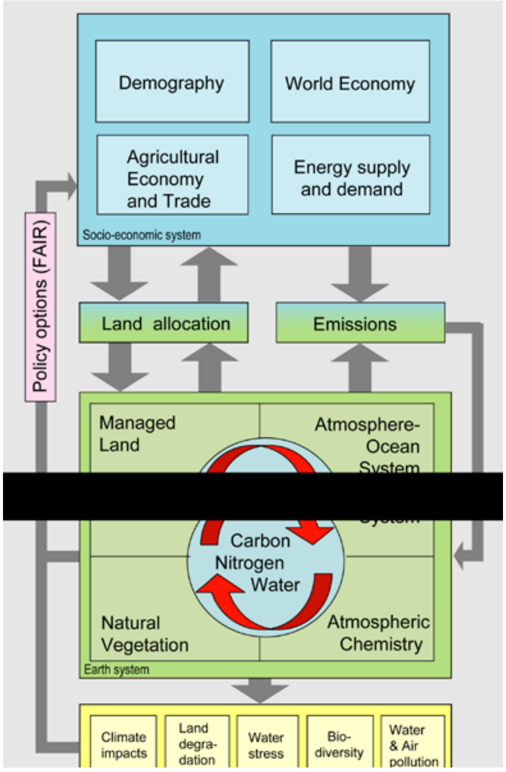
The most important subsystems are the "socio-economic system" and the "earth system" (Figure A1). In the socio-economic system, detailed descriptions of the energy and food consumption and production are developed using TIMER and agricultural trade and production models. The two main links between the socio-economic system and the earth system are land use and emissions. First, production and demand for food and biofuels lead to a demand for managed land. Second, changes in energy consumption and land-use patterns give rise to emissions that are used in calculations of the biogeochemical circles, including the atmospheric concentration of greenhouse gases and some atmospheric pollutants, such as nitrogen oxides and sulphur oxides. Changes in concentration of greenhouse gases, ozone precursors and species involved in aerosol formation form the basis for calculating climatic change. Next, changes in climate are calculated as global mean changes and downscaled to grid level.

The land-cover submodels in the earth system simulate the change in land use and land cover at 0.5 x 0.5 degrees (driven by demands for food, timber and biofuels, and changes in climate). A crop module based on the FAO agro-ecological zones approach computes the spatially explicit yields of the different crop groups and the grass, and the areas used for their production, as determined by climate and soil quality. Where expansion of agricultural land is required, a rule-based "suitability map" determines the grid cells selected (on the basis of the grid cell's potential crop yield, its proximity to other agricultural areas and to water bodies). The earth system also includes a natural vegetation model to compute changes in vegetation in response to climate change. An important aspect of IMAGE is that it accounts for important feedbacks within the system, such as temperature, precipitation and atmospheric CO_2 feedbacks on the selection of crop types, and the migration of ecosystems. This allows for calculating changes in crop and grass yields and, as a consequence, the location of different types of agriculture, changes in net primary productivity and migration of natural ecosystems.

The IMAGE model has been involved in many international assessments on scenarios. The model has been used in the development of IPCC's Special Report on Emission Scenarios (SRES). The model was also used as the integrating modeling framework in the development of the Millennium Ecosystem Assessment scenarios and the scenarios for UNEP's Global Environmental Outlook. The IMAGE model was used recently to develop a set of elaborated mitigation scenarios. This set was extensively assessed in

IPCC's 4th Assessment Report. The IMAGE modeling team also contributes to the University of Stanford based Energy Modeling Forum.

Figure A1: IMAGE 2 integrated assessment framework.



[redacted]

A.1.2: Application for mitigation scenarios

Assumptions in the different subsystems and marginal abatement costs

We use a hybrid approach in determining the abatement effort among the different categories of abatement options. At a more aggregated level, the possible abatement in different parts of the system (energy, carbon plantations, non-CO_2) are translated into baseline- and time-dependent MAC curves that are used in the FAIR model to distribute the mitigation effort among these different categories. At the more detailed level, the potential reductions, their costs, and the actual implementation in different subcategories are determined in the different 'expert' models used. For instance, for energy, the TIMER model determines a consistent description of the energy system under the global emission constraint set by FAIR-SiMCaP.

Some harmonization has been applied across the different submodels. Most assumptions (e.g., technology development and life-style) have been harmonized on the basis of storyline of the different scenarios that are implemented. In terms of land use, both carbon plantations and biofuel calculation start of from the same land use scenario (and implementation factors prevent them using the same land) and the same land price equations. In principle, a 5% social discount rate is used. In the energy system, however, investment decisions are assumed to be made by private parties and here a 10% discount rate was used in model calibration.

Energy

The TIMER MAC curves are constructed by imposing a carbon tax and recording the induced reduction of CO_2 emissions. Several responses occur in TIMER based on the carbon tax. 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. Two different tax profiles were used to explore responses, i.e. one that assumes a linear increase from 2010 to the carbon tax value in the end-year and one that reaches a maximum value 30 years earlier. The second profile results in more CO_2 reductions, as the energy system has a longer time period to respond. In FAIR, depending on the pathway of the actual carbon tax in the stabilization scenario, a combination is made of the linear tax MAC curves and the block tax MAC curves.[2]. 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 into energy efficiency than into energy supply, which is based on historic evidence (barriers to demand-side investments include lack of information, more diffuse investors, higher risks, 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 partly the case as a result of 1) increased attention to ways to reduce carbon emissions (leading to more information) and 2) availability of capital flows, also to developing countries, that could possibly result from carbon trading (or other flexible mechanisms).

Carbon plantations

The MAC curves for carbon plantations have been derived using the IMAGE 2.3 model (Strengers et al. 2005). In IMAGE, at a 0.5 x 0.5 grid the potential carbon sequestration of plantation tree species is estimated in comparison to the carbon sequestered by natural vegetation for land that are abandoned from agriculture. Next, only those grid cells are considered where the sequestration by plantations is larger than the sequestration by the natural vegetation. In the calculations, we assume that carbon plantations are harvested at regular time-intervals, and the wood is used to fulfill existing wood demand. This is a crucial assumption as it increases the benefit of plantations substantially compared to a carbon plantation that is not harvested. Based on grid cells that are potentially attractive for carbon plantations, carbon sequestration supply curves are constructed for each IMAGE region. These are converted into MAC curves, by adding two kinds of costs: land costs, and establishment costs. We find that under the SRES scenarios, the cumulative abandoned agricultural area ranges from 700 and 940 Mha in 2100, potentially sequestering 110 to 140 GtC over the century. The major part of this potential can be supplied at cost levels mostly below 200 US$/tC.

Non-CO_2 gasses

For non-CO_2, the starting point of our analysis are the MAC curves provided by EMF-21 (Weyant et al. 2005). 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. As the EMF-21 dataset has several shortcomings, including potentials and cost developments in time, (Lucas et al. 2005) have extended this set on the basis of a literature survey and expert judgment on long-term abatement potential and costs. These assume technology development process and removal of implementation barriers.

Table A1: Direct and indirect emissions from bio-energy

	Woody	Sugar cane	Maize
N_2O emissions from fertilizer application (grCO_2-eq/MJ feedstock)	2.95	4.4 (S-America) 9.1 (rest)	16.3
Energy use in conversion (MJ/MJ)	0.15	0.12	0.5
Energy use in cropping (MJ/MJ)	0.03	0.01	0.09

Sources for data: (Harmelink and Hoogwijk 2008; Smeets et al. 2008)

A.2 MESSAGE Model

Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE) is a systems engineering optimization model used for medium- to long-term energy system planning, energy policy analysis, and scenario development (Messner and Schrattenholzer 2000). The model provides a framework for representing an energy system with all its interdependencies from resource extraction, imports and exports, conversion, transport, and distribution, to the provision of energy end-use services such as light, space conditioning, industrial production processes, and transportation.

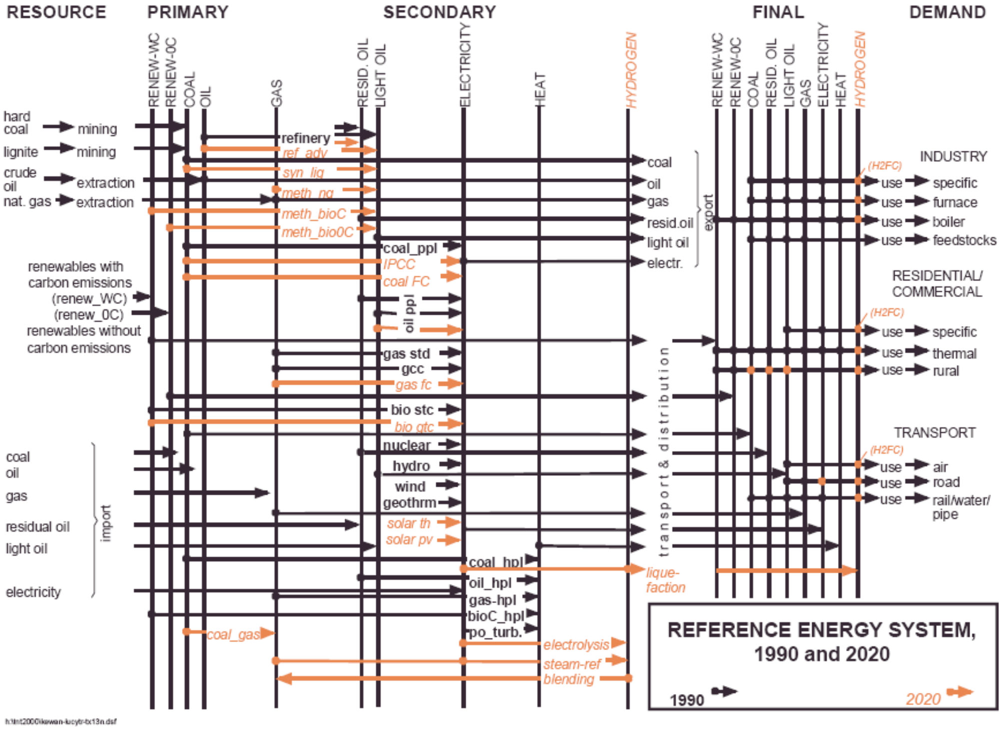
Scenarios are developed by MESSAGE through minimizing the total systems costs under the constraints imposed on the energy system. Given this information and other scenario features such as the demand for energy services, the model configures the evolution of the energy system from the base year to the end of the time horizon. It provides the installed capacities of technologies, energy outputs and inputs, energy requirements at various stages of the energy systems, costs, emissions, etc.

In addition to the energy system the model includes also the main other greenhouse-gas emitting sectors agriculture and forestry. The framework covers all greenhouse gas (GHG)-emitting sectors, including agriculture, forestry, energy, and industrial sources for a full basket of greenhouse gases and other radiatively active gases - CO_2, CH_4, N_2O, NO_x, volatile organic compounds (VOCs), CO, SO_2, BC/OC, CF4, C_2F6, HFC125, HFC134a, HFC143a, HFC227ea, HFC245ca and SF_6. MESSAGE is used in conjunction with MAGICC (Model for Greenhouse gas Induced Climate Change) version 4.0 (Wigley and Raper 2001) for calculating internally consistent scenarios for atmospheric concentrations, radiative forcing, annual-mean global surface air temperature and global-mean sea level implications.

The model's principal results comprise among others estimates of technology-specific multi-sector response strategies for specific climate stabilization target. By doing so, the model identifies the least-cost portfolio of mitigation technologies. The choice of the individual mitigation options across gases and sectors is driven by the relative economics of the abatement measures, assuming full temporal and spatial flexibility (i.e., emissions-reduction measures are assumed to occur when and where they are cheapest to implement). For the intertemporal optimization, a discount rate of 5% is used.

The degree of technological detail in the representation of an energy system is flexible and depends on the geographical and temporal scope of the problem being analyzed. A typical model application is constructed by specifying performance characteristics of a set of technologies and defining a Reference Energy System (RES) to be included in a given study/analysis that includes all the possible energy chains that the model can make use of (see Figure A.2). In the course of a model run, MESSAGE then determines how much of the available technologies and resources are actually used to satisfy a particular end-use demand, subject to various constraints, while minimizing total discounted energy system costs.

Figure A.2: Schematic diagram of the basic energy system structure in the MESSAGE model.



The global MESSAGE model hosts 11 macro-regions and has a time horizon until 2100 that is divided into 10-year steps. It provides information on the utilization of domestic resources, energy imports and exports and trade-related monetary flows, investment requirements, the types of production or conversion technologies selected (technology substitution), pollutant emissions, inter-fuel substitution processes, as well as temporal trajectories for primary, secondary, final, and useful energy.

MESSAGE includes endogenous technology learning (ETL) for various technologies using a Mixed Integer Programming (MIP) approach. ETL can either be used with the 11-regional MESSAGE model or with a more aggregated 4-regional version. MESSAGE is also an integral part used for developing the integrated assessment modeling framework of the Greenhouse Gas Initiative at IIASA (Riahi et al. 2007)

The Development of full scenarios comprises model linkages to agricultural modeling tools BLS and AEZ (Fischer et al. 2007)and the DIMA forest sector model (Rokityanskiy et al. 2007). The integrated assessment framework including a description of linkages to land-use modeling tools can be found in Riahi et al., (Riahi et al. 2007).