Low Stabilization Scenarios and Implications for Major World Regions from an Integrated Assessment Perspective

*Detlef P.van Vuuren†, Morna Isaac, Michel G.J. den Elzen, Elke Stehfest and Jasper van Vliet**

In order to limit global mean temperature increase to less than 2˚C, long-term greenhouse gas concentrations must remain low. This paper discusses how such low concentrations can be reached, based on results from the IMAGE modelling framework (including TIMER and FAIR). We show that the attainability of low greenhouse gas concentration targets, in particular 450 and 400 ppm CO_2 equivalent critically depends on model assumptions, such as bio-energy potentials. Under standard model assumptions, these targets can be reached, although the lowest requires the use of bio-energy in combination with carbon-capture-and-storage. Regions are affected differently by ambitious climate policies in terms of energy and land use, although stringent emission reductions will be required in all regions. Resulting co-benefits of climate policy (such as energy security and air pollution) are also different across world regions.

1. INTRODUCTION

It is not possible to unambiguously translate the objective of the UN Framework Convention on Climate Change (i.e. to avoid dangerous anthropogenic climate change) (UNFCCC, 1992) into greenhouse gas (GHG) concentration targets. One reason is that the relationship between climate impacts and GHG concentration targets is beset with uncertainties (see for instance IPCC, 2007). In addition, subjective choices play an important role. These choices are concerned with, for instance, estimates of the ability to adapt to various forms of climate change and risk avoidance in relation to future generations (Hof et al., 2008; Rayner and Malone, 1998). Some countries have proposed a maximum increase of 2°C compared to pre-industrial levels as an interpretation of the UNFCCC-

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* Affiliation all authors: Netherlands Environmental Assessment Agency
† Corresponding author: E-mail: detlef.vanvuuren@pbl.nl, Tel.: 31-30-2742046.

objective (EC, 2006). It is clear that to limit global mean temperature change to about 2°C with a high probability (e.g. more than 80%), it is necessary to stabilize GHG concentrations below 400 parts per million (400 ppm) carbon dioxide equivalent (CO_2 eq) (Meinshausen et al., 2006; Meinshausen et al., 2009). A 50% probability of staying below a 2°C temperature increase corresponds to a stabilization level of around 450 ppm CO_2 eq.

Although several authors have explored the possibility of achieving such low targets, the literature on low stabilization scenarios is still relatively scarce (Fisher et al., 2007). As a result, limited insight exists on how strategies and associated costs for achieving low stabilization targets differ across models. There is also limited insight into the dependence on critical model assumptions such as the role of different countries and regions and sectors in climate policy and the availability (or acceptability) of various technologies.

This paper forms part of a model comparison exercise in which the attainability of low stabilization targets was explored by a set of models (Knopf et al., 2009). Each model ran a wide range of stabilization targets and sensitivity tests. This paper describes the results of the experiments run with the IMAGE framework (i.e. IMAGE, TIMER and FAIR models) (MNP, 2006) for stabilization targets (400 ppm, 450 ppm and 550 ppm CO_2 eq). The main research question was to determine how strategies for achieving low GHG targets appear in the IMAGE modeling framework and how critical model assumptions regarding the bio-energy potential influence the results. It should be noted that for the 400 and 450 ppm concentration target a certain overshoot, or peaking, is assumed: concentrations may first increase to 480 and 510 ppm before stabilizing at 400 and 450 ppm, respectively. This overshooting is necessary as a result of the present concentration levels and to avoid drastic sudden reductions (den Elzen and van Vuuren, 2007). As the attainability of climate policy critically depends on the contribution of different regions, we focus here on five important regions for international climate policy: USA, Western Europe, China, India and the Russian Federation. These regions are among the largest GHG emitting regions (together they are responsible for about 60% of global emissions) – and thus play a critical role in future international climate policy.

2. METHODOLOGY

2.1 Scenarios Explored in the Analysis

Several papers have looked at the attainability of low GHG concentration targets, either at global or regional levels (Azar et al., 2006; den Elzen et al., 2008; den Elzen and van Vuuren, 2007; Edenhofer et al., 2006; Fujino et al., 2008; IEA, 2008; Meinshausen et al., 2006; Metz and van Vuuren, 2006; Riahi et al., 2007; Strachan et al., 2008; van Vuuren et al., 2007; van Vuuren et al., 2006a; van Vuuren et al., 2008a). These studies, from a limited set of modeling groups, all focus on concentration targets of 450 ppm or less, or comparable targets. Each of these studies suggests that low targets are attainable, but depend on model assumptions such as the assumption of full participation of all countries and regions in emission reduction. Some general findings of these studies include the need for an early peak in global emissions and the use of a portfolio of reduction options, including bio-energy. Some studies have looked specifically at the attainability of stabilization targets under differential regional commitments (delayed participation) (den Elzen and Höhne, 2008; Edmonds et al., 2008; IEA, 2008; Keppo and Rao, 2007). It should, however, be noted that some of these focus on less stringent targets.

The probability of staying below a specific temperature targets obviously increases at lower GHG concentrations. At the same time, the difficulty of achieving such targets and the related costs also increase. Several studies allow some form of overshoot for concentration targets. Den Elzen and van Vuuren (2007) explicitly show that overshoot profiles can provide similar environmental outcomes at lower costs.

Most models include assumptions that limit emission reductions rates and thus the feasibility of achieving low stabilization targets: 1) a limited rate of introduction of new technologies, 2) limited rate of substitution across different energy carriers, 3) a given technical life-time of capital, 4) limits in reduction potential (e.g. potential for bio-energy or assumption on reduction potential for CH_4 emissions from agriculture) and 5) limiting the carbon price at certain maximum values. The reduction potential is further limited by the fact that almost all studies focus on technical measures and macro-economic changes but do not explicitly include the impact of behavioral change such the impact of low-meat diets (e.g. Stehfest et al., 2009).

In contrast, most models are very optimistic in assuming that new technologies and policies are globally applicable and can be introduced over relatively short periods of time. For instance, in most studies (including the one presented here) it is assumed that some form of global climate policy can be implemented soon after 2010 in all regions, without taking into account delays in formulating international climate policy, or the possibility of delayed introduction of policy in key regions.

Van Vuuren et al. (2007) identified assumptions on bio-energy potential, technology change, and energy efficiency, in addition to participation assumptions, to be critically important for the mitigation potential in the IMAGE modeling framework. The availability of carbon capture and storage (CCS) was found to be especially important when nuclear energy was also restricted. Other crucial assumptions in the IMAGE modeling framework with respect to the feasibility of different targets were: 1) carbon taxes restricted to 1000 US$ per tC, 2) emission reduction rates constrained to 3% per year, 3) emission reductions bounded by available potential (e.g. for renewable energy, bio-energy, non-CO_2 emission reduction, sinks (see also Section 2.2).

In this study, as part of the model comparison study (Knopf et al., 2009), we focus on a range of targets from 550 ppm down to 400 ppm, exploring how findings depend on stabilization levels and selected model uncertainty. The following main model runs are explored in this paper:

- *A baseline scenario*, describing development in emissions in the absence of climate policy;
- *Mitigation scenarios,* focussed at stabilising long-term concentration at 550, 450 or 400 ppm. These targets corresponds to a probability of around 20, 50 or 80%, respectively, keeping global mean temperature increase below 2°C, based on the uncertainty in climate sensitivity of the GHG concentration, (den Elzen et al., 2007; Meinshausen, 2006).
- *Uncertainty analysis,* focussing on the influence of assumptions on bio-energy and availability of key-technologies.

In all our scenarios, we assume a cap-and-trade regime with full international emission trading from 2013 onwards. We also assume that emissions allowances are allocated on the basis of the Contraction and Convergence regime with a convergence year of 2050. In other words, the regime allocates emission allowances on an equal per capita basis in 2050 with a linear convergence across the different regions from 2010 onwards. Transaction costs on emission trading are assumed at 2% of the revenues and a fixed value of 2$ per tC (den Elzen et al., 2008). Under the full trade assumption, regional emission reductions after trade, barely depend on the allocation emission allowances. However, the allocation determines the region that finances these reductions, and thus regional costs or benefits. The Contraction and Convergence regime is used because it is relatively simple and often utilised in comparable mitigation studies (see Hof et al., 2009).

2.1.1 Baseline Scenario

The baseline used here has been described in van Vuuren et al. (2009a). This scenario is based on medium-development assumptions. For population, the scenario follows the UN Medium scenario. For income, the model projection was made by the E3MG model (Barker et al., 2006). For developments in the energy sector, the POLES and IMAGE modelling teams worked together to build a common baseline projection estimated to be representative of current trends.

2.1.2 Mitigation Scenarios (Low Greenhouse Gas Concentrations)

For the mitigation scenarios, previously developed emission profiles were used. For the 550 ppm stabilization scenario, we used the scenario published earlier by van Vuuren et al. (2007). For the 450 and 400 ppm stabilization scenarios, recently published updates are used (van Vuuren et al., 2009b). Given the limited flexibility in timing of emission reductions for such ambitious targets, it was not judged necessary to develop a new emission profile. For the lowest scenario (400 ppm), two additional categories of mitigation measures are implemented in order to achieve low stabilization. The first is CCS in combination with bio-energy. This measure is unique in being able to sequester carbon absorbed from the atmosphere during the growth of energy crops, thus resulting in "negative emissions" (see Azar et al., 2006). This helps provide the extremely rapid emissions reductions required for achieving low stabilization. The second category is increased agricultural productivity, which reduces agricultural emissions. Although we have not accounted for the costs of this measure, in a scenario in which all other conceivable types of mitigation measures are taken, it is reasonable to assume that it will also be possible to accelerate productivity growth in agriculture beyond the "business-as-usual" rate of growth.

2.1.3 Uncertainty Analysis

Bio-energy plays a critical role in scenarios that aim for low GHG concentrations. However, large-scale use of bio-energy is controversial. While some authors find that it is an essential element of an ambitious climate policy, others emphasize the possible trade-offs with production of food and protection of biodiversity. In order to explore the impact of bio-energy availability on the attainability of low concentration targets, a sensitivity test was performed in which this availability was varied from 100-400 EJ p.a.

2.2 The IMAGE Modeling Framework IMAGE[1]

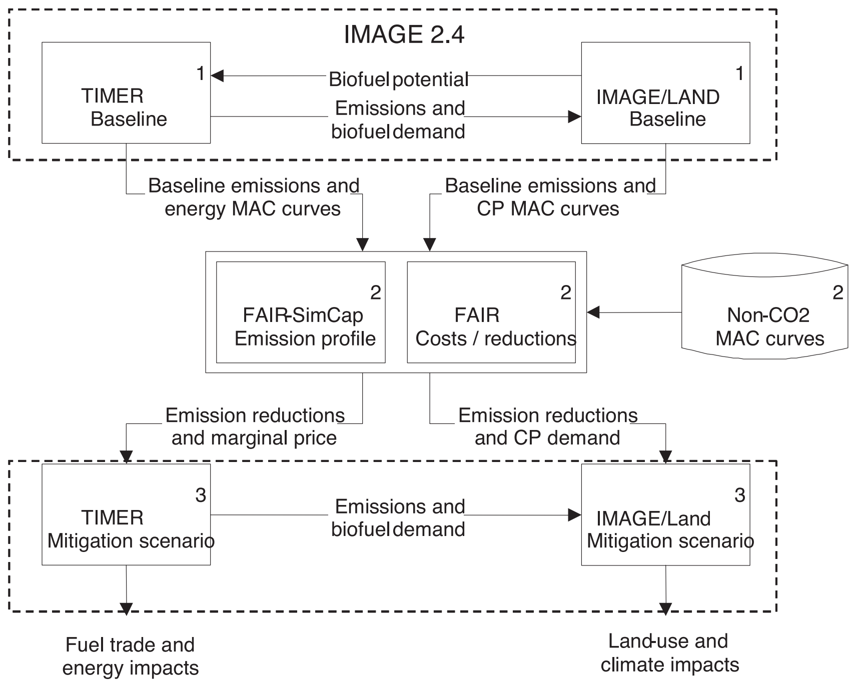
For the construction of the stabilization scenarios, we use the modeling framework IMAGE 2.4 Integrated Assessment model (MNP, 2006). The IMAGE model consists of a set of linked and integrated models that together describe important elements of the long-term dynamics of global environmental change, such as air pollution, climate change, and land-use change. The global energy model that forms part of this framework, TIMER (van Vuuren et al., 2006b), describes the demand and production of primary and secondary energy and the related emissions of GHGs and regional air pollutants. The FAIR-SiMCaP 2.0 model is a combination of the abatement costs model of FAIR and the SiMCaP model (den Elzen et al., 2007). The land and climate modules of IMAGE describe the dynamics of agriculture and natural vegetation, and, together with input from TIMER and FAIR, resulting climate change.

The analysis consists of three major steps (Figure 1):

1. The baseline emission scenario is constructed using the energy (TIMER) and land modules of IMAGE. These models also provide information on the potential emission reduction and associated abatement costs for the energy and land use systems.
2. The FAIR-SiMCaP model is used to develop global emission pathways that lead to a long-term concentration target. The FAIR

1 The model names are acronyms. IMAGE = Integrated Model to Assess the Global Environment; TIMER = The IMage Energy Regional model; FAIR = Framework to Assess International Regimes for the differentiation of commitments

Figure 1. Linkage and Information Flows Between the Models IMAGE/ TIMER and FAIR



Note CP = Carbon plantations; MAC = Marginal Abatement Costs). Step 1 – 3 are explained in the text (and see also van Vuuren et al., 2007).

model distributes the global emission reduction from baseline to meet the global emission pathway, assuming a cost-optimal implementation of available reduction options over the different regions, gases and sources, using the marginal abatement costs, and using a constant discount rate of 5%.

3. The energy (TIMER) and land modules of IMAGE implement 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).

Abatement costs of each scenario are calculated based on the marginal permit prices and the actual reductions. They represent the direct additional costs due to climate policy, but do not capture the macro-economic implications of these costs. We also do not account for (avoided) damages and adaptation costs of climate change.

2.2.1 FAIR/SiMCaP

The climate policy model FAIR (den Elzen et al., 2007) is used to determine the reduction rates across different emission sources. The SiMCaP pathfinder module makes use of an iterative procedure to find multi-gas emission paths that correspond to a predefined climate target. Global climate calculations make use of the simple climate model, MAGICC 4.1 (Wigley, 2003; Wigley and Raper, 2001). The FAIR cost model distributes the required emission reductions from baseline among the regions following a least-cost approach using regional marginal abatement costs curves (MACs) for the different emissions sources (den Elzen et al., 2008). The emission reduction potential for CO_2 emissions from the energy sector are derived from the TIMER model (van Vuuren et al., 2006b), the emission reductions by reforestation activities (carbon plantations) are based on IMAGE calculations (Strengers et al., 2008) and the non-CO_2 gas reductions on scaled marginal abatement curves (Lucas et al., 2007).

2.2.2 IMAGE/ Energy (TIMER)

The energy system simulation model (TIMER) describes the long-term dynamics of the production and consumption of about 10 primary energy carriers for 5 end-use sectors in 26 world regions. The model's behavior is mainly determined by substitution processes of various technologies based on long-term prices and fuel-preferences. These two factors drive multinomial logit models that describe investments into new energy production and consumption capacity[2]. The demand for new capacity is limited by the assumption that capital is only replaced after the end of the technical lifetime. The long-term prices that drive the model are determined by resource depletion and technology development. Resource depletion is important both for fossil fuels and for renewables (for which depletion and costs depend on annual production rates). Technology development is determined by learning-curves or through exogenous assumptions. Emissions from the energy system are calculated by multiplying energy consumption and production flows with emission factors. A carbon tax can be used to induce a dynamic response such as increased use of low or zero-carbon technologies, energy efficiency improvement and end-of-pipe emission reduction technologies.

2.2.3 IMAGE Land and Climate

The agricultural model of IMAGE models the productivity of 7 crop groups and 5 animal categories based on the Agro-Ecological Zone (AEZ) approach (Leemans and Born (1994)). Productivity is based on soil conditions, (changing) temperature and precipitation, atmospheric CO_2 concentration and agricultural management (via a regional management factor). Scenarios of

2. A multinomial logit model assigns market shares to fuel or technologies based on their relative costs. Low costs options get a large market share; high costs options a low (or even zero) market share.

agricultural demand, trade and agricultural management are obtained either from an agricultural economy model linked to IMAGE, or prescribed from other studies. In this study we use the Millennium Ecosystem Assessment's Adapting Mosaic Scenario which was developed using the IMAGE model and IMPACT agricultural economy model (Alcamo et al., 2005). The regional production of agricultural goods is distributed spatially on the basis of a set of allocation rules (Alcamo et al., 1998). For the historical period agricultural land cover is calibrated with data from FAO (2007). The potential for bioenergy crop production is based on the assumption that these crops are produced on abandoned agricultural land and natural grasslands only, so do not directly cause deforestation[3]. Both changes in land use and agricultural activities are used to model land use-related emissions. The emissions of GHGs are used by the MAGICC model (Wigley and Raper, 2001) included in IMAGE to calculate global mean temperature change. Finally, temperature changes at 0.5 x 0.5 degree are obtained using pattern-scaling approaches on the basis of the outcomes of complex climate models (Carter et al., 1994; Schlesinger et al., 2000).

3. DESCRIPTION OF THE SCENARIOS

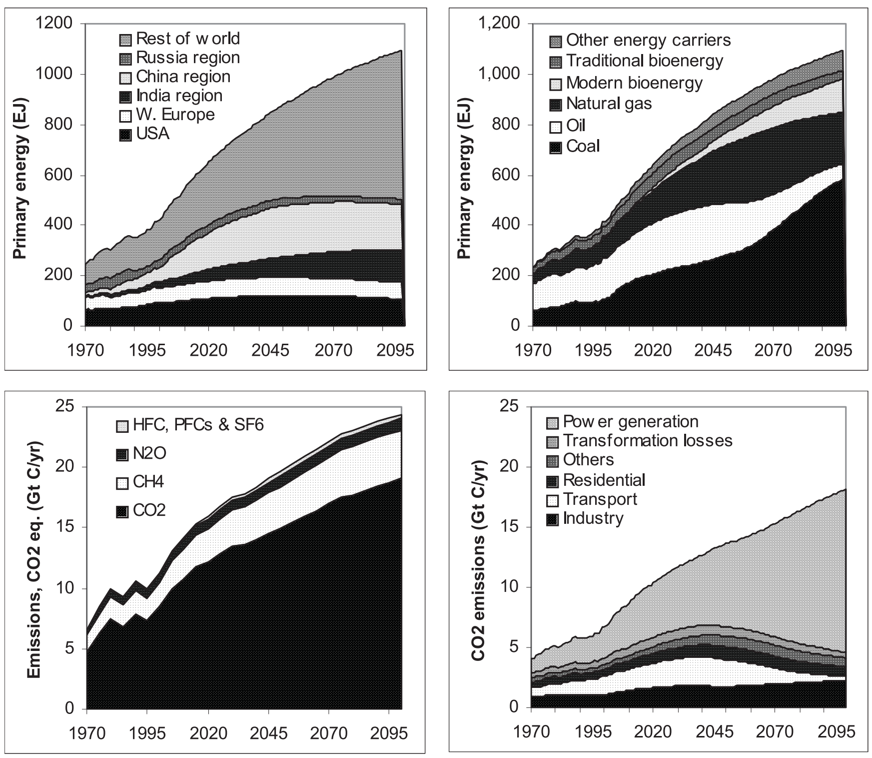
3.1 The ADAM Baseline Scenario

The ADAM baseline shows global population steadily increasing to almost 9.1 billion people by 2050 and stabilizing at about 9.2 billion people in 2100. In terms of economic growth, the ADAM scenario is a medium-high scenario, which is mainly the result of optimistic growth assumptions for China and India. In per capita terms, the current OECD regions remain by far the richest in the world. In terms of total economic activity, however, the importance of developing regions grows rapidly, especially in much of Asia (above all – China and India) and in Latin America. The GDP per capita growth rate is between 0% and 2% p.a. in most regions. In Asia, it slowly declines from the current rapid growth rates to around 3% p.a. in 2050. This largely reflects the end of the catch-up process and an economic slowdown as consequence of the ageing population in China.

Energy use and the resulting emissions, increase throughout the century (Figure 2). Primary energy supply increases from around 400 EJ p.a. today to above 1000 EJ p.a. in 2100. Fossil fuels continue to dominate global energy supply. Within this group, coal gains market share, especially in the second half of the century, as a result of depletion of low-cost oil and natural gas resources. In contrast to oil and natural gas prices, coal prices are expected to stay relatively stable given the large resources. Modern biofuels and renewables also gain market share.

3 In the land use scenario used here, the potential for bioenergy (excluding energy from residues) increases from almost 100 EJ globally in 2000 to 360 EJ in 2100. In this paper, the main mitigation scenarios are all based on this bioenergy potential, while limiting bioenergy to 200 EJ or 100 EJ in 2100 is looked at as sensitivity analysis.

Figure 2. Baseline Scenario: Primary Energy Use for the Five Major Regions and the Rest of the World (Top Left); Global Primary Energy Use by Energy Carrier (Top Right); Global Emissions by Gas (Bottom Left); Global Energy-Related CO_2-Emissions by Sector (Bottom Right)



In 1970, the USA and Western Europe were responsible for nearly 40% of total emissions. Since then, China has become as big an emitter of GHG as the USA. Together, the five largest regions in terms of emissions (USA, Western Europe, Russian Federation, China and India) are responsible for about 60% of total emissions. In the baseline scenario, this share remains more-or-less constant until 2050 after which it drops as a result of a continuing rise in energy demand in other world regions. Within the group of large emitting countries/regions the relative contributions change over time: emissions from both India and China grow faster than those of USA, Western Europe and China. The underlying factors of emission growth (economic growth, change in energy intensity, change in carbon intensity) are summarized in Table 1. Both the energy intensity improvement and carbon intensity improvement in most regions is similar to historic rates. The Indian region shows a more rapid improvement in energy intensity driven

Table 1. Average Annual Change in Income Levels, Energy Intensity, Carbon Intensity and CO_2 Emissions

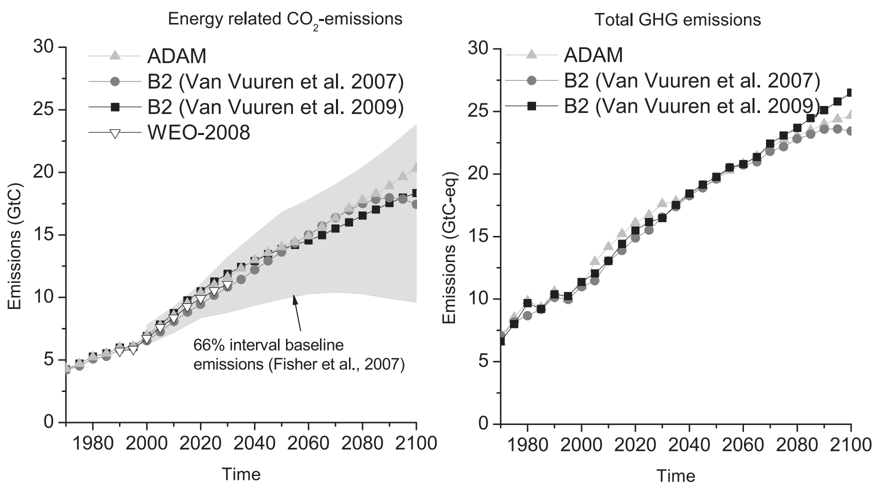
			USA	W. Europe	Russia region	India region	China region	Global
Historic	1971-2005	GDP	3.0%	2.3%	2.2%	5.3%	8.4%	3.0%
		Energy intensity	-1.8%	-1.5%	-1.7%	-1.4%	-3.4%	-1.1%
		Carbon intensity	0.0%	-0.5%	-0.2%	1.8%	1.2%	-0.1%
		CO_2-emissions	1.1%	0.3%	0.3%	5.7%	6.0%	1.8%
Baseline	2005-2050	GDP	2.0%	1.8%	3.4%	5.8%	6.2%	3.0%
		Energy intensity	-1.7%	-1.7%	-3.4%	-3.4%	-3.9%	-1.7%
		Carbon intensity	-0.2%	-0.2%	-0.1%	0.6%	0.0%	0.0%
		CO_2-emissions	0.1%	-0.1%	-0.2%	2.8%	2.1%	1.2%
550	2005-2050	GDP	2.0%	1.8%	3.4%	5.8%	6.2%	3.0%
		Energy intensity	-1.8%	-1.8%	-3.9%	-3.7%	-4.2%	-2.1%
		Carbon intensity	-2.9%	-2.5%	-1.7%	-1.8%	-1.9%	-2.1%
		CO_2-emissions	-2.7%	-2.5%	-2.3%	0.1%	-0.2%	-1.3%
450	2005-2050	GDP	2.0%	1.8%	3.4%	5.8%	6.2%	3.0%
		Energy intensity	-2.0%	-1.9%	-4.1%	-3.9%	-4.4%	-2.2%
		Carbon intensity	-3.4%	-2.9%	-2.4%	-2.1%	-2.2%	-2.5%
		CO_2-emissions	-3.4%	-3.0%	-3.2%	-0.5%	-0.7%	-1.8%
400	2005-2050	GDP	2.0%	1.8%	3.4%	5.8%	6.2%	3.0%
		Energy intensity	-1.9%	-1.8%	-4.1%	-3.9%	-4.4%	-2.2%
		Carbon intensity	-4.2%	-4.2%	-2.7%	-2.5%	-2.6%	-3.0%
		CO_2-emissions	-4.1%	-4.2%	-3.5%	-0.9%	-1.1%	-2.3%

by structural changes in the economy, incorporating a decreasing share of heavy industry.

Currently, fossil fuel-related CO_2 emissions form about 60% of total GHG emissions which increases during the scenario period. Methane (CH_4) and Nitrous Oxide (N_2O) emissions (from agriculture and energy combustion) form about 15-20% and around 5% of total emissions, respectively. CO_2 emissions from land use change remain an important source of emissions in the first decades (about 10-15%) – but become less important over time. Within the category 'fossil fuel related CO_2 emissions', electricity and hydrogen generation particularly stands out as relatively large sources that are expected to continue growing rapidly in the coming century. The direct emissions from the transportation sector also increase rapidly in the first few decades – but are projected to decline in the second half of the century as result of the penetration of fuel cells and electric vehicles (shifting emissions from the transport sector itself to coal-based hydrogen production).

In previous studies, other baseline scenarios have been used. Figure 3 compares baseline scenarios of previous IMAGE studies, existing literature ranges and the ADAM baseline. In terms of global GHG emissions the differences between the IMAGE baseline scenarios are relatively small. The ADAM baseline has emissions slightly above the baseline used in Van Vuuren et al. (2007). The energy-related CO_2 emissions in the ADAM scenario are also comparable to

Figure 3. Comparison of Global Greenhouse Gas Emissions in Different Studies (ADAM = this study; WEO-2008 = World Energy Outlook (IEA, 2008); B2 Indicates the Implementation of the IPCC B2 Scenario by the IMAGE Model in Two Different Studies)



those depicted in the World Energy Outlook of the International Energy Agency (IEA) of 2008.

3.2 Overall Emission Reductions of the Mitigation Scenarios

Substantial emissions reductions are required in order to reach low stabilization targets. Figure 4 shows the GHG emissions (by gas) for each target in comparison to the baseline emissions assuming a cost-optimal implementation of available reduction options over the GHGs, sources and regions. Sufficient emission reduction potential exists in the model to reach each of the concentration targets, but for the lowest target nearly all options are exhausted. Compared to baseline, emissions in 2100 decrease by nearly 80% for 550 ppm and more than 90% for 400 ppm. Emission reductions by 2050, compared to 2000 are 55% for the 450 ppm scenario and 60% for the 400 ppm profile.

Reductions in CO_2 emissions are the most substantial of all the greenhouse gases. This is particularly the case for the lowest target (400 ppm), where the energy sector becomes a net CO_2 sink through the large scale use of bio-energy in the power sector together with CCS. The relative emission reductions of CH_4 and N_2O are *more* than proportional to CO_2 emission reductions in the first two decades (due to relatively low costs of reductions for non CO_2 gases), but *less* than proportional later on. The latter is due to the lack of sources of credible emission reductions (see Lucas et al., 2007).

Figure 4. Global Greenhouse Gas Emissions (Kyoto Gases Only) by Gas for the 550 ppm, the 450 ppm and the 400 ppm Scenario (Filled Area), and Avoided Emissions Compared to Baseline (Striped Area)

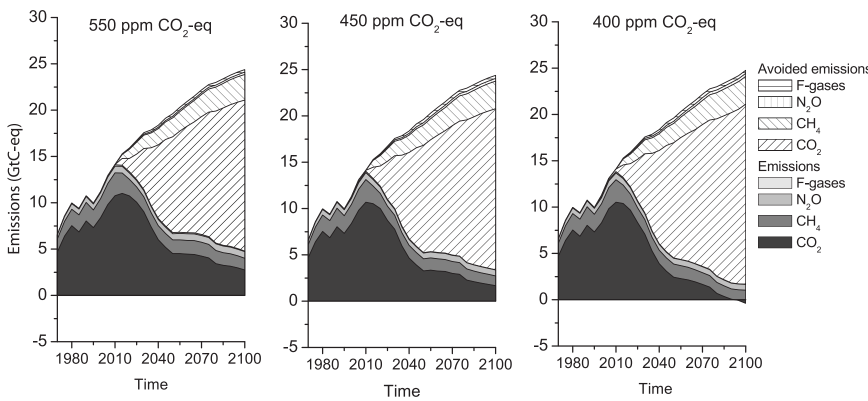


Figure 5 shows the CO_2-eq. emissions by region, both in absolute and in per capita terms[4]. Chinese emissions, as a result of rapid growth, remain the largest in the world in the baseline scenario. India has already surpassed Western Europe and, according to the ADAM baseline, will reach parity with the USA around 2050. The lower panels of Figure 5 show per capita emissions: despite large total emissions, per capita emissions in China and India remain at a lower level than those of the USA and Western Europe throughout the century. Together, the two figures demonstrate the potential challenge in international negotiations in dealing with the large differences in absolute and per capita emissions between regions. Still, at least theoretically, cap-and-trade regimes can be designed in such a way that most parties can benefit from a broad participation of countries in emission reductions (den Elzen et al., 2006).

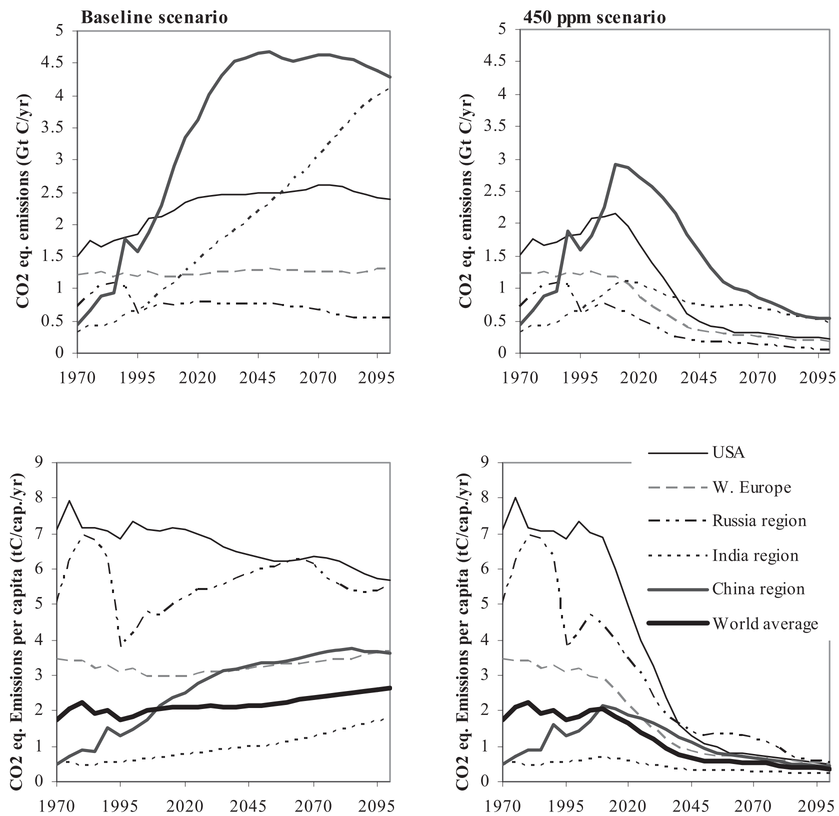
3.3 Sectoral Consequences of the Mitigation Scenarios

3.3.1 Energy Consumption

Figure 6 shows the impacts of our various mitigation scenarios on total primary energy use at a global scale. First, improved energy efficiency reduces total energy use. There is also a clear shift in the type of energy carriers that are used. Coal and oil consumption reduce significantly in the mitigation scenarios. Compared to baseline, the reduction is comparable for both energy carriers. In the 450 ppm scenario oil reduces by nearly 40% while coal reduces by slightly less

4. Emissions from international bunker fuels were not taken into account in the allocation of emission reductions

Figure 5. Greenhouse Gas Emissions (Sum of CO_2, CH_4, N_2O, HFC, PFCs and SF_6 from Energy, Industry and Land Use) for the Five Regions Studied – Absolute Values (Top) And Per Capita (Bottom), for the Baseline (Left) and 450 ppm Scenario (Right)

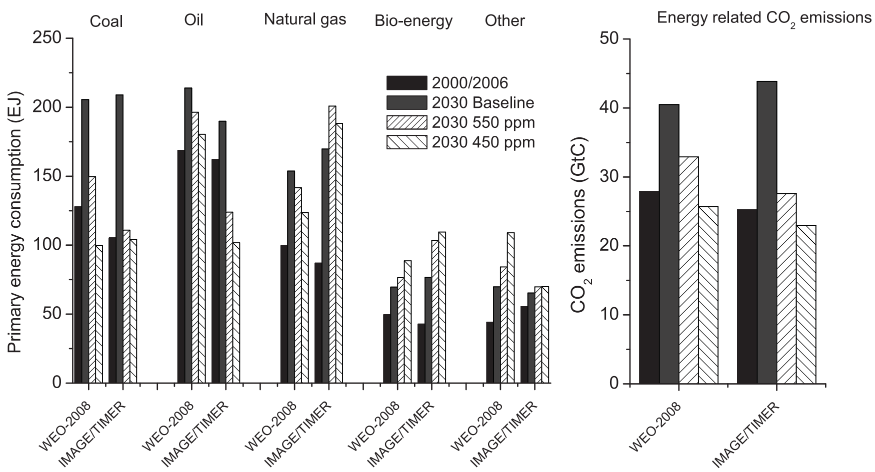


The 450 ppm scenario was developed assuming cost-optimal implementation of available reduction options over the greenhouse gases, sources and regions.

than 20% compared to 2000. In contrast, the use of natural gas, bio-energy and other energy carriers increases under the mitigation scenarios. For natural gas, the 550 ppm scenario shows a 10-20% increase compared to baseline – which is partly reduced again in the 450 ppm case. For bio-energy and other energy carriers the 450 ppm and 550 ppm cases show similar changes.

Comparing the results of this study to those of the IEA's World Energy Outlook 2008 (IEA, 2008) shows similar changes overall, with some noticeable exceptions. First of all, the reductions in the IMAGE framework are slightly

Figure 6. Comparison of Global Primary Energy Consumption in 2000 and 2030 by Energy Carrier Between This Study and the WEO 2008 (IEA, 2008), for the Baseline and Mitigation Scenarios



stronger in 2030 than those of the WEO-2008 (WEO-2008 is also relatively high compared to other studies). The results for coal and bio-energy are comparable between the two studies. For oil, the WEO-2008 shows significantly less reduction in 2030 (as IEA expects oil to continue to dominate the transport sector). For natural gas, the IEA study shows less impact on consumption than for oil – but no increase as depicted here. This is partly due to less use of natural-gas fired CCS plants. Finally, the IEA shows a stronger growth in other energy carriers, notably nuclear and renewable energy.

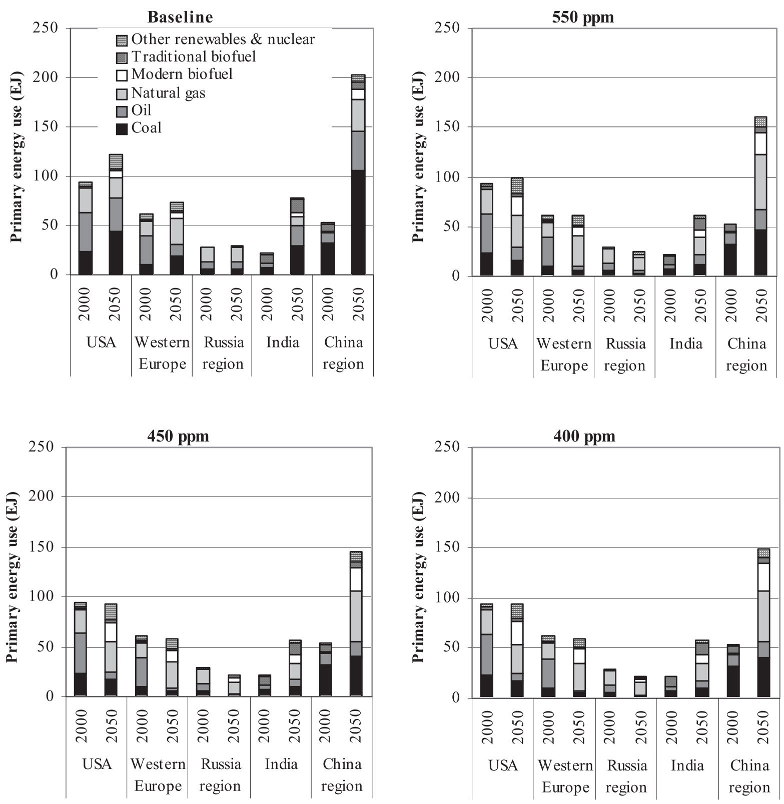
Figure 7 focuses on the regional energy use of the scenarios. In the baseline, energy use increases only slightly in the 2000-2050 period in the two developed regions shown (USA and Western Europe). The increase is somewhat faster in the USA than in Western Europe, driven by a higher population growth. In China and India, the ADAM baseline projects a rapid growth of energy consumption, almost quadrupling 2000 levels by 2050. In China, energy consumption remains more or less constant after 2050, as population starts to decline. In India, in contrast, energy use continues to grow, though less rapidly. Both the Chinese and Indian energy systems continue to be dominated by domestically produced coal. In terms of annual carbon intensity improvement (emissions per unit of energy) the baseline depicts a continuation of historic trends, i.e. little change over time (Table 1).

Energy use patterns change dramatically in the mitigation scenarios. Improved energy efficiency results in the stabilization of energy use in Western Europe and the USA. Annual energy intensity improvement increases from around 1.7% per year in the baseline to 1.8-2.0% per year in the mitigation scenarios (levels comparable to those during the period of high oil prices in the late 1970s and 1980s). In the developing regions, annual energy intensity improvement increases from around 3.4-3.9% in the baseline to 4-4.4% in the mitigation scenarios. Given economic growth in these regions, primary energy use still grows, but less strongly than in the baseline. Interestingly, the constraint on GHG emissions means that the mitigation scenarios energy systems across regions are more similar to each other than in the baseline. All regions respond to the need for emission reduction by introducing similar sets of zero/low GHG emitting technologies (in particular increased efficiency, CCS, bio-energy, wind power, and nuclear energy). Emission trading contributes to this similarity, as it equalizes pressure to improve energy efficiency across regions. The introduction of zero/low GHG emitting technologies in the mitigation scenarios leads to a dramatic improvement in carbon intensity compared to both the historic and the baseline trends (Table 1). Carbon intensity decreases rather rapidly over time; around 1.7-2.9% per year in the 550 ppm scenario up to 2.5-4.2% in the 400 ppm scenario. This indicates that the contribution of the changes in the energy mix to reducing emissions is larger than that of energy efficiency improvement.

Figure 7 also shows that the use of coal is substantially lower in all regions under the mitigation scenarios and remaining coal use is mostly combined with CCS. The use of oil also falls significantly, and in the transport sector oil is replaced by biofuels. Natural gas use does not change much compared to baseline and in fact, in most regions natural gas use grows, increasingly combined with CCS technology. The use of other renewables and nuclear power and bio-energy increases in all regions compared to the baseline case. In the scenario with the lowest target, in which the increased application of bio-energy in the power sector is also combined with CCS, there is some reallocation of bio-energy from transport to power generation.

A crucial technology in the current TIMER outcomes is CCS. In choosing an energy technology, the model evaluates the costs of technologies with CCS against fossil-fuel fired technologies without CCS but also against other low and zero GHG emitting technologies. Often, CCS technologies are found to be competitive. The model takes into account estimates of CO_2 storage capacity by region (Hendriks et al., 2002). The total capacity for CO_2 storage (including aquifers) is found to be large in most regions. The capacity of empty natural gas and oil fields is far more constrained and exhausted completely in several regions by the end of the century. In selecting CCS as a key mitigation technology, the model results rely heavily on the transport and storage, within each region, of very large amounts of CO_2. In the USA, Western Europe, China and India the rate of carbon capture increases gradually, until it stabilises towards the end of the century (Figure 8). The decline in CO_2 storage in some regions is driven by decreasing baseline CO_2 emissions, but also by exhaustion of good storage sites.

Figure 7. Regional Primary Energy Use in 2000 and 2050 by Energy Carrier, in the Baseline and Mitigation Scenarios for the Five Regions Studied, for the Baseline, 550 ppm, 450 ppm and 400 ppm Scenarios

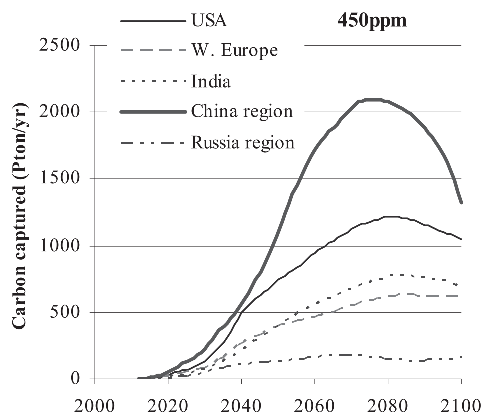


The 450 ppm scenario was developed assuming cost-optimal implementation of available reduction options over the greenhouse gases, sources and regions.

3.3.2 Energy Production and Trade

The changes in the energy system due to the efforts to reduce GHG emissions also influence energy production and energy trade. In Figure 9 the production of energy in the different regions is compared to their energy consumption. The USA, Western Europe, India and China all consume more than they produce, making them net importers of energy, whereas Russia is an exporter. The impact of energy policy on the production of various energy

Figure 8. Amounts of Carbon Captured in the Five Regions Studied in the 450 ppm Scenario



carriers is visible in Figure 9. In all regions, coal production reduces substantially compared to baseline. This has consequences particularly for regions with high coal production levels: USA, India and China. Oil production also reduces, which has a major impact in the Russian Federation. Natural gas production, on the other hand, increases and, for the Russian Federation largely offsets the reduced production level of oil, allowing it to remain a net exporter of energy in the mitigation scenarios. Bio-energy production significantly increases in all regions; in absolute terms this increase is most evident in the USA. Some other regions become important in producing bio-energy – including in particular Brazil. The use of other renewables and nuclear for power generation also increases, but remains relatively low.

Figure 10 focuses more directly on energy trade by showing the net imports and exports. The impact of climate policy is obvious: coal and oil trade are greatly reduced. Oil imports decrease in the USA, Western Europe and China and exports from the Russian Federation also reduce. The trade in bio-energy increases, with the USA, Western Europe, India and China again being net importers. Overall, this suggests that for the USA and Western Europe, climate policy coincides with regional objectives to improve energy security by reducing energy imports. In the USA, under the mitigation scenario, imports are still larger than in 2000, but they are smaller than in the baseline. In Western Europe, total imports are even lower than in 2000. For India and China, implementation of climate policy primarily leads to a shift in energy imports (natural gas and bio-energy), rather than reducing the absolute amount consumed. This is brought about by a strong reduction in domestic coal production. Obviously, the regions

Figure 9. Energy Production and Consumption in Selected Regions in 2000 and 2050 for the Baseline and the 450 ppm Scenario

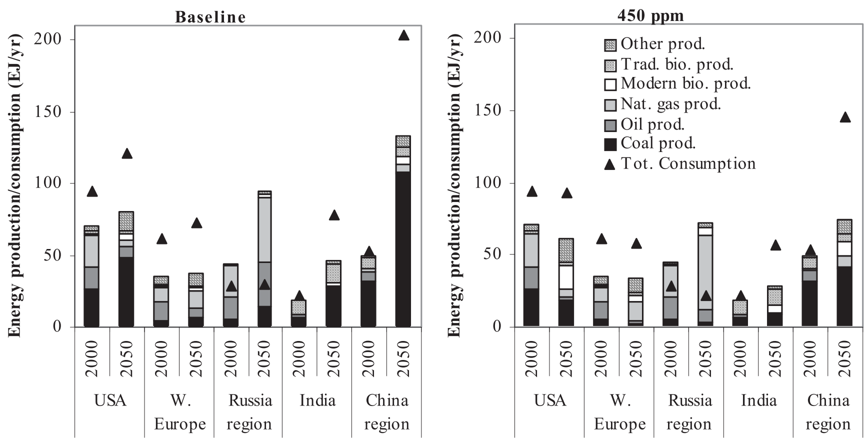
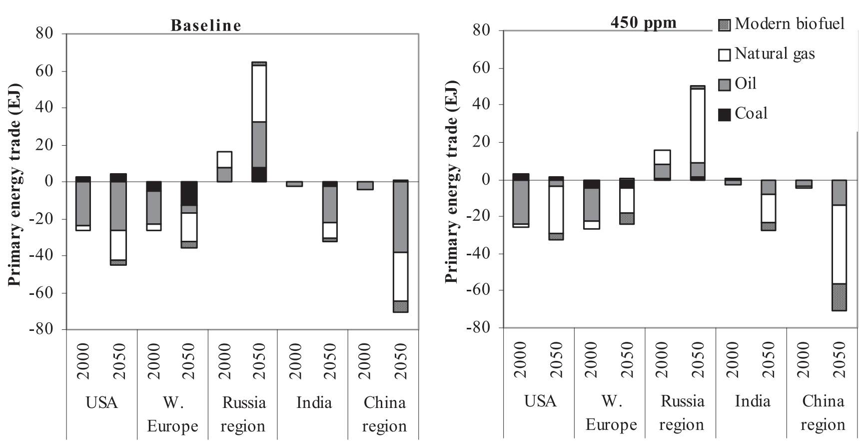


Figure 10. Energy Trade in 2000 and 2050 in Selected Regions for the Baseline and 450 ppm Scenarios; Positive Values Represent Net Export

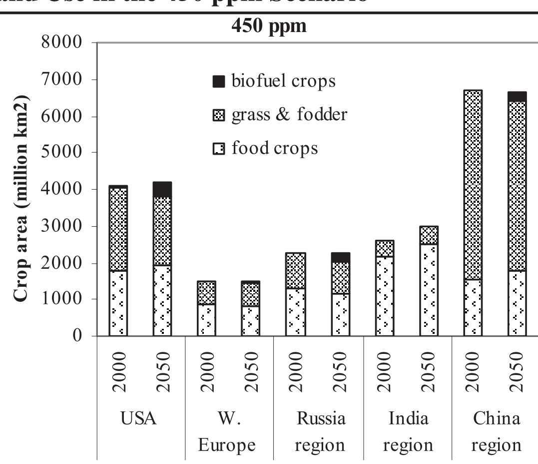


could also decide to keep coal use at higher levels (in combination with CCS) but this would come at a cost. For regions that export fossil fuels, such as the Russian Federation, the situation is reversed: the potential to export fossil fuels will be reduced, with the extent of the reduction depending on the use of CCS technology.

3.3.3 Land Use

Land use change is largely determined by demand for agricultural products and assumptions on agricultural intensification. Compared to the range of other land use scenarios, the ADAM baseline is comparatively optimistic in terms of agricultural area, but remains within the range of possible "baseline" land use trends (cf. (van Vuuren et al., 2008b)). In the baseline, there is some expansion of land use for bio-energy production and this trend is strengthened in the mitigation cases, partly offsetting baseline trends in reducing agricultural area. As we allocate bio-energy only on abandoned agricultural land and natural grasslands, the impacts on remaining land use are small. We therefore discuss baseline trends and the trends in the mitigation scenarios together (using the results of the 450 ppm scenario; Figure 11). Most of the land bio-energy for bio-energy in Figure 11 is additional for the mitigation case. All scenarios shows declining agricultural area in the USA, Western Europe, the Russian Federation and China – and an increase in India (Figure 11). The different trends in different world regions are related to trends in population, dietary patterns and food trade, resulting in a shift in agricultural production from temperate regions to tropical regions. Underlying these trends are: 1) the lower production costs in developing countries due to lower labor and land prices, 2) the higher rate of improvement of agricultural yields, 3) the assumed continuation of trade liberalization and 4) the faster growth of agricultural demand in developing countries. Climate change could drive the system in an opposite direction, but its impact is less important. Differences between the baseline and mitigation scenario in land use for food, grass and fodder are small.

Figure 11. Land Use in the 450 ppm Scenario



3.3.4 Air Pollutant Emissions

Policies for the reduction of GHG emissions also influence the emissions of air pollutants as shown in Figure 12 (see also van Vuuren et al., 2006c). In the USA and Western Europe, emissions of SO_2 and NO_x decline in the baseline scenario as a result of further introduction of pollution control technologies. Such technologies are also introduced to some degree in India and China, but here activity growth causes an increase in emissions under the baseline. In the mitigation scenarios, the changes to the energy system also reduce emission of air pollutants. SO_2 emission reductions in 2050 in the 450 ppm scenario are in the order of 70-80% compared to the baseline scenario, i.e. comparable to the reductions for CO_2. For $NO_{x,}$ impacts are less substantial at around 50% compared to the baseline scenario. This discrepancy is because several technologies, such as bio-fuels, that reduce CO_2 emissions also reduce SO_2 emissions but not NO_x emissions.

3.4 Costs of the Mitigation Scenarios

As a metric of costs, we use annual abatement costs expressed as percentage of GDP. As shown in Figure 13, these costs reach a level of around 1% of global GDP in 2040 for the 550 ppm scenario (followed by a decline in relative terms) and nearly 2% in 2030 in the 450 ppm scenario. The costs of the 400 ppm scenario are similar to the 450 ppm scenario, but it should be noted that these cannot be easily compared. The 400 ppm scenario uses one additional technology (the combination of bio-energy and carbon capture and storage) and also relies on improvement of agriculture yields (for which no costs could be calculated).

Regional costs, as shown in Figure 14, depend strongly on international agreements. These include the differentiation of commitments across regions and the overall target at a global level (den Elzen et al., 2008). Given the large differences in income between the regions, the costs (or gains) are presented as percentages of regional GDP levels using Purchasing Power Parity (PPP$) rates. These are considered a better indicator of costs differences across regions than the Market Exchange Rates (MER) GDP value basis used for global costs. Under the Contraction & Convergence regime used in this paper, the Russian and Indian regions can initially benefit from selling emission rights. For Russia, this period of being a seller is short and it becomes the region with the highest costs after 2040. India experiences net positive costs from 2050 onwards, with costs still below world average level. Both the USA and Western Europe experience medium cost levels. The China-region bears relatively high costs. This is because (1) in a Contraction & Convergence regime with converging per capita emissions, China would, before long, have to reduce per capita emissions, when they exceed the (declining) world average per capita emissions; (2) The relatively high baseline emissions for China also lead to higher abatement costs. In our earlier study (den Elzen et al., 2008) the baseline emissions by 2050 for China were about three

Figure 12. SO_2 and NO_x Emissions in the Year 2000 and in the Year 2050 for the Baseline and 450 ppm Scenarios

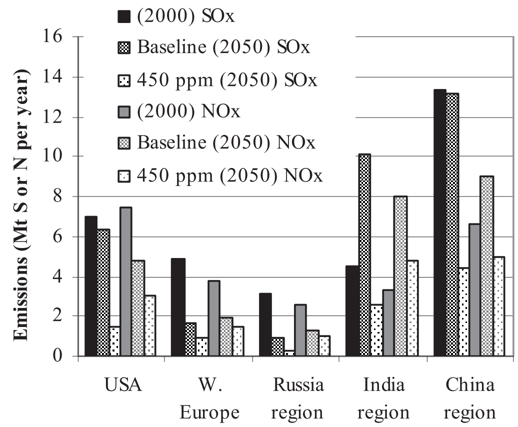
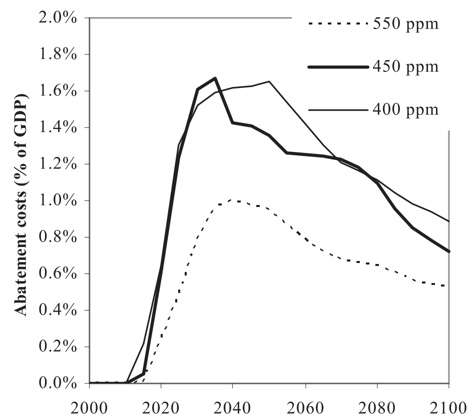


Figure 13. Annual Global Abatement Costs of the 550 ppm, 450 ppm and 400 ppm Scenarios as Percentage of Global GDP (Measured in Market Exchange Rates)

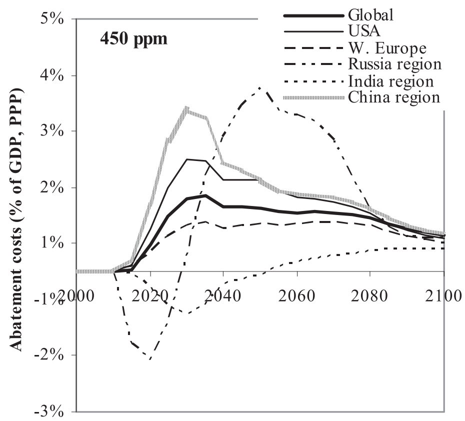


times 1990 levels, whereas in this study there is a six fold increase, leading to higher abatement costs. Obviously, other proposals with different commitments would produce varying results.

4. SENSITIVITY ANALYSIS AND DISCUSSION

There are many uncertainties that can have a major impact on the attainability (and costs) of low stabilization scenarios. Important factors include

Figure 14. Annual Regional Abatement Costs of the 450 ppm Scenario in Selected Regions Expressed as Percentage of GDP (Measured in Purchasing Power Parity)



Calculations are done assuming allocation based on a contraction and convergence regime with convergence year 2050 and assuming full global trade. A region may have negative costs when earnings due to the sale of carbon credits are higher than costs.

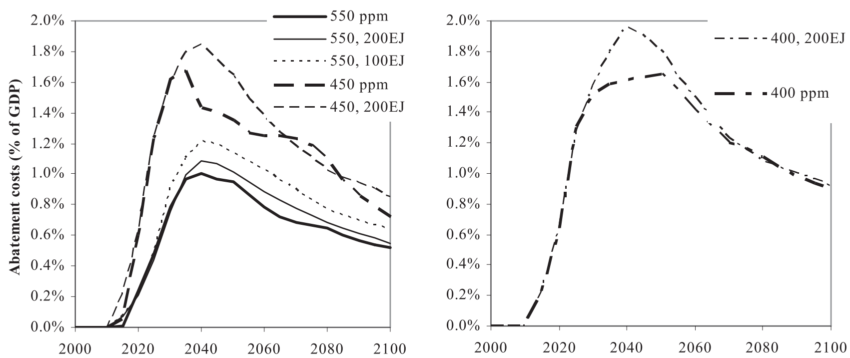
baseline assumptions, technology improvement rate, bio-energy potentials and the accessibility of various reduction options (van Vuuren et al., 2007). Of these uncertainties, here we focus on the influence of bio-energy assumptions and the removal of key technologies.

4.1 Bio-energy

Scenarios with a reduced potential for bio-energy were run in order to examine the sensitivity of the results to this parameter (Figure 15). The scenarios described in the previous sections are based on a potential for bioenergy that increases with time, reaching 360 EJ p.a. (excluding agricultural residues) in 2100. The sensitivity of the results to a reduced bioenergy potential was tested by running scenarios with a potential that increases less rapidly, reaching only 200 EJ p.a. in 2100, and with a potential that remains constant at the global level, at about 100 EJ p.a.

In the baseline scenario, a lower bioenergy potential leads to a decrease in the (already relatively low) use of modern biofuels, which are replaced by coal and natural gas, with a concomitant increase in emissions. In mitigation scenarios, a reduced bioenergy potential results in higher mitigation costs. Additional reductions mostly come from increased energy efficiency and a greater use of fossil-fuel based CCS.

Figure 15. Abatement Costs of the 550 ppm, 450 ppm and 400 ppm Scenarios at Different Levels of Bioenergy Potential: 360 EJ p.a., 200 EJ p.a. and 100 EJ p.a. in 2100 (Excluding Agricultural Residues)

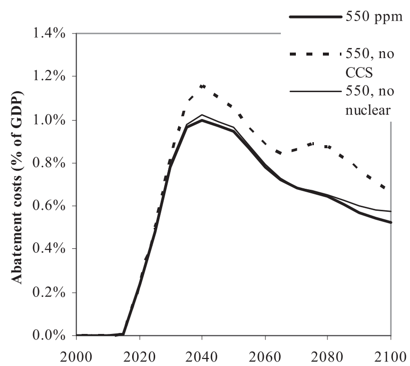


In the 550 ppm scenario (the least ambitious mitigation case), the carbon price stays below 350 US$ per tC for the high bio-energy potential, increases more rapidly to a level of 360 US$ per tC in the 200 EJ p.a. bio-energy potential case, and reaches 390 US$ per tC in the 100 EJ p.a. case (all costs are in 1995 $). This translates to annual abatement costs of a maximum of 1.0% of GDP in 2040 for the first case, 1.1% for the 200 EJ p.a. case and 1.2% for the 100 EJ p.a case (Figure 15). In other words, restrictions on bio-energy use could lead to a cost increase of about 20% at 550 ppm compared to the reference calculations previously presented. At lower stabilization levels (450 ppm) the restricted bio-energy potential (200 EJ p.a. versus the 400 EJ p.a. reference), a peak carbon price of over 900 US$ per tC is reached. Under 100 EJ p.a. the target cannot be achieved at prices below 1000 US$ per tC (feasibility criterion). With a 400 ppm target, the maximum carbon price of 1000 US$ per tC is reached even with high bio-energy supply, and the lower bioenergy potential makes the target infeasible (Figure 15). In other words, the bio-energy potential is important for the feasibility of low targets. This is partly a consequence of the fact that in TIMER the use of different energy technologies and carriers are not fully optimized, but depend on their competitiveness in different sectors. For example, bio-energy will continue to be used in the transport sector, at a reduced level, even if it would be better from an overall perspective on abatement costs to use it (with CCS) in the power sector.

4.2 Availability of Technology Options

Besides bioenergy potentials, we also studied the importance of CCS and of nuclear energy (Figure 16). This sensitivity analysis was carried out for

Figure 16. Abatement Costs of the Standard 550 ppm Scenario, a Scenario in Which Nuclear Energy is Excluded as Mitigation Measure and a Scenario Without CCS



the 550 ppm target only, since for the more ambitious targets both technologies are essential. In TIMER, CCS is a relatively cheap mitigation measure, whereas nuclear energy is relatively expensive. Hence, the amount of mitigation through an increase in nuclear energy is relatively minor, while CCS is a very important measure. The result is that excluding nuclear energy as mitigation measure has relatively little effect on the abatement costs, while excluding CCS has an effect comparable to severely limiting bioenergy (Figure 16).

5. CONCLUSIONS

- **It is possible to keep greenhouse gas emissions within the emission pathways that lead to long-term stabilization at 550, 450 and 400 ppm CO_2-eq in the IMAGE modeling framework (including TIMER and FAIR).** With carbon prices below 1000 US$ per tC, it is possible to find strategies that lead to emission reduction in the order of 80%-95% below baseline emission levels (without climate policy) by 2100. The reductions differ by greenhouse gas: while energy-related CO_2 emission can be reduced to zero or even become negative (meaning that more carbon is stored than emitted), emission reductions for non-CO_2 gases are only around 75% for methane and 35% for nitrous oxide (compared to the baseline scenario). Hence, non-CO_2 gases dominate emissions by the end of the century.
- **Climate policy has different consequences for different regions.** The model runs show that the impacts of climate policy differ between the regions that were considered: USA, Western Europe, Russia, India and China. This is a result of large differences in per capita emissions and in the design of the energy system. For instance, climate policy reduces import dependency in USA

and Western Europe, changes imports in China and India and reduces export options from the Russian Federation.

- **Several critical model assumptions play a key role in the attainability of low stabilization targets. Bio-energy potential is an example.** The model runs assume that all regions participate in global climate policy from 2013 onwards. In this paper we have not tested how much the attainability of low stabilization targets depends on global participation. We have suggested elsewhere however, that participation of key developing countries needs to occur before 2020 in order to keep low greenhouse gas targets attainable (den Elzen and Höhne, 2008). Another key factor is the potential for bio-energy production as determined for example, by agricultural development, changes in yields, and sustainability criteria. In the current modeling framework, the lowest target explored here (400 ppm) becomes unattainable with low bio-energy potential, as the use of bio-energy (and carbon capture-and-storage) is required to provide the negative emissions mentioned above.

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