Report 728001031/2005

Meeting the EU 2°C climate target: global and regional emission implications

M.G.J. den Elzen*
M. Meinshausen**

* Corresponding author: Netherlands Environmental Assessment Agency (MNP associated with the RIVM), PO Box 1, 3720 BA Bilthoven, The Netherlands, e-mail: michel.den.elzen@mnp.nl; tel +31 30 2744584; fax: +31 30 2744464

** Swiss Federal Institute of Technology (ETH Zurich), Environmental Science Department, Rämistrasse 101,CH-8092 Zurich, Switzerland, e-mail: malte.meinshausen@env.ethz.ch.
At present, visiting scientist at: Climate and Global Dynamics Division, National Center for Atmospheric Research (NCAR), P.O. Box 3000, Boulder, CO 80307-3000, USA.

This research was performed with the support of the Dutch Ministry of Housing, Spatial Planning and the Environment as part of the International Climate Change Policy Project (M/728001 Internationaal Klimaatbeleid)

Netherlands Environmental Assessment Agency (MNP associated with the RIVM), PO Box 303, 3720 AH Bilthoven, The Netherlands, telephone: +31 30 274 274 5, website: www.mnp.nl

Abstract

Meeting the EU 2°C climate target: global and regional emission implications
This report presents a set of multi-gas emission pathways for different CO_2-equivalent concentration stabilization levels, i.e. 400, 450, 500 and 550 ppm CO_2-equivalent, along with an analysis of their global and regional reduction implications and implied probability of achieving the EU climate target of 2°C. The effect of different assumptions made for baselines, technological improvement rates, or delay of global action on the resulting emission pathways is also analysed. For achieving the 2°C target with a probability of more than 60%, greenhouse gas concentrations need to be stabilized at 450 ppm CO_2-equivalent or below, if the 90% uncertainty range for climate sensitivity is believed to be 1.5 to 4.5°C. A stabilization at 450 (400) ppm CO_2-equivalent requires global emissions to peak around 2015, followed by substantial overall reductions in the order of 30% (50%) compared to 1990 levels in 2050. In 2020, Annex I emissions need to be approximately 15% (30%) below 1990 levels. Non-Annex I emissions may increase compare to the 1990 levels, but not compared to their baseline emissions (15-20% reduction). A further delay in peaking of global emissions by 10 years doubles maximum reduction rates to about 5% per year, and very likely leads to high costs. In order to keep the option open of stabilising at 400 and 450 ppm CO_2 equivalent, the USA and major advanced non-Annex I countries will have to participate in an agreement aimed at reductions within 10-15 years.

Keys words: multi-gas emission pathway, climate target, post-2012 commitments

Rapport in het kort

Het behalen van de EU 2 graden klimaatdoelstelling: mondiale en regionale emissie implicaties

Dit rapport presenteert mondiale broeikasgas emissiepaden die leiden tot stabilisatie van de concentraties van de broeikasgassen op verschillende niveaus, i.e. 400, 450, 500 and 550 ppm CO_2-equivalent. Daarnaast analyseert dit rapport de benodigde regionale en mondiale broeikasgas emissiereducties en de waarschijnlijkheden voor het behalen van de EU 2 graden doelstelling. Ook wordt het effect van verschillende veronderstellingen ten aanzien van baseline emissie scenario's, technologische verbeteringen en vertragingen in het stabiliseren van de mondiale emissies op de uiteindelijke emissiepaden geanalyseerd. Om een zekerheid van meer dan 60% te hebben dat de EU 2 graden doelstelling wordt gehaald, dienen de broeikasgas concentraties gestabiliseerd te worden op het niveau van 450 ppm CO_2-equivalent of minder (400 ppm), als het 90%-onzekerheidsinterval voor de klimaatgevoeligheid tussen de 1,5 en 4,5°C ligt. De mondiale emissies zouden daartoe rond 2015 hun maximum bereikt dienen te hebben, gevolgd door substantiële emissiereducties in de orde van 30% (50%) in 2050. Om de mondiale emissies binnen 20 jaar hun maximale niveau te laten bereiken zijn in 2020 verdergaande emissiereducties van de industrielanden nodig, in de order van 15% (30%) onder het 1990-niveau. De ontwikkelingslanden mogen hun emissies laten groeien ten opzichte van het 1990-niveau, maar zullen moeten reduceren ten opzichte van hun baseline (15-20%). Een verder uitstel van het stabiliseren van de mondiale emissies met meer dan 10 jaar verdubbelt de maximale mondiale reductiesnelheden tot meer dan 5% per jaar, en zal mogelijk leiden tot hoge kosten. Verder zal om de concentratie stabilisatiedoelstellingen van 400 en 450 ppm te halen, het noodzakelijk zijn dat de VS en de voornaamste ontwikkelingslanden hun emissies moeten gaan reduceren binnen 10-15 jaar.

Trefwoorden: multi-gas emissiepaden, klimaatdoelstelling target, post-2012 lastenverdelingen

Acknowledgements

This study was performed within the framework of International Climate Change Policy Support project (M/728001 Internationaal Klimaatbeleid). We would like to thank our colleagues, in particular Marcel Berk, Bas Eickhout, Paul Lucas and Detlef van Vuuren (MNP), as well as Bill Hare from the PIK Institute in Germany, for their comments and contributions. Finally, we thank Ruth de Wijs for language editing assistance. Any errors in the report are the responsibility of the authors.

Contents

1 INTRODUCTION 6

2 METHOD FOR DEVELOPING EMISSION PATHWAYS WITH COST-EFFECTIVE MULTI-GAS MIXES 9

3 EMISSION PATHWAYS AND THEIR TRANSIENT TEMPERATURE IMPLICATIONS 15

3.1 CO_2-equivalent concentration and radiative forcing 15
3.2 Temperature increase 16
3.3 Emission pathways 18

4 GLOBAL EMISSION ABATEMENT COSTS 20

5 THE REGIONAL EMISSION IMPLICATIONS 22

6 THE IMPACT OF FURTHER DELAY IN EMISSION REDUCTIONS 26

6.1 Delay in peaking of global emissions 26
6.2 The impact of a further delay in USA involvement in emission reductions 27

7 CONCLUSIONS 30

REFERENCES 32

APPENDIX A DESCRIPTION OF THE EMISSION PATHWAYS CALCULATION 36

APPENDIX B SOURCE OF INFORMATION ON MARGINAL ABATEMENT COSTS 38

APPENDIX C GLOBAL GREENHOUSE GAS EMISSIONS OF THE PATHWAYS PRESENTED 39

APPENDIX D COMPARISON WITH IMAGE 2.2 MULTI-GAS EMISSION PATHWAYS 40

1 Introduction

The aim of this study is to explore allowable emissions levels of the set of the six greenhouse gases covered under the Kyoto Protocol in the long and short term that are compatible with any long-term climate policy targets to avoid dangerous climate change. In order to determine allowable levels of greenhouse gas emissions, we have to back-calculate from acceptable levels of climate change to emissions. This is not simple. Apart from the question of what an acceptable level of climate change constitutes – a political issue – there are major scientific uncertainties in the cause–effect chain. This is the relationship between levels of greenhouse gas emissions and the impacts related to the human-induced climate change. Thus, we take a pragmatic route: the point of departure of our analysis will be the long-term EU climate target of limiting the global mean temperature increase to 2°C above pre-industrial levels (1861-1890), as adopted in 1996, and recently (March 2005) reconfirmed by the European Council (1996; 2005). It should be kept in mind though that 2°C cannot be regarded as harm-free or 'safe', as shown by many reviews in the scientific literature (Smith et al., 2001; Hare, 2003; ACIA, 2004; Hitz and Smith, 2004). For example, the human-induced climate change up to the present has already doubled the risk of heat waves, such as the European heat wave of 2003 and the resulting unusually large numbers of heat-related deaths (Allen and Lord, 2004; Stott et al., 2004).

To deal with the large uncertainties in the cause-effect chain we have adopted a probabilistic approach and focus on the uncertainty in climate sensitivity. Climate sensitivity summarizes the key uncertainties for long-term climate projections and is expressed as the expected warming of the earth's surface for a doubling of pre-industrial CO_2 concentrations (2x278=556ppm). Several studies have estimated probability density functions[1] for climate sensitivity, of which we select two as examples: Firstly, the one by Wigley and Raper (2001), which is built to match the conventional IPCC 1.5 to 4.5°C uncertainty range, and secondly a recent estimate derived by Murphy et al. (2004) using a large ensemble of GCM runs.

We developed multi-gas abatement pathways and analysed the associated risks[2] of them overshooting the EU climate target of 2°C (Hare and Meinshausen, 2004; Meinshausen, 2005). Earlier analysis of emission pathways leading to climate stabilization focuses mainly on CO_2 only (Enting et al., 1994; Wigley et al., 1996; Swart et al., 1998; Hourcade and Shukla, 2001). Consistent information on reduction potential for the non-CO_2 gases has been lacking for a long time, which is why most studies on the implications of a multi-gas reduction strategy are more recent (see e.g. Reilly et al., 1999; Eickhout et al., 2003). Reducing non-CO_2 emissions can have important advantages in terms of avoiding climate impacts (Hansen et al., 2000; Meinshausen et al., 2004; Wigley et al., submitted). Recent studies exploring the impacts of including non-CO_2 gases in the analysis of the Kyoto Protocol have found that major cost reductions can initially be obtained through the relatively cheap abatement options for some of the non-CO_2 gases and the increase in flexibility (Hayhoe et al., 1999; Reilly et al., 1999). Multi-gas studies on long-term stabilization targets also show considerably lower costs for a multi-gas strategy than under a

[1] These probability density functions provide information on how likely the real climate sensitivity can be found in a certain interval.

[2] Note that throughout this report, the term 'risk of overshooting' is used for the 'probability of exceeding a threshold'. Technically speaking, 'risk' is used in this respect to describe the product of likelihood and consequence with 'consequence' described as a step function with the value 0 below and 1 above the threshold (Meinshausen, 2005).

CO_2-only strategy (e.g., Tol, 1999; Manne and Richels, 2001; van Vuuren et al., 2003; 2004). However, the time-dependent share of non-CO_2 gases depends on the use of 100-year Global Warming Potentials (GWPs) (e.g., van Vuuren et al., 2005). Under a multi-gas strategy using the 100-year GWPs, the contribution of the non-CO_2 gases in total reductions is very large early in the scenario period (50-60% in the first two decades (e.g., van Vuuren et al., 2003; 2004), although CO_2 remains by far the most important human-induced radiative forcing agent in the long term. Not using GWPs (but instead determining the substitution on the basis of cost-effectiveness in realizing a long-term target) implies that the primary focus of mitigation in the near-term rests on CO_2 (e.g., Manne and Richels, 2001) Other studies have explored the methodological issues of a multi-gas approach, such as which type of climate targets (for instance, concentration or temperature targets) can best be set for such a diverse group of gases (see Manne and Richels, 2001; Richels et al., 2004; Fuglestvedt et al., 2003; O'Neill, 2003).

Obviously, it is much more complicated to define emission pathways for stabilising CO_2-equivalent concentrations[3] than for CO_2 only, because these can be reached through various combinations of greenhouse gases, which also have different contributions to the total radiative forcing over time. So far, there are roughly five ways of accounting for non-CO_2 emissions:

(i) simple scenario assumptions, for example, the common non-intervention scenario[4] (SRES A1B) for non-CO_2 emissions in the IPCC Third Assessment Report (Cubasch et al., 2001) or a certain CO_2-equivalent concentration (e.g. 100 ppm) to be added to a CO_2-concentration stabilization target (Eickhout et al., 2003);

(ii) 'scaling', concentrations or radiative forcing, which are proportionally scaled with CO_2: e.g. 23% of CO_2 forcing (see Raper and Cubasch, 1996);

(iii) accounting for source-specific reduction potentials for all gases, as in the post-SRES scenarios (Morita et al., 2000; Swart et al., 2002),

(iv) different approaches assuming cost-optimal implementation of available reduction options over the greenhouse gases, sources and regions (van Vuuren et al., 2003) and/or over time (Manne and Richels, 2001) and

(v) meta-approaches that make use of the multi-gas characteristics in existing scenarios derived by any of the previous approaches (e.g., Meinshausen, 2004).

Here we focus on a cost-optimisation variant (iv), which closely reflects the political reality of pre-set caps on aggregated emissions and individual cost-optimising actors. Specifically, the actors are assumed to choose a cost-minimizing mix of reductions across the different greenhouse gases to achieve the preset global emission level for each five year period.

Further on in this study we will focus on the development of multi-gas emission pathways for the lower concentration stabilization targets (400, 450, 500 and 550 ppm CO_2-eq.), as opposed to 550 and 650 ppm CO_2-eq. as in our earlier study on emission pathways (Eickhout

[3] 'CO_2 equivalence' summarises the climate effect ('radiative forcing') of all human-induced greenhouse gases, tropospheric ozone and aerosols, following the IPCC definition, as if we only changed the atmospheric concentrations of CO_2 (see Schimel et al., 1997).

[4] Following the terminology of Meinshausen et al. (2004), we can draw a distinction here between *scenarios* and emission *pathways*. While the emission pathway focus solely on emissions, a *scenario* represents a more complete description of possible future states of the world, including their socio-economic characteristics and energy and transport infrastructures. According to this definition, many of the existing '*scenarios'* are in fact *pathways*, including the ones derived in this study.

et al., 2003)[5], so as to achieve more certainty in reaching the EU 2 degree Celsius target (e.g., Hare and Meinshausen, 2004). For these lower concentration targets, we assume a certain overshooting (or peaking), i.e. concentrations may first increase to an 'overshooting' concentration level up to 480, 500 and 525 ppm then decrease before stabilizing at 400, 450 and 500 ppm CO_2-equivalence, respectively. This overshooting is partially reasoned by the already substantial present concentration levels and the attempt to avoid drastic sudden reductions in the presented emission pathways.

This study also explores the step that succeeds the development of global emission pathways: i.e. the issue of differentiating post-2012 commitments, in other words, how to allocate the global emission reduction on a regional level. This quantitative analysis of allocation-based regime proposals is based on earlier work (e.g. den Elzen et al., 2005a; 2005b).

The analysis here focuses on four questions for climate-change policy-making:

1. What are the emission pathways compatible meeting the EU two degree Celsius target, and what is the certainty of achieving this?
2. What is the effect of different assumptions made for the baseline and technological improvement rates of abatement potential and costs on the emission pathways, and their resulting emissions reductions and abatement costs?
3. What are the global and regional emission reduction implications?
4. What are the implications of a further delay in mitigation actions?

The next chapter presents the overall method used for this analysis of linking global emission pathways with climate targets. Chapter 3 contains the results of the analysis for various concentration stabilization targets, and analyses the impact of some of the major uncertainties (question 1). Chapter 4 presents the global abatement costs (question 2), while Chapter 5 analyses the regional emission implications based on a post-2012 climate regime for future commitments (question 3). Chapter 6 analyses questions with regard to the effects of a delay in emission reductions. The final chapter (Chapter 7) draws up several conclusions.

---

[5] These emission pathways were used in the EU research project 'Greenhouse gas reduction pathways in the UNFCC post-Kyoto process up to 2025', which forthwith will be known as the GRP study (Criqui et al., 2003).

2 Method for developing emission pathways with cost-effective multi-gas mixes

In order to assess the emission implications of different stabilization levels, this study presents new multi-gas emission pathways for the scenario period, 2000-2400, derived by a method for a cost-effective mitigation of emissions. This method calculates the cost-optimal mixes of greenhouse gas emission reductions for a given global emission pathway. The emission pathway is determined iteratively to match prescribed climate targets of any level, as described in detail below. It should be kept in mind though that this approach does not derive cost-effective pathways over the whole scenario period per se, but focuses on a cost-effective split among different greenhouse gas reductions for given emission limitations on GWP-weighted and aggregated emissions. For example, based on the current model version with static cost assumptions, we cannot make definitive judgments on how a delay in global action will affect overall mitigation costs over time. However, the model framework surely accommodates an analysis of the existing policy framework with preset caps on Global Warming Potential (GWP)-weighted overall emissions under the assumption of cost-minimizing national strategies. The emissions that have been adapted to meet the pre-defined stabilization targets include those of all major greenhouse gases (fossil CO_2, CH_4, N_2O, HFCs, PFCs and SF_6, i.e. the so-called six Kyoto greenhouse gases), ozone precursors (VOC, CO and NO_x) and sulphur aerosols (SO_2).

For our method we used the policy decision support tool FAIR 2.0 in combination with another climate policy tool called SiMCaP.

The FAIR (Framework to Assess International Regimes for the differentiation of commitments) 2.0 model developed at the National Institute for Public Health and the Environment (RIVM) in the Netherlands (www.mnp.nl/fair) is a policy decision-support tool, which aims to assess the environmental and abatement costs implications of climate regimes for differentiation of post-2012 commitments (den Elzen and Lucas, 2003; 2005). For the calculation of the emission pathways, only the (multi-gas) abatement costs model of FAIR is used. This model distributes the difference between baseline and global emission pathway over the different regions, gases and sources following a least-cost approach, taking full advantage of the flexible Kyoto Mechanisms (emissions trading) (see den Elzen et al., 2005b). For this purpose, it makes use of (time-dependent) Marginal Abatement Cost (MAC) curves[6] for the different regions, gases and sources as described below. The FAIR model also uses baseline scenarios, i.e. potential greenhouse gas emissions in the absence of climate policies, from the integrated assessment model IMAGE[7] and the energy model, TIMER.[8]

The SiMCaP ('Simple Model for Climate Policy Assessment') developed at the ETH in Zurich, Switzerland (www.simcap.org). The SiMCaP pathfinder module makes use of an iterative procedure to find emission paths that correspond to a predefined arbitrary climate

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

[7] The IMAGE 2.2 model is an integrated assessment model consisting of a set of integrated models that together describe important elements of the long-term dynamics of global environmental change, such as agriculture and energy use, atmospheric emissions of greenhouse gases and air pollutants, climate change, land-use change and environmental impacts (IMAGE-team, 2001) (www.mnp.nl/image).

[8] The global energy model TIMER 1.0, as part IMAGE, describes the primary and secondary demand and production of energy and the related emissions of greenhouse gases and on a regional scale (17 world regions) (de Vries et al., 2002).

target. The global climate calculations make use of the simple climate model, MAGICC 4.1 (Wigley and Raper, 2001; 2002; Wigley, 2003). More specifically, the pathfinder module of SiMCaP makes use of an iterative procedure to find emission paths that correspond to a predefined arbitrary climate target.[9]

The integration of both models, the 'FAIRSiMCaP' 1.0 model, allows the strengths of both models to be combined to: (i) calculate the cost-optimal mixes of greenhouse gas reductions for a global emissions profile under a least costs approach (FAIR) and (ii) find the global emissions profile that is compatible with any arbitrary climate target (SiMCaP).

More specifically, the FAIRSiMCaP calculations consist of four steps (Figure 1):

1. Using the SiMCaP model to construct a parameterised global CO_2-equivalent emission pathway, which is here defined by sections of linear decreasing or increasing emission reduction rates R_I (initial 2010 value), R_x, R_y and R_z and years (X, Y and Z) at which the reduction rates change (see for a detailed description of the methodology Appendix A). This CO_2-equivalent emission pathway[10] includes the anthropogenic emissions of six Kyoto greenhouse gases. One exception is formed by the LUCF (land use and land use change related) CO_2 emissions; this because no MAC curves are available for these, although the option of sink-related uptakes is parameterised in FAIR as one mitigation option. The LUCF CO_2 emissions are described by the baseline scenario. Up to 2012, the pathway incorporates the implementation of the Annex I Kyoto Protocol targets for the Annex I regions excluding Australia and the USA.[11] Although the USA follows the proposed greenhouse-gas intensity target (White-House, 2002), this leads to emissions which do not significantly differ from their baseline emissions (van Vuuren et al., 2002).

2. The abatement costs model of FAIR is used to allocate the global emissions reduction objective (except LUCF CO_2 emissions): i.e. the difference between the baseline emissions and the global CO_2-equivalent emission pathway (see Figure 2) of step 1. Here a least-cost approach (cost-optimal allocation of reduction measures) is used for five year intervals over the 2000-2100[12] period for the six Kyoto greenhouse gases; 100-year GWP indices, different numbers of sources (e.g. for CO_2: 12; CH_4: 9; N_2O: 7) and seventeen world regions[13] are employed, taking full advantage of the flexible Kyoto Mechanisms – International Emissions Trading (IET), Joint Implementation (JI) and the Clean Development Mechanism (CDM).

[9] For further details such as assumptions with regard to natural forcing, see Meinshausen et al. (2004).

[10] The global baseline and emission pathways are expressed in CO_2-equivalent emissions, calculated using the emissions of the six greenhouse gases combined with the 100-year Global Warming Potentials (GWPs) (IPCC, 2001). Despite its limitations, the GWP concept is used here in a manner consistent with the current practices in policy documents, such as in the Kyoto Protocol.

[11] Here, we do not analyse the impact of other implementations of the Kyoto Protocol on the final emission pathways: i.e. (1) a 'strong' Kyoto implementation, in which the USA and Australia also implement their Kyoto targets and the emissions of economies in transition (Russia and Eastern European countries) follow the lower of their Kyoto targets and their baseline emissions, and their 'hot air' will not be sold, or a 'failure' of the Kyoto Protocol, in which all countries implement their baseline emissions, since implementation of both cases does not seem very realistic politically. The impact of these Kyoto implementations on the global CO_2 emission pathways aiming at 400, 450 and 550 ppm CO_2-only stabilization was analysed by Höhne (2005).

[12] After 2100, there are no marginal abatement cost estimates, but another methodology is followed. More specifically, the CO_2 equivalent emission reductions rates are assumed to apply to each individual gas, except where non-reducible fractions (0.7) have been defined (N_2O, CH_4).

[13] Calculations were done for 17 regions, i.e. Canada, USA, OECD-Europe, Eastern Europe, FSU, Oceania and Japan (Annex I regions); Central America, South America, the Middle East and Turkey (middle- and high-income non-Annex I regions); Northern Africa, Southern Africa, East Asia (incl. China) and South-East Asia (low-middle income non-Annex I regions); Western Africa, Eastern Africa and South Asia (incl. India) (low-income non-Annex I regions) (IMAGE-team, 2001).

Figure 2 shows the contribution of the different greenhouse gases in the global emissions reduction to, in this case, reach the 450 ppm CO_2-equivalent concentration level. The figure clearly shows that up to 2025, there are potentially large incentives for sinks and non-CO_2 abatement options (cheap options), so that the non-CO_2 reductions and sinks form a relatively large share in the total reductions. Later in the scenario period, the focus is more on the CO_2 reductions, and the contribution of most gases becomes more proportional to their share in baseline emissions. The emission pathways of the different greenhouse gases can then be constructed in this way.

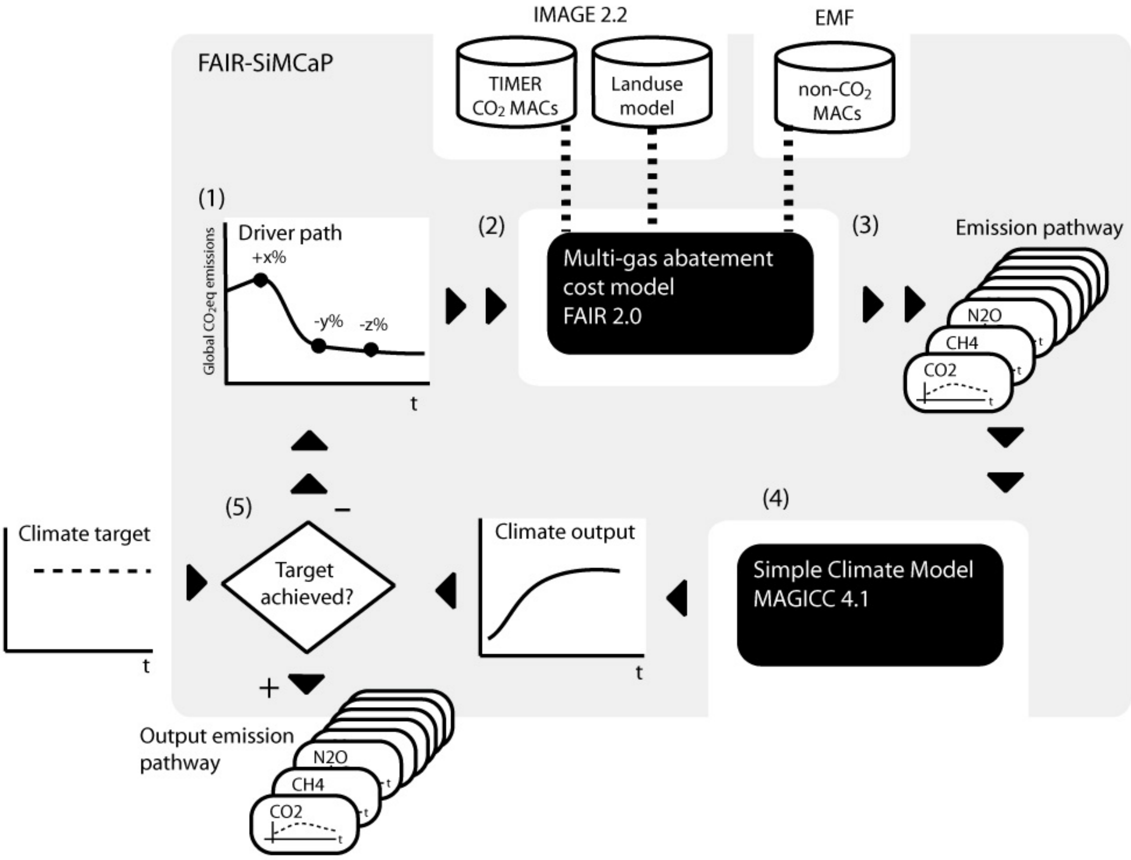


Figure 1. The FAIRSiMCaP model. The calculated global emission pathways were developed by using an iterative procedure as implemented in SiMCaP's 'pathfinder' module, using MAGICC to calculate the global climate indicators, the multi-gas abatement costs and the FAIR model to allocate the emissions of the individual greenhouse gases and the IMAGE 2.2 and TIMER model for the baseline emissions scenarios along with the MAC curves.

Different sets of baseline- and time-dependent MAC curves for different emission sources are used here. For energy- and industry-related CO_2 emissions (energy, feedstock and cement production), the impulse response curves calculated with the energy model, TIMER 1.0 (de Vries et al., 2002) are used. This energy model calculates regional energy consumption, energy-efficiency improvements, fuel substitution, and the supply and trade of fossil fuels and renewable energy technologies, as well as carbon capture and storage. A carbon tax on fossil fuels is imposed for constructing the MAC curves to induce emission abatements, taking into account technological developments, learning effects and system inertia (van Vuuren et al., 2004a). The TIMER response curves were calculated assuming a linear increase of the permit price after the first commitment period and the final value in the evaluation year. In this way, the MAC curves do take into account (as a first-order approximation) the time pathway of earlier abatement, although not dynamically. For CO_2 sinks the MAC curves of the IMAGE model are used (van Vuuren et al., 2004b).

For non-CO_2, exogenously determined MAC curves from EMF-21 (DeAngelo et al., 2004; Delhotal et al., 2004; Schaefer et al., 2004) are used. This set is based on detailed abatement options, and includes curves for CH_4 and N_2O emissions from both energy- and industry-related emissions and some agricultural sources, as well as abatement options for the halocarbons (see Appendix B). The non-CO_2 MACs were constructed mainly for 2010, and do not include technological improvements in time. Furthermore, the curves were constructed against a hypothetical baseline that assumes that no measures are taken in the absence of climate policy (‘frozen emission factors’). Therefore, the non-CO_2 MAC curves have been corrected for measures already applied under our baseline scenario; this is to increase consistency within the analysis (see van Vuuren et al., 2003 for the methodology used). Finally, increases are assumed in the abatement potentials due to the technology process and removal of implementation barriers. Here, a relatively conservative value of an increasing potential (at constant costs) due to technology progress and removal of implementation barriers for all other non-CO_2 MAC curves of 0.4% per year is assumed (simply incorporated by multiplying the MAC curves by this technological rate, as illustrated in Figure 3 (Graus et al., 2004; van Vuuren et al., 2004b). There are still some remaining agricultural emission sources of CH_4 and N_2O, where no MAC curves were available (e.g. for N_2O agricultural waste burning, indirect fertiliser, animal waste and domestic sewage). As it is unlikely that these sources will remain unabated under ambitious climate targets, we assumed a linear reduction towards a maximum of 35% compared to baseline levels within a period of 30 years (2040).

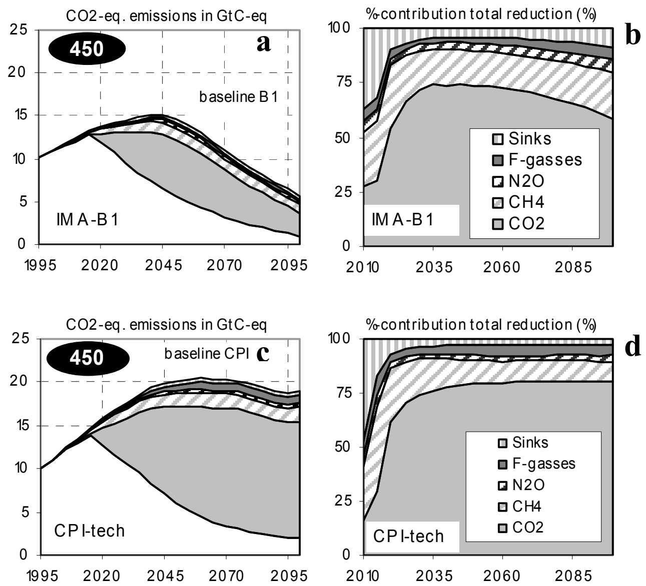


Figure 2. Contribution of greenhouse gases in total emission reductios under the emission pathways for a stabilization at 450ppm CO_2-equivalent concentration of the IMA-B1 (a,b) and CPI+tech scenario (c,d).

Finally, in addition to the end-of-pipe measures, as summarized in the non-CO_2 MAC curves, CH_4 and N_2O emissions can also be reduced by systemic changes in the energy system (for instance, the reduction in the use of coal and/or gas reduce CH_4 emissions during production and transport of these fuels). As seen in van Vuuren et al. (2004b) we account for these effects by a coupled analysis of the FAIR and TIMER models. It should be noted, however, that the total impact of these indirect reductions are relatively small (a maximum of about 0.1-0.2 GtC) (compared to the overall reduction objective of more than 10 GtC in 2050) and have therefore not been taken into account in the analysis here. For a detailed description of the MAC curves we refer to van Vuuren et al. (2004a; 2004b).

3. The greenhouse gas concentrations, and global temperature and sea level rise are calculated using the simple climate model MAGICC 4.1.

4. Within the iterative procedure of the SiMCaP model, the parameterizations of the CO_2-equivalent emission pathway (step 1) are optimized (repeat step 1, 2 and 3) until the climate output and the prescribed target show sufficient matches.

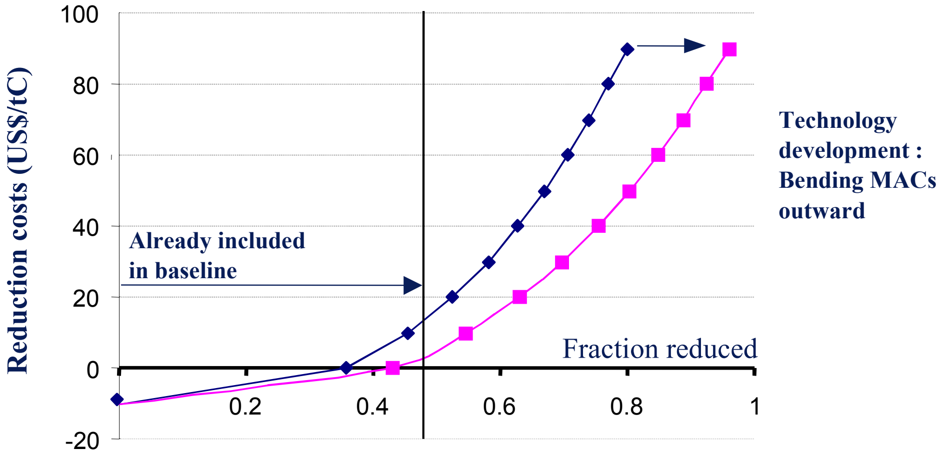


Figure 3: Incorporation of Marginal Abatement Curves in FAIR 2.0 (van Vuuren et al., 2004b). Note: The marginal abatement curves are corrected for the improvements already assumed in the baseline scenario, and bend outward in time as a result of technology development.

These emission pathways have been developed for three underlying baseline scenarios:

1. CPI: the Common POLES IMAGE (CPI) baseline (van Vuuren et al., 2003; van Vuuren et al., 2004b) scenario with the fixed LUCF CO_2 emissions of this scenario (Appendix C) and with the default MAC curves . The CPI scenario assumes a continued process of globalization, medium technology development and a strong dependence on fossil fuels. This corresponds to a medium-level emissions scenario when compared to the IPCC SRES emissions scenarios (Figure 2c).

2. CPI+tech: the CPI baseline scenario with the fixed LUCF CO_2 emissions of the IMA-B1 scenario (less deforestation) and with MAC curves assuming additional technological improvements. As current studies (e.g., Azar et al., 2004; Nakicenovic and Riahi, 2003) indicate that more technological improvements in abatement potential and reduction costs are possible than assumed in the CPI baseline, we have analyzed the impact of more optimistic assumptions. For this, we made the following, rather arbitrary, assumptions: (1) for the MAC curves of energy CO_2, an additional technological improvement factor of 0.2%/year; (2) for the MAC curves of the non-CO_2 gases, a technological improvement rate of 1%/year instead of 0.2%/year and (3) for the sources of non-CO_2 gases, where no MAC curves were available, a maximum reduction of 80% instead of 30% in 2040.

3. IMA-B1: the IMAGE IPCC SRES B1 baseline (IMAGE-team, 2001) scenario with the fixed LUCF CO_2 emissions of this scenario and the default MAC curves (Appendix C). This scenario assumes continuing globalisation and economic growth, and a focus on the social and environmental aspects of life. The baseline emissions are given in Figure 2a;

The CPI scenario has been selected as this is a medium-level emissions scenario, also used in our earlier study (Eickhout et al., 2003) and the GRP study (Criqui et al., 2003). Here, two additional baselines, namely CPI+tech and IMAGE B1 have been selected for two reasons. First of all, emissions are uncertain and the two scenarios explore the situation of more optimistic improvements of the abatement potential and reduction costs. Secondly, there might be reasons why climate policies could inevitably shift the 'baseline', i.e. the development of future emissions in case no further climate policies were undertaken. The method used in our study intends to capture these effects, but may underestimate its consequences. In addition, there is some evidence that technological 'lock-in' effects might cause low-emissions paths being achievable at very low additional costs (Gritsevskyi and Nakicenovic, 2000). Obviously, with lower baseline scenarios, it will be easier to achieve ambitious mitigation pathways. In fact, the combination of the CPI baseline and the standard set of MAC curves renders the derivation of 450 and 400 ppm CO_2-equivalent stabilization levels impossible.

3 Emission pathways and their transient temperature implications

3.1 CO_2-equivalent concentration and radiative forcing

This chapter presents various global multi-gas emission pathways for stabilization at CO_2-equivalence levels[14] of 550 ppm (3.65W/m^2), 500ppm (3.14W/m^2), 450 ppm (2.58W/m^2) and 400 ppm (1.95W/m^2). The latter three pathways are assumed to peak at 525 ppm (3.40W/m^2), 500 ppm (3.14W/m^2) and 480 ppm (2.92W/m^2) before they return to their ultimate stabilization levels around 2150 (Figures 4 and 5). This peaking is partially reasoned by the already substantial present net forcing levels (Hare and Meinshausen, 2004) and the attempt to avoid drastic sudden reductions in the emission pathways presented. These lower two stabilization pathways are within the range of the lower mitigation scenarios in the literature (Swart et al., 2002; Nakicenovic and Riahi, 2003; Azar et al., 2004; Hare and Meinshausen, 2004) (Figure 5).

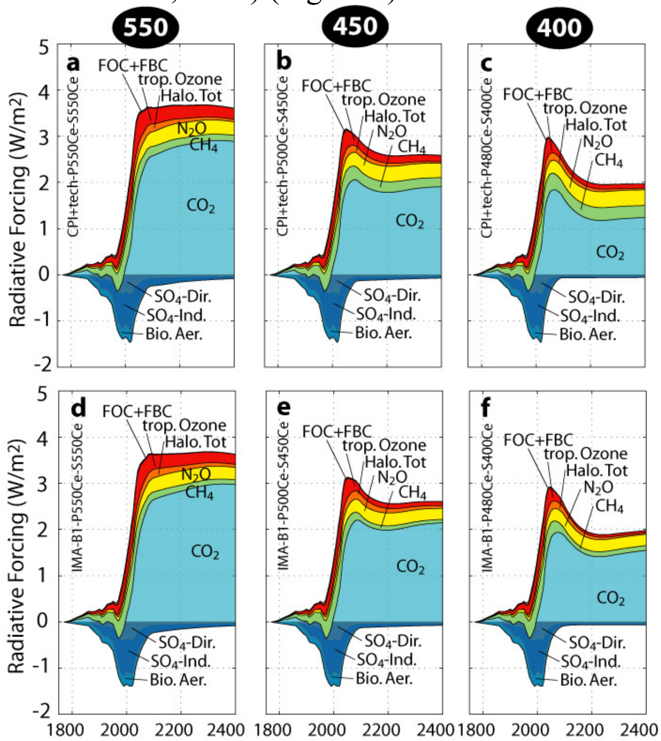


Figure 4. The contribution to net radiative forcing by the different forcing agents under the three default emission pathways for a stabilization at (a,d) 550, (b,e) 450 and (c,f) 400 ppm CO_2-equivalent concentration after peaking at (b,e) 500 and (c,f) 475 ppm, respectively for the (a-c) CPI+tech and (d-f) IMA B1 baseline scenarios. The upper line of the stacked area graph represents net human-induced radiative forcing. The net cooling due to the direct and indirect effect of SOx aerosols and aerosols from biomass burning is depicted by the lower negative boundary, on top of which the positive forcing contributions are stacked (from bottom to top) by CO_2, CH_4, N_2O, fluorinated gases (including the cooling effect due to stratospheric ozone depletion), tropospheric ozone and the combined effect of fossil organic and black carbon.

[14] As previously mentioned the CO_2-equivalent concentration is based on radiative forcing of all greenhouse gases, tropospheric ozone and aerosols, but not natural forcings (solar and volcanic forcing), whereas in our earlier study in Eickhout et al. (2003) CO_2-equivalent concentration is based on the radiative forcing of only the six Kyoto greenhouse gases. The impact of this difference together with other differences (some already discussed before, i.e. lower final concentration levels, peaking concentration strategy) on the final emission pathways will be discussed in Appendix D.

Figure 5 also shows CO_2-equivalent concentration profiles corresponding with a range of CO_2 concentration profiles due to different baselines and abatement potentials and costs. For example, 550 CO_2-eq. corresponds approximately with 475-500 CO_2 ppm, and 400 ppm CO_2-eq. corresponds with 350-375 ppm CO_2 only. As previously mentioned, no emission pathways for 450 and 400 ppm CO_2-eq. level were derived for the CPI baseline.

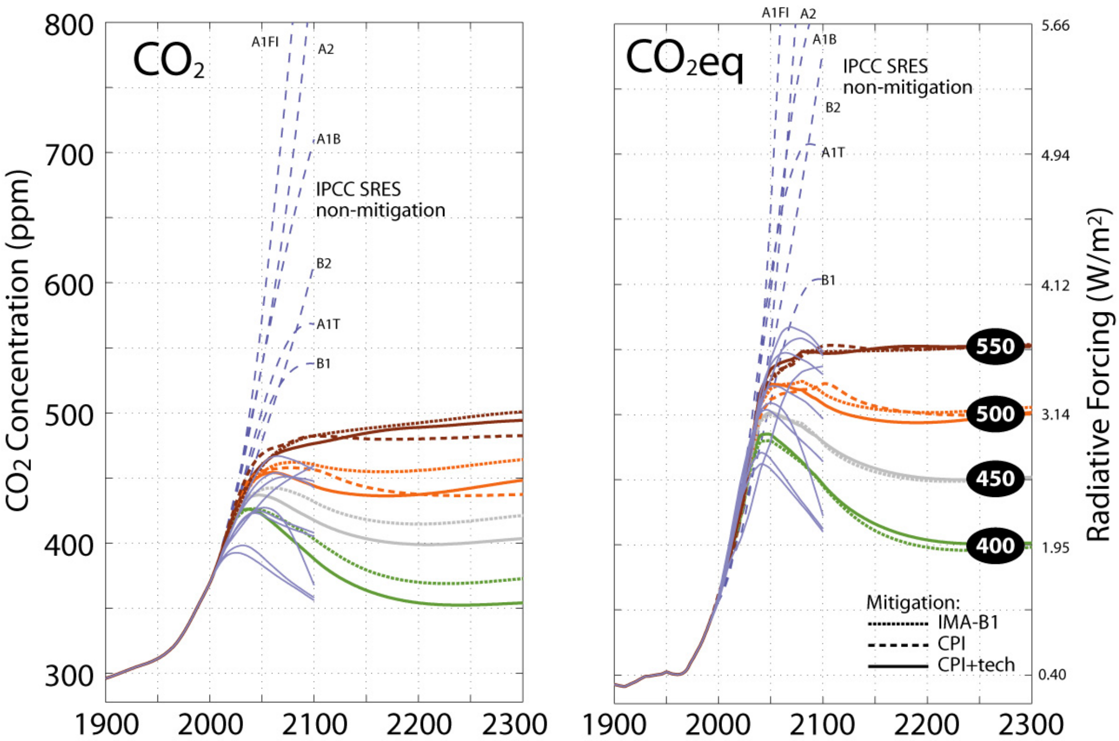


Figure 5. The CO_2 (a) and CO_2-equivalent (b) concentrations for the stabilization pathways at 550, 500, 450 and 400 ppm CO_2-equivalent concentrations for the three baseline scenarios (CPI, CPI+tech and IMA-B1). For comparison, the concentration implications of the IPCC-SRES non-mitigation scenarios (grey dotted lines) and the lower range of published mitigation scenarios (Azar et al., 2004; Nakicenovic and Riahi, 2003; Swart et al., 2002) (grey solid lines) are also plotted (see details in Hare and Meinshausen, 2004).

3.2 Temperature increase

Figure 6a shows the probabilistic temperature implications of the overshoot concentration profiles based on the climate sensitivity PDF of Wigley and Raper (2001)[15], for the emission pathways under the B1 scenario.[16] In these transient calculations, we included the natural forcings (i.e. solar and volcanic forcings) (see for more details, Hare and Meinshausen, 2004).[17] The results under the other scenarios are similar.

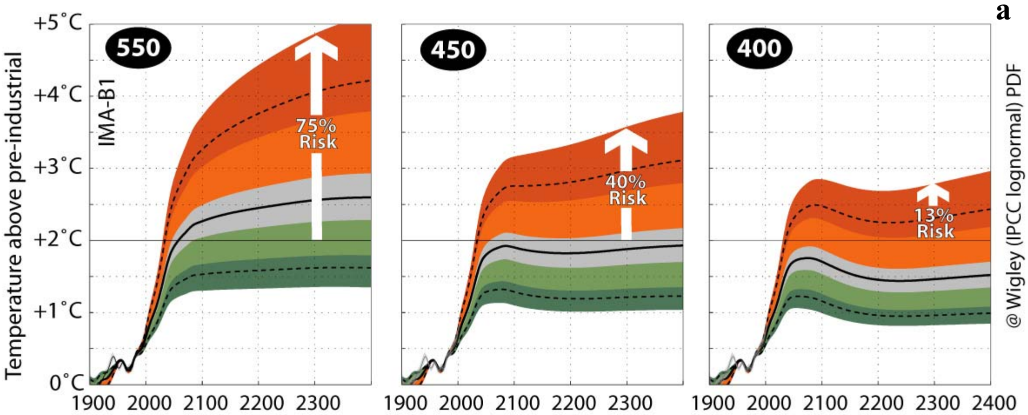
[15] The PDF of Wigley and Raper (2001) assumes the conventional 1.5 to 4.5°C climate sensitivity uncertainty range as being a 90% confidence interval of a lognormal PDF.

[16] The temperature projection for the emission pathway for 550 ppm CO_2-eq. for the median is already above 2 degree Celsius in 2100, which seems in contrast with the temperature projection below 2 degree Celsius of the emission pathway in 2100 for a stabilization at 550 ppm CO_2-eq. of our earlier study (Eickhout et al., 2003). The reasons for our higher projection now are: (i) the natural forcing that contributes about 0.2 to 0.3°C, if assuming the last 20-year average of solar forcing and the last 100 years of volcanic forcing, which are assumed here; (ii) the higher emissions in our emission pathway for 550 ppm CO_2-eq, and (iii) the use of a median estimate of 2.6°C climate sensitivity (instead of 2.5°C). Appendix D compares the emission pathways presented here in more detail with those of our earlier study.

[17] An exception has been made for the calculations on the risk of overshooting the 2°C target in equilibrium. There, equilibrium temperatures have been directly derived from anthropogenic radiative forcings (Hare and Meinshausen, 2004) (see, for example, Figure 6 - the number on the white arrows).

Due to the inertia of the climate system, the peak of radiative forcing (3.14W/m^2) before stabilization at 450 ppm CO_2-eq. (2.58W/m^2) does not translate into a comparable peak in global mean temperatures. However, for the 400 ppm CO_2-eq. stabilization pathway presented, the initial peak at 480ppm CO_2-eq. seems to be decisive with regard to the question of whether the 2°C or any other temperature threshold will be crossed (Figure 6).

Figure 6a shows that for a stabilization at 550 ppm CO_2-eq. (corresponding approximately to a 475 ppm CO_2 only stabilization), the risk of overshooting 3°C is still about 33%. There is even a risk of about 10% that 4°C is exceeded. The probability that warming exceeds 2°C is very high, approximately 75%. For the long-term stabilization at 500 ppm CO_2-eq. (approximately 450 ppm CO_2 stabilization) too, the probability of exceeding 2°C is likely, about 60% (not shown). Only for a stabilization at 400 ppm CO_2-eq. (approximately 350-375 ppm CO_2 stabilization) and, to a lesser extent, at 450 ppm CO_2-eq. (about 400 ppm CO_2 only stabilization), is the possibility of equilibrium warming exceeding 2°C strongly reduced, to less than about 13% and 40%, respectively. If a different uncertainty distribution is assumed, for example, the one by Murphy et al. (2004), the risk still sharply decreases with lower stabilization levels, although the risk of overshooting generally increases. Specifically, stabilization at 450 ppm CO_2-eq. would imply a risk of overshooting 2°C of about 78% (see Figure 6b).



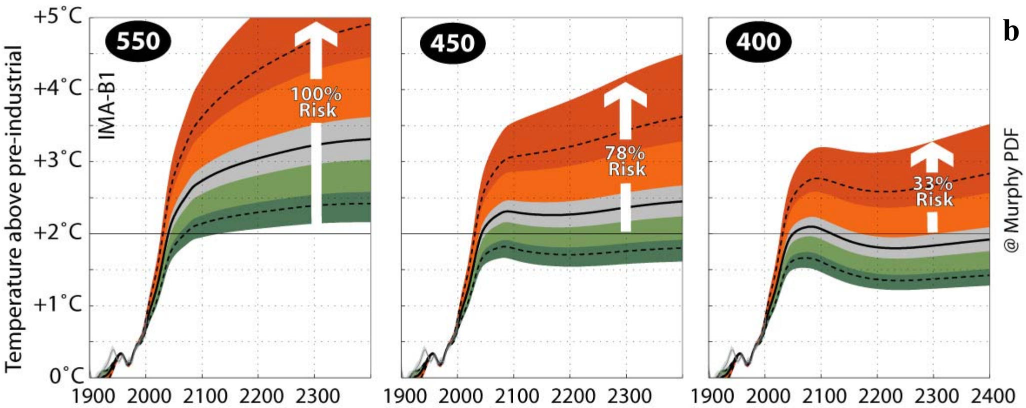


Figure 6. The probabilistic temperature implications for the stabilization pathways at (a) 550 ppm, (b) 450 ppm and (c) 400 ppm CO_2-equivalent concentrations for the B1 baseline scenario based on the climate sensitivity PDF by Wigley and Raper (2001) (IPCC lognormal) (top row) and the PDF by Murphy et al. (2004) (bottom row). Shown are the median (solid lines) and 90% confidence interval boundaries (dashed lines), as well as the 1%,10%,33%,66%,90%, and 99% percentiles (borders of shaded areas). The historical temperature record and its uncertainty from 1900 to 2001 is shown (grey shaded band) (Folland et al., 2001).

3.3 *Emission pathways*

The emissions of the pathways for stabilization at 550, 450 and 400 ppm CO_2-eq. concentrations can be summarized in their GWP-weighted sum of six Kyoto gases emissions, as illustrated in Figure 7. Clearly, there are different pathways that can lead to the ultimate stabilization level. Here, we assume that the global emission reduction rates should not exceed an annual reduction of 2.5%/year for all default pathways (at least not over longer time periods). The reason is that a faster reduction might be difficult to achieve given the inertia in the energy production system: electrical power plants, for instance, have a technical lifetime of 30 years or more. Fast reduction rates would require early replacement of existing fossil-fuel-based capital stock, which may be associated with large costs. A maximum rate of 2%/year is hardly exceeded for the majority of the post-SRES mitigation scenarios, apart from some lower stabilization scenarios (Swart et al., 2002; Eickhout et al., 2003; Nakicenovic and Riahi, 2003; Azar et al., 2004; Hare and Meinshausen, 2004). As a result of this assumed condition the departure from baseline emissions, reductions from the baseline takes place relatively early, and global emissions peak around 2015-2020.

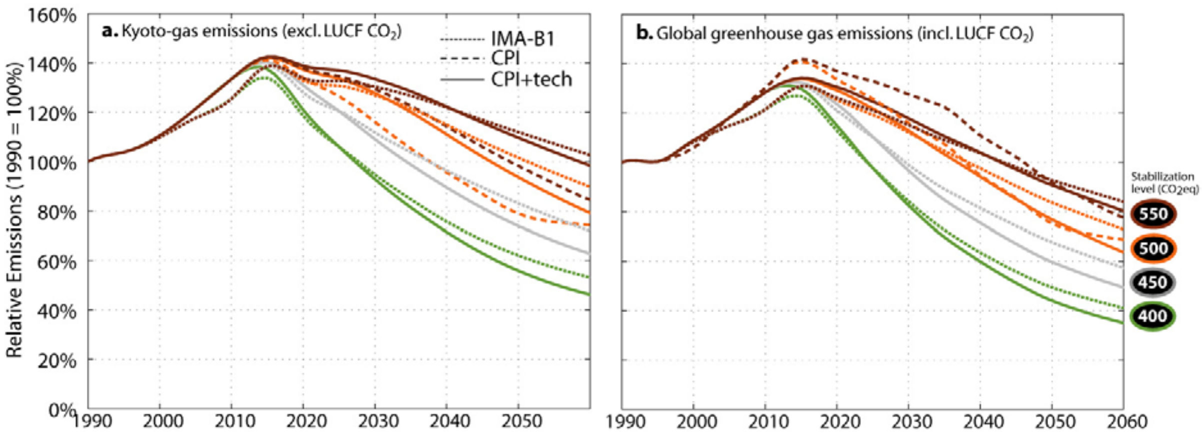


Figure 7. Global emissions relative to 1990 excluding (a) and including (b) LUCF CO_2 emissions for the stabilization pathways at 550, 500, 450 and 400 ppm CO_2-equivalent concentrations for the three scenarios (CPI, CPI+tech and IMA-B1).

For all stabilization pathways, the global reduction rates remain below 2.5%/year for the whole scenario period, except for the pathways at 400 ppm CO_2-eq., with maximum reduction rates of 2.5-3%/year over 20 years. Chapter 6 discusses the impact of a delay in the peaking of the global emissions on the final reduction rates.

As previously mentioned, all mitigation pathways assumed either the CPI LUCF CO_2 baseline emissions or those of the IMAGE B1 baseline. Thus, we left unchanged these baseline LUCF CO_2 emissions, based on a detailed calculation of landuse changes on the basis of regional consumption, production and trading of food, animal feed, fodder, grass and timber, with consideration of local climatic and terrain properties (IMAGE-team, 2001) (see Figure C.2, Appendix C).

Greenhouse gas emission reductions *excluding* and *including* LUCF CO_2 emissions are analyzed here. Given the assumption of these static LUCF scenarios with decreasing emissions, the quantified reduction requirements obviously differ, depending on whether the reduction requirements refer to all greenhouse gas emissions including LUCF CO_2 or Kyoto gas emissions (excl. LUCF CO_2). In general, emission pathways for the CPI+tech and B1 baselines have slightly higher greenhouse gas emissions (excl. LUCF CO_2) compared to the pathways under the CPI baseline for the same concentration target, because the LUCF CO_2 emissions for the CPI+tech and B1 scenario are assumed to be lower (see Figure C.2).

By 2050, global greenhouse gas emissions (excl. LUCF CO_2) will have to be near 40-45% below 1990 levels for stabilization at 40 ppm CO_2-eq. For higher stabilization levels, e.g. 450 ppm CO_2-eq. stabilization, greenhouse gas emissions (excl. LUCF CO_2) may be higher, namely 15-25% below 1990 levels (Table 1). For the CPI+tech scenario, the reductions for 400 ppm (450 ppm) CO_2-eq. are 50% (30%) in 2050 compared to 1990 levels. However, if LUCF CO_2 emissions do not decrease as rapidly as assumed here, but continue at presently high levels, an additional reduction of Kyoto-gas emissions (excl. LUCF CO_2) by around 10% are required up to 2050.

Global greenhouse gas emissions (incl. LUCF CO_2) will have to decrease to 5% to 10% below 1990 levels by 2050 for stabilization at 550 ppm CO_2-eq. For stabilization at 500 ppm CO_2-eq., global Kyoto-gas emissions would need to be 15 to 25% below 1990 levels in 2050. The reduction requirements now become as high as 50-55% and 30-40% below 1990 levels in 2050 to reach the 400 ppm and 450 ppm CO_2-eq. target, respectively (instead of 40-45% and 15-25%, respectively) (see Figure 7b). These reductions are about 10-15% higher than the reductions of the Kyoto gas emissions excluding LUCF CO_2.

In general, when we compare the reductions for the different concentration levels, we find that about 15-20% additional reductions by 2050 are needed for every 50 ppm lower stabilization level. We also see that higher near-term emissions need to be compensated by lower future emissions (compare CPI and CPI+tech with B1 of the 500 ppm level, for example).

Appendix C shows the emission pathways of the individual greenhouse gases for the stabilization pathways.

Table 1: Change of global GHG emissions (incl. and excl. LUCF CO_2 emissions) compared to 1990 levels (in %) (rounded to the nearest multiple of 5%).

	2020						2050					
	Incl. LUCF CO_2			Excl. LUCF CO_2			Incl. LUCF CO_2			Excl. LUCF CO_2		
Baseline	CPI	CPI+tech	B1	CPI	CPI+tech	B1	CPI	CPI+tech	B1	CPI	CPI+tech	B1
400ppm	–	15	15	–	20	20	–	-55	-50	–	-45	-40
450ppm	–	25	20	–	30	30	–	-40	-30	–	-25	-15
500ppm	35	30	25	35	35	35	-25	-25	-15	-20	-5	0
550ppm	35	30	25	40	40	35	-10	-10	-5	0	10	10

4 Global emission abatement costs

In its Third Assessment Report (TAR), the IPCC presents estimates for macro-economic costs (i.e. loss in GDP growth) of stabilization of the CO_2 concentration. For stabilization of the CO_2 concentration at 450 ppm (comparable to 500-525 ppm CO_2-eq.), GDP reductions for 2050 have to be 1.0-4.0% (see Figure 8.18 in Hourcade and Shukla (2001).The range is primarily derived from the assumption of different baseline scenarios (B1 to A1FI, respectively). These are global estimates, with some sectors and also regions (e.g. the oil-exporting regions) being likely to be more severely affected (e.g., van Vuuren et al., 2003).

These GDP costs have to be seen in perspective though. On the one hand, such long-term GDP abatement costs are approximately equivalent to a delay of only a couple of years with respect to a point in time, while the world might experience a twenty-fold increase in its GDP around 2100 compared to present levels (Azar and Schneider, 2002; 2003). Furthermore, the climate damage avoided and ancillary benefits are not included in such cost estimates, although they might be comparable in scale.

Here, we present some results of the global abatement costs as a percentage of world GDP for the different CO_2-equivalent concentration levels. Before presenting the costs, it should be noted that these costs only represent the direct-cost effects based on MAC curves but not the various linkages and rebound effects via the economy or impacts of carbon leakage. In other words, there is no direct link with macro-economic indicators such as GDP losses or other measures of income of utility loss. The cost figures are also very dependent on our assumptions about abatement potentials and reduction costs for all greenhouse gases. For a further discussions on the limitations, but also the strengths of this cost methodology we refer to den Elzen et al. (2005b).

Global costs increase for lower stabilization levels. The emission pathways show an increase of the costs up to 2050, and then a general decrease as GDP growth outstrips the growth in calculated abatement costs for most of the pathways (Figure 8).

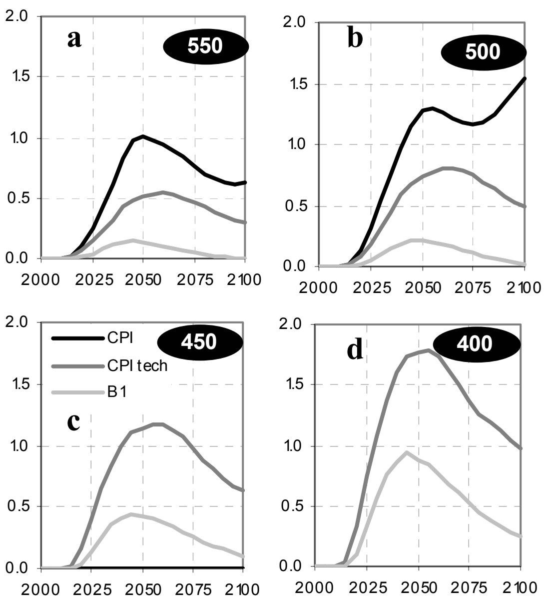


Figure 8. Global abatement costs as % of GDP for the stabilization pathways at (a) 550 ppm, (b) 500 ppm, (c) 450 ppm and (d) 400 ppm CO_2-equivalent concentrations for the three baseline scenarios (CPI, CPI+tech and IMA-B1).

The Figure also shows that the global abatement costs are even more influenced by the baseline emissions and the assumed improvements in technical change of the abatement potentials and costs than the final concentration stabilization level, as was also concluded by the IPCC. More specifically, the baseline emissions directly determine the reductions that are required to reach the emission profile for stabilization. The economic assumptions also obviously influence the relative cost measures such as GDP losses or abatement costs such as percentage of GDP.

Another crucial uncertainty is the rate at which the abatement costs for CO_2 and non-CO_2 emission reductions develop in time (compare the CPI and CPI+tech baseline scenario – see chapter 2). Given these uncertainties and limitations (mainly that ancillary benefits are not included and climate damage avoided), the results should be taken as qualitatively indicative, but not as quantitatively robust.

5 The regional emission implications

This chapter analyses the implications of the global emission pathways for the regional emission allowances for two international regimes for differentiating future (post-2012) commitments: the Multi-Stage and Contraction & Convergence approach using the FAIR 2.0 model. These regimes are outlined below:

(1) The *Multi-Stage approach* is an incremental but rule-based approach, which assumes a gradual increase in the number of Annex I Parties involved who adopting binding quantified emission intensity targets or absolute reduction objectives, whether absolute or dynamic (Berk and den Elzen, 2001; den Elzen, 2002). More specifically, the Multi-Stage approach here is based on three consecutive stages for the commitments of non-Annex I regions beyond 2012: i.e. Stage 1 – no commitment (baseline emissions), Stage 2 – emission limitation targets (intensity targets) and Stage 3 – absolute reduction targets. Participation thresholds are used for the transition from Stage 1 to 2, and from Stage 2 to 3 (see also den Elzen et al., 2005a; 2005b). Participation thresholds are based on a Capability–Responsibility index (e.g., Criqui and Kouvaritakis, 2000), and is defined as the sum of per capita GDP income (in PPP€1000 per capita[18]), which relates to the capability to act, and of per capita CO_2-equivalent emissions (in tCO_2 per capita), reflecting the responsibility in climate change. Current (2000) index values vary widely between countries, ranging from below 2 for Eastern and Western Africa, 4 for India and 8 for China, 11 for Central and South America, 12 for the Middle-East to as high as 29 for Europe and 54 for the USA.[19]
For Stage 2, the intensity improvement targets are defined as a linear function of per capita income level, and thereby relax the emission limitations for the low-income, non-Annex I regions. A maximum rate is adopted to avoid de-carbonization rates that would outpace those of economic growth, here this is 3% at 50% of 1995 Annex I per capita GDP income (in PPP€). In Stage 3, the total reduction effort to achieve the global emissions profile is shared by all participating regions on the basis of a burden-sharing key (here, per capita emissions). All Annex I regions (including the USA)[20] are assumed to have reached Stage 3 after 2012.

(2) The *Contraction & Convergence* approach assumes universal participation and defines emission allowances on the basis of convergence of per capita emission allowances (starting after 2012) in 2050 for all countries under a contracting global emissions profile (Meyer, 2000).

The Contraction & Convergence approach is the most widely known, transparent and comprehensive approach, and has much appeal in the developing world. The Multi-Stage approach is selected here, as this approach best satisfies the various types of criteria

[18] GDP levels of different countries are normally compared on the basis of conversion to a common currency using Market Exchange Rates (MER). However, this is known to underestimate the real income levels of low-income countries. Therefore, an alternative conversion has been developed on the basis of purchasing power parity (PPP). Here, we have usually used PPP-based GDP estimates; however, MER-based estimates for comparison were used where required.

[19] The CR values for 2025 under the CPI baseline scenario for the non-Annex I regions are: 5 for Eastern and Western Africa, 10 for India and 18 for China, 17 for Central and South America and 18 for the Middle East (see for more details den Elzen et al., 2005a).

[20] Obviously, there is no certainty that this will happen. However, it is hard to conceive of any global climate regime that is compatible with stabilising GHG concentrations at 550 ppmv equivalent or lower if the USA decides against joining the international effort to reduce emissions, even after 2012. This is analysed in Chapter 6.

(environmental, political, economic, technical, institutional) in the multi-criteria evaluation of various approaches by Höhne et al. (2003) and den Elzen et al. (2003).

The basic methodology of the analysis consists of two steps:
1. starting with a baseline emissions scenario and a global emission pathway; defining the global emission reduction objective;
2. calculating regional emission reduction targets for the two regimes within the context of this global reduction objective.

The reference cases of the Multi-Stage and Contraction & Convergence for the 550 ppm pathway are described in detail in den Elzen et al. (2005a; 2005b), and correspond to the cases in the EU research project 'Greenhouse gas reduction pathways in the UNFCC post-Kyoto process up to 2025' (Criqui et al., 2003). As for the 550 ppm concentration pathway, the Multi-Stage parameters are chosen such that the Annex I countries take the lead in the reduction efforts compared to the baselines, followed by the middle- and high-income non-Annex I regions and, finally, the low-income non-Annex I regions (Table 2).

Table 2: The reference cases of the Multi-Stage and Contraction & Convergence regimes for the four CO_2 equivalence stabilization pathways

	Parameters	400 ppm	450 ppm	500 ppm	550 ppm
Multi-Stage	• First participation threshold for stage 2	CR[a] index = 2	CR index = 3	CR index = 4	CR index = 5
	• Second participation threshold for stage 3	CR index = 9	CR index = 10	CR index = 11	CR index = 12
Contraction & Convergence	• Convergence year	2050	2050	2050	2050

[a] CR = Capability–Responsibility

The Annex I commitments need to be intensified in all cases after 2012 (see Figures 9 and 10). In 2020, Annex I Kyoto-gas emissions[21] need to be reduced by approximately 25-30% in comparison with 1990 levels for 400 ppm, and approximately 15-20% for 450ppm stabilization. The reductions compared to the CPI baseline are about 10-15% higher. In 2050, the reductions below 1990 levels stand at about 90% (400 ppm) and 80% (450 ppm), respectively.

Most non-Annex I regions will need to reduce their emissions by 2020 compared to baseline levels, but emissions can increase compared to 1990 under all regimes analysed. For non-Annex I regions, the results are generally more differentiated for the various commitment schemes and time horizons (2020 versus 2050) than for Annex I regions. For the low-income regions (Southern Asia (India), Western Africa and Eastern Africa (not shown)), the reductions in 2020 are less than 10% compared to the baseline level for all stabilization pathways. Emission allowances for these regions may even exceed baseline emissions for these low-income regions under 500 ppm and 550 ppm CO_2-eq. for the Contraction & Convergence regime. For the middle- and high-income non-Annex I regions, the reductions compared to the baseline emissions in 2020 are below the reductions for the Annex I regions, about 20-25% and 30-40% for 450 and 400 ppm, respectively, but increase to about 70% and

[21] Kyoto gas emissions are here defined as including fossil CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6 emissions; GWP-weighted; excluding LUCF CO_2 emissions.

80% for 450 and 400 ppm, respectively by 2050. These reductions are still less than the Annex I reductions compared to their baseline emissions.

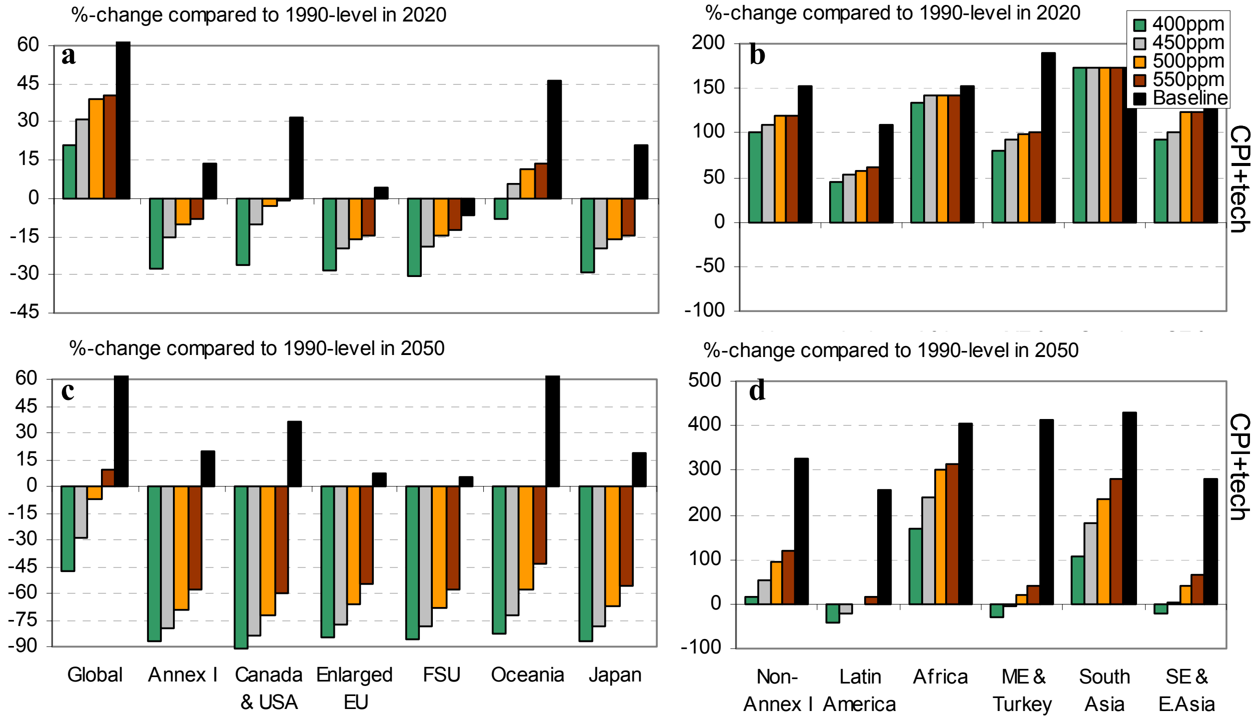


Figure 9. Change in Kyoto-gas emission allowances (excluding LUCF CO_2 emissions) before emissions trading from 1990 to 2020 (upper) and 2050 (lower) for the Annex I regions (a,c) and non-Annex I regions (b,d) under the Multi-Stage approach for the stabilization pathways at 550, 500, 450 and 400 ppm CO_2-equivalent concentrations for the CPI+tech scenario.

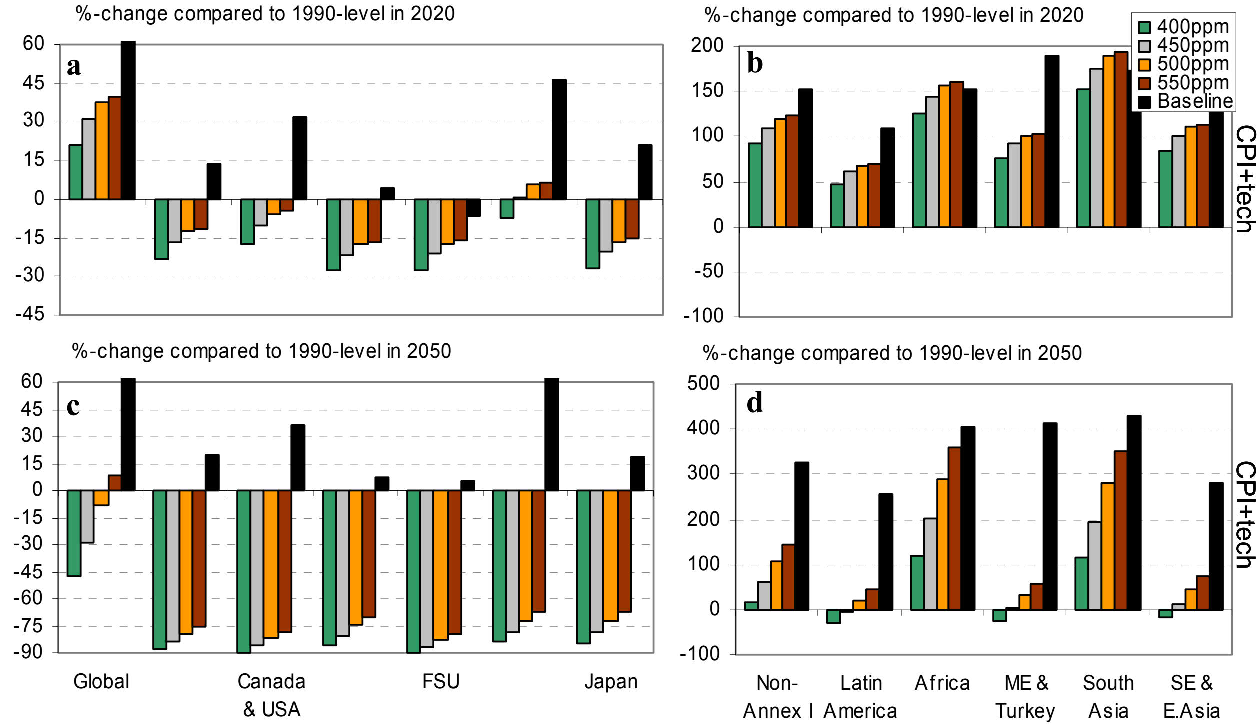


Figure 10. Same as Figure 9, but now under the Contraction & Convergence regime.

Stabilization levels versus regime – In comparing Figures 9 and 10 we also see that the average emission reductions over the two regimes for each region are more influenced by the assumed stabilization pathways than by the regime options explored. In general, the Multi-Stage cases give quite similar results to the Contraction & Convergence case. The main difference is the somewhat higher reductions for the Annex I and middle- and high-income non-Annex I regions by 2020 under Multi-Stage, as these regions have to compensate the surplus emissions (hot air) of the low-income regions. Similar to the Contraction & Convergence case, the Multi-Stage case leads, to some convergence in the per capita emissions by around 2050 too as a result of the applied burden-sharing key based on per capita emissions. This is not a full convergence, though, and therefore, the reductions of the Annex I regions are, in the long-term (2050), somewhat less under the Multi-Stage regime.

6 The impact of further delay in emission reductions

6.1 Delay in peaking of global emissions

To underscore the importance of early action, an analysis was performed, in which the date of global emissions peaking is delayed. Figure 11 shows the emissions of the Kyoto gases (including LUCF CO_2 emissions) applied to the different delayed simulations for stabilization at 400 ppm and 450 ppm CO_2-eq. The default and the sensitivity pathways imply by construction the same risk of overshooting 2°C.[22] Specifically, emissions peak around 2015 under the default pathway, and at a 5% higher peak at 2015 for the first sensitivity pathway and around 2020 for the second delayed pathway. For 450 ppm, emissions peak at 2015 for default pathway '0' and pathway '1' and 2020 for pathways '2', and '3', with pathways '1' and '3' assuming a slower decrease after peaking compared to '0' and '4' (Figure 11). Absolute levels turn out lower than the default pathway around 2040 in order to compensate for the initially higher emissions. Not only will absolute emission levels beyond 2050 have to be lower under the delayed emission pathways, but the required emission reduction rates around 2025 will also have to be steeper. If we delay the peaking of the global emissions until 2020, this needs to be compensated by steeper maximum reduction rates hereafter, i.e. in the order of 5.4%/year for 400 ppm CO_2-eq. and 3.9%/year for 450 ppm CO_2-eq., for at least 20 years. Another five-year delay for the 450 ppm target also leads to maximum reduction rates in the order of 5%/year.

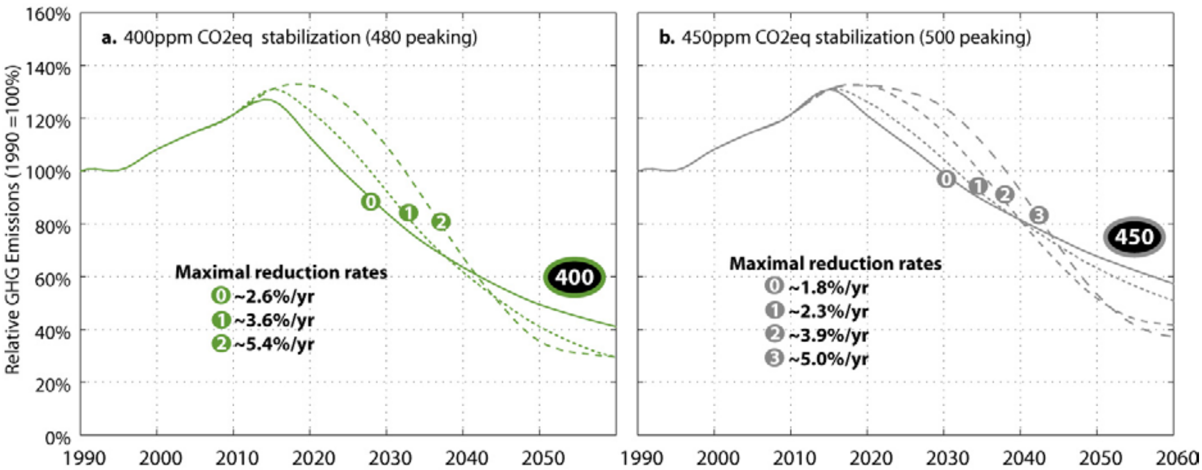


Figure 11. The impact of delaying action for greenhouse gas emission reductions (incl. LUCF CO_2) for the stabilization pathways at (a) 450 ppm and (b) 400 ppm CO_2-equivalent concentrations for the baseline scenario IMA-B1. The delayed paths (1,2,3) meet the condition that the risk of overshooting 2°C is not increased compared to the default path (0).

Concluding, global emissions will have to peak in 10 to 15 years to limit the risk of overshooting 2°C to reasonable levels. The consequences of delay are lower absolute emissions after around 2050, and steeper maximal reduction rates from as early as 2020 and 2025.

[22] Practically speaking, the condition imposed on the delayed emission pathways was that they would have to peak at the same temperature level as in the default scenario.

6.2 *The impact of a further delay in USA involvement in emission reductions*

A special case of a further delay in emission reductions is a further delay in the USA involvement in the emission reductions. In the previous calculations of future commitments, we assumed that the USA would participate in the reductions from 2012 onwards, and thus re-enters in the post-2012 regime for differentiation of future commitments. However, a change in the USA position under the Bush administration is very unlikely. A change of USA involvement seems possible for a subsequent administration, at the earliest after the next presidential elections (2008), though. Even then, the timing of emission reductions to be expected by the USA is very uncertain. Here, we want to explore two possible scenarios, besides the re-entrance case of the USA from 2012 onwards. The first scenario assumes that the USA does not take on commitments for at least the coming two decades after 2012. A second scenario assumes the USA adopts the target proposed in the Senate Bill 139 (S.139), the Climate Stewardship Act of 2003. This legislation, proposed by USA Senators McCain and Lieberman, is the most detailed effort to date to design an economy-wide cap-and-trade system for USA greenhouse gas emissions reductions. The Act caps sectors at their 2000 emissions in Phase I of the program, running from 2010 to 2015, and then to their 1990 emissions for Phase II starting 2016. The program would apply to greenhouse gas emissions from major sectors – electric utilities, transportation, and industry – covering roughly 80% of USA emissions. Several economic and policy analyses have been performed in the past (e.g., EIA, 2003; Paltsev et al., 2003; Berk and den Elzen, 2004). Here, we will also analyse the impact of the re-entrance of the USA under the Climate Stewardship Act. In our calculations we assume the same trajectory of the total greenhouse gas emissions as estimated in EIA (2003), i.e. a return of USA total greenhouse gas emissions to 2000 levels by 2025, with the gradual decline in USA total emissions starting in 2012.

Here, we want to explore two possible cases, besides the re-entrance case of the USA from 2012 (default Case 0) onwards:

- Case 1 ('USA and non-Annex I no action'): the USA (and Australia) just follow their baseline emissions for at least the following two decades. No non-Annex I Parties take on commitments beyond 2012.
- Case 2 ('USA Lieberman-McCain and advanced non-Annex I action'): the USA follows our implementation of the Lieberman-McCain Climate Stewardship Act of 2003 (S.139)[23], with the USA total greenhouse gas emissions reaching 2000 levels by 2025. Australia and the non-Annex I regions with a CR-index above 12 (advanced or middle- and high- income regions) adopt income-dependent intensity targets after 2012 (Stage 2 of Multi-Stage). The same holds for the USA after 2025.

For both cases the EU and the rest of the Annex I share the total reductions needed to achieve the global emission pathway for the stabilization pathways at 550, 500, 450 and 400 ppm CO_2-equivalent concentrations, as summarized in Table 3 and illustrated in Figure 12. Here, also the results of Case 0, US re-entrance by 2012, are given for comparison. The analysis uses the emission pathways under the CPI+tech scenario, which basically employs the CPI as baseline emission scenario (see Chapter 2), as this is a medium-level scenario. The reductions presented in this section are baseline-dependent, and will be less under the B1 scenario.

For Case 1, the EU and the rest of Annex I have to reduce emissions by more than 55% for 550 ppm in 2020 compared to 1990 levels and to more than 95% for 400 ppm. By the year 2030, their emissions reach zero levels. Figure 12 shows the world emissions to outgrow the emission pathway of 400 and 550 ppm CO_2-eq. by 2025 and 2030, respectively.

[23] See: http://www.climatenetwork.org/csa.htm, for links to useful resources about the bill.

For Case 2, the EU and the rest of Annex I need to reduce their emissions by 35-40% in 2020 for the 500 and 550 ppm targets, whereas for 400 and 450 ppm the reductions are more than 55% (450 ppm) to 80% (400 ppm). By the year 2030, the zero emission levels are reached for 400 and 450 ppm, and reductions are more than 50% for the higher concentration levels.

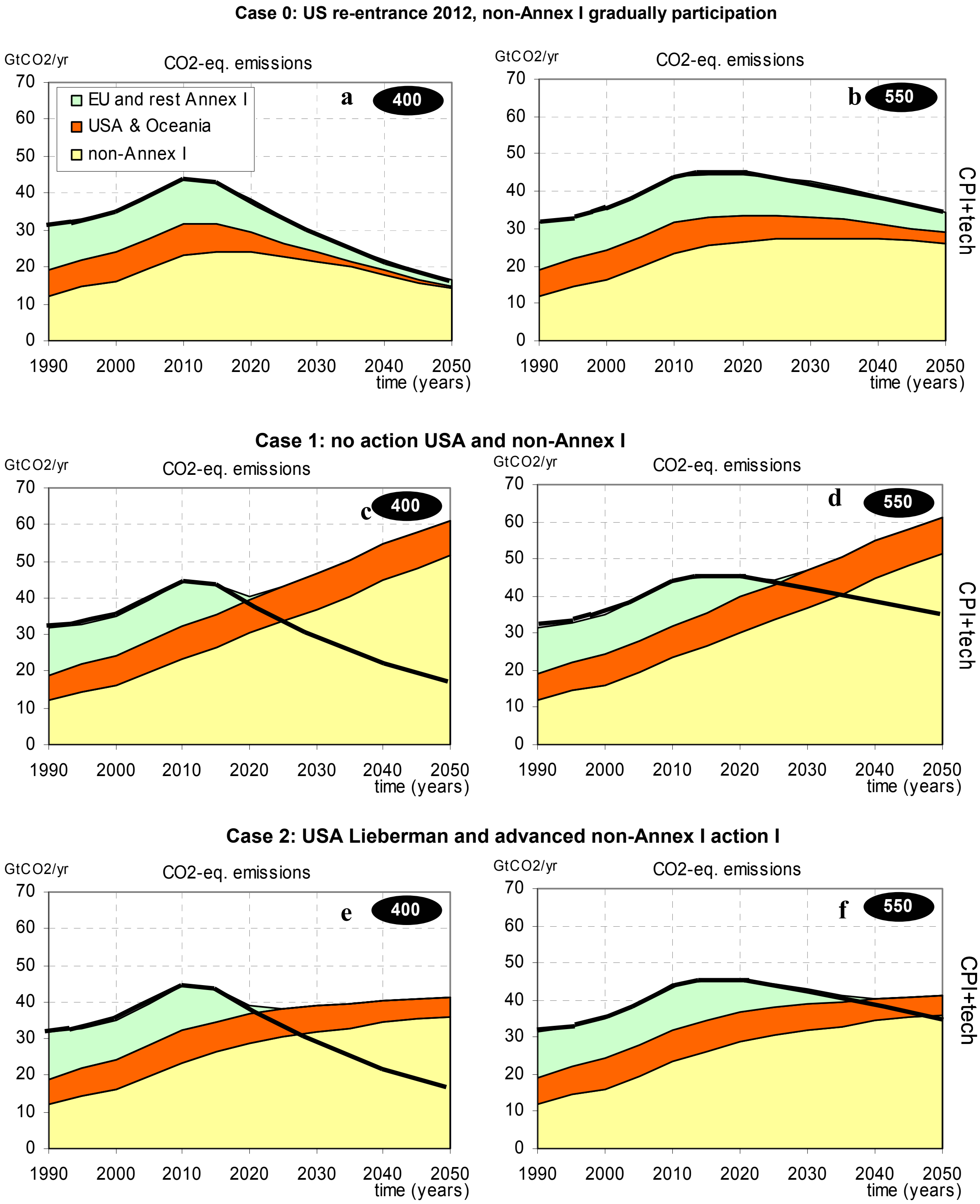


Figure 12. The impact of 2012 re-entrance of the USA (Case 0) versus no or partial involvement of the USA (Case 1 and 2) in the emission reductions for the stabilization pathways (excluding LUCF CO_2) at 400 ppm (a,c,e) and 550 ppm (b,d,f). The point where the stacked emissions surpass the stabilization pathways (black bold line) indicates the date on which world emissions outgrow the emission pathway.

Table 3: The total emission reduction targets below 1990 levels (in %) for the enlarged EU for the four stabilization pathways for the default emission pathways for the CPI+tech scenario. Note: the rest of the Annex I Parties (Canada, FSU and Japan) show similar reductions.

	Stabilization level	2020	2025	2030
Case 0: Default (all Parties participate gradually)	400ppm	-29	-45	-59
	450ppm	-20	-32	-45
	500ppm	-16	-23	-30
	550ppm	-15	-20	-26
Case 1: USA and non-Annex I no action	400ppm	**X**	**X**	**X**
	450ppm	-79	**X**	**X**
	500ppm	-61	**X**	**X**
	550ppm	-57	-92	**X**
Case 2: USA Lieberman-McCain and advanced non-Annex I action	400ppm	-82	**X**	**X**
	450ppm	-54	**X**	**X**
	500ppm	-38	-58	-82
	550ppm	-34	-49	-66

***X**= reductions of more than 95% (almost zero emission allowances).*

This analysis clearly shows that partial or no involvement of the USA in the reductions in the coming two decades will lead to ‘unrealistic’ fast and deep emission reduction commitments for the EU and the rest of Annex I in order to achieve the low stabilization levels. Such deep reductions seem politically, technically and economically unfeasible. In order to keep the options open for achieving the 2°C target with a reasonable certainty, it is necessary to have much more substantial USA involvement in the reductions than formulated in the McCain-Lieberman Bill. The more advanced non-Annex I countries (big emitters, such as China) will also need to take on reduction commitments before 2025.

7 Conclusions

This study describes a method to derive multi-gas pathways that closely reflects the existing international framework of pre-set caps on aggregated emissions and individual cost-optimising actors. Thus, cost-optimal mixes of greenhouse gases reductions are derived for a given global emission pathway. The presented emission pathways stabilize CO_2-equivalent concentration at 550, 500, 450 and 400 ppm. Here, we follow a 'peaking strategy', allowing concentrations to peak then decrease before stabilising, i.e. going up to 480-500 ppm CO_2-equivalent before going down to levels such as 400 or 450 ppm equivalent later on.

As previously shown (see e.g. Hare and Meinshausen, 2004) emission pathway leading to a 550ppm CO_2-equivalent stabilization is unlikely to meet the climate target of limiting global mean temperature rise to 2°C above pre-industrial levels (EU 2°C target). In order to achieve such the EU 2°C target with a probability of more than 85% (60%) (assuming the probabilistic density function of Wigley and Raper, 2001), greenhouse gas concentrations need to be stabilized below 450 (400) ppm CO_2-equivalent or lower. This, in turn, requires global emissions to peak around 2015 in order to avoid global reduction rates exceeding more than 2.5%/year, followed by substantial overall reductions by as much as 40 to 45% (15 to 25%) in 2050 compared to 1990 levels, excluding LUCF CO_2 emissions. The reduction requirements become as high as 50 to 55% (30 to 40%) below 1990 levels in 2050 for all greenhouse gas emissions, including LUCF CO_2.

The analysis here shows that abatement costs will depend heavily on the emission growth in the baseline scenario, as well as on further developments of the abatement potential and reduction costs for all greenhouse gases in the future. Along with this, early action to achieve the benefits from learning and induced technological progress, as well as the removal of implementation barriers, are likely to highly influence the costs of mitigation efforts to achieve certain climate targets. The allowable delay in the peaking emissions is limited, less than 5-10 years delay. In order to avoid climate impacts that are associated with a global mean temperature rise of 2°C and more, the global emissions within the next two decades will need to be peaked.

The analysis of the regional emission implications of two post-2012 regimes for differentiating commitments, i.e. a convergence and multi-stage regime, for the default emission pathways shows that Annex I emissions in 2020 will need to be reduced by about 15-30% below 1990 levels for 400-450 ppm CO_2-eq. To realize these concentration levels major non-Annex I countries will have to participate in the reductions within the near future (next two decades).

The analysis of delaying global action shows that the emission reduction implications of a further delay in peaking of just five years could be significant, resulting in much steeper reductions from as early as 2020 and 2025. A delay in action to reduce emissions up to 2020-2025 leads to a doubling of the maximum rates of emission reductions to about 5%/year, in order to meet concentration levels of 450 ppm CO_2-equivalent or lower. Such high reduction rates are difficult to achieve, given the inertia in the energy production system, and will lead to large costs that would be associated with the premature retirement of existing fossil-fuel-based capital stock. Thus, in order to avoid climate impacts that are associated with a global mean temperature rise of 2°C and more, global emissions will need to peak around 2015. We also analysed a further delay in USA involvement in emission reductions. In order to keep the option open of stabilising concentrations at 400 and 450 ppm CO_2-equivalent, the participation of the USA and the advanced non-Annex I countries in the reduction commitments well before 2025 is needed. Otherwise, 'unrealistic' rapid and sharp emission reduction requirements for the EU and the rest of Annex I will be the result if the probability of overshooting 2°C shall be limited to reasonable levels.

References

ACIA, 2004. Impacts of a Warming Arctic - Arctic Climate Impact Assessment.

Allen, M. R. and Lord, R., 2004. The blame game - who will pay for the damaging consequences of climate change? Nature, 432: 2 December 2004.

Azar, C., Linddgren, K., Larson, E. and Möllersten, K., 2004. Carbon capture and storage from fossil fuels and biomass - Costs and potential role in stabilizing the atmosphere. Climatic Change (submitted).

Azar, C. and Schneider, S. H., 2002. Are the economic costs of stabilising the atmosphere prohibitive? Ecological Economics, 42(1-2): 73-80.

Azar, C. and Schneider, S.H., 2003. Are the economic costs of (non-)stabilizing the atmosphere prohibitive? A response to Gerlagh and Papyrakis. Ecological Economics, 46(3): 329-332.

Berk, M.M. and den Elzen, M.G.J., 2001. Options for differentiation of future commitments in climate policy: how to realise timely participation to meet stringent climate goals? Climate Policy, 1(4): 465-480.

Berk, M.M. and Elzen, M.G.J. den, 2004. What if the Russians don't ratify? RIVM report 728001028, National Institute for Public Health and the Environment, Bilthoven, the Netherlands (www.mnp.nl/ieweb).

Criqui, P., Kitous, A., Berk, M.M., den Elzen, M.G.J., Eickhout, B., Lucas, P., van Vuuren, D.P., Kouvaritakis, N. and Vanregemorter, D., 2003. Greenhouse gas reduction pathways in the UNFCCC Process up to 2025 - Technical Report. B4-3040/2001/325703/MAR/E.1 for the DG Environment, CNRS-IEPE, Grenoble, France.

Criqui, P. and Kouvaritakis, N., 2000. World energy projections to 2030. International Journal of Global Energy Issues, 14(1-4): 116-136.

Cubasch, U., Meehl, G. A., Boer, G. J., Stouffer, R. J., Dix, M., Noda, A., Senior, C. A., Raper, S. and Yap, K.S., 2001. Projections of Future Climate Change. In: J.T. Houghton et al. (Editors), Climate Change 2001: The Scientific Basis. Cambridge University Press, Cambridge, UK.

de Vries, H.J.M., van Vuuren, D.P., den Elzen, M.G.J. and Janssen, M.A., 2002. The Targets Image Energy model regional (TIMER) - Technical documentation. RIVM report 461502024, National Institute for Public Health and the Environment, Bilthoven, the Netherlands.

DeAngelo, B. J., DelaChesnaye, F. C., Beach, R. H., Sommer, A. and Murray, B. C., 2004. Methane and nitrous oxide mitigation in agriculture. Energy Journal (in press).

Delhotal, K. C., DelaChesnaye, F. C., Gardiner, A., Bates, J. and Sankovski, A., 2004. Mitigation of methan and nitrous oxide emissions from waste, energy and industry. Energy Journal (in press).

den Elzen, M.G.J., 2002. Exploring climate regimes for differentiation of future commitments to stabilise greenhouse gas concentrations. Integrated Assessment, 3(4): 343-359.

den Elzen, M.G.J., Berk, M.M., Lucas, P., Criqui, C. and Kitous, A., 2005a. Multi-Stage: a rule-based evolution of future commitments under the Climate Change Convention. International Environmental Agreements (in press).

den Elzen, M.G.J., Berk, M.M., Lucas, P., Eickhout, B. and Vuuren, D.P. van, 2003. Exploring climate regimes for differentiation of commitments to achieve the EU climate target. RIVM-report 728001023, National Institute for Public Health and the Environment, Bilthoven, the Netherlands (www.mnp.nl/ieweb).

den Elzen, M.G.J. and Lucas, P., 2003. FAIR 2.0: a decision-support model to assess the environmental and economic consequences of future climate regimes, www.mnp.nl/fair. RIVM-report 550015001, National Institute for Public Health and the Environment, Bilthoven, the Netherlands (www.mnp.nl/ieweb).
den Elzen, M.G.J. and Lucas, P., 2005. The FAIR model: a tool to analyse environmental and costs implications of climate regimes. Environmental Modeling & Assessment, accepted for publication.
den Elzen, M.G.J., Lucas, P. and van Vuuren, D.P., 2005b. Abatement costs of post-Kyoto climate regimes. Energy Policy, 33(16): pp. 2138-2151.
EIA, 2003. Analysis of S.139, the Climate Stewardship Act of 2003: Highlights and Summary. Energy Information Administration Report SR/OIAF/2003-02/S, Energy Information Administration, Washington, DC.
Eickhout, B., den Elzen, M.G.J. and van Vuuren, D.P., 2003. Multi-gas emission profiles for stabilising greenhouse gas concentrations. RIVM-report 728001026, National Institute for Public Health and the Environment, Bilthoven, the Netherlands (www.mnp.nl/ieweb).
Enting, I.G., Wigley, T.M.L. and Heimann, M., 1994. Future emissions and concentrations of carbon dioxide, Mordialloc, Australia.
European-Council, 1996. Communication on Community Strategy on Climate Change, Council Conclusions, European Council, Brussels.
European-Council, 2005. Presidency conclusions, European Council, Brussels.
Folland, C. K., Rayner, N. A., Brown, S. J., Smith, T. M., Shen, S. S. P., Parker, D. E., Macadam, I., Jones, P. D., Jones, R. N., Nicholls, N. and Sexton, D. M. H., 2001. Global temperature change and its uncertainties since 1861. Geophysical Research Letters, 28(13): 2621-2624.
Fuglestvedt, J.S., Berntsen, T.K., Godal, O., Sausen, R., Shine, K.O. and Skodvin, T., 2003. Assessing metrics of climate change - current methods and future possibilities. Climatic change, 58: 267-331.
Graus, W., Harmelink , M. and Hendriks, C., 2004. Marginal GHG-Abatement curves for agriculture, Ecofys, Utrecht, the Netherlands.
Graveland, C., Bouwman, A.F., de Vries, H.J.M., Eickhout, B. and Strengers, B.J., 2002. Projections of multi-gas emissions and carbon sinks, and marginal abatement cost functions modelling for land-use related sources. RIVM-report 461502026, National Institute for Public Health and the Environment, Bilthoven, the Netherlands (www.mnp.nl/ieweb).
Gritsevskyi, A. and Nakicenovic, N., 2000. Modeling uncertainty of induced technological change. Energy Policy, 28(13): 907-921.
Hansen, J., Sato, M., Ruedy, R., Lacis, A. and Oinas, V., 2000. Global warming in the twenty-first century: An alternative scenario. Proceedings of the National Academy of Sciences of the United States of America, 97(18): 9875-9880.
Hare, W.L., 2003. Assessment of Knowledge on Impacts of Climate Change – Contribution to the Specification of Art. 2 of the UNFCCC, WBGU - German Advisory Council on Global Change, Potsdam, Berlin.
Hare, W.L. and Meinshausen, M., 2004. How much warming are we committed to and how much can be avoided?, Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany.
Hayhoe, K., Jain, A., Pitcher, H., MacCracken, C., Gibbs, M., Wuebbles, D., Harvey, R. and Kruger, D., 1999. Costs of multigreenhouse gas reduction targets for the USA. Science, 286: 905-906.
Hitz, S. and Smith, J., 2004. Estimating global impacts from climate change. Global Environmental Change Part A, 14(3): 201-218.

Höhne, N., 2005. Impact of the Kyoto Protocol on Stabilization of Carbon Dioxide Concentration, Scientific Symposium "Avoiding Dangerous Climate Change", Met Office, Exeter, United Kingdom.
Höhne, N., Galleguillos, C., Blok, K., Harnisch, J. and Phylipsen, D., 2003. Evolution of commitments under the UNFCCC: Involving newly industrialized countries and developing countries. Research-report 20141255, UBA-FB 000412, ECOFYS Gmbh, Berlin.
Hourcade, J-C. and Shukla, P.R., 2001. Global, regional and national costs and ancillary benefits of mitigation. In: B. Metz, Davidson, O., Swart, R., Pan, J. (Editor), Climate Change 2001: Mitigation; Contribution of Working Group III to the Third Assessment Report of the IPCC. Cambridge University Press, Cambridge, UK.
IMAGE-team, 2001. The IMAGE 2.2 implementation of the SRES scenarios. A comprehensive analysis of emissions, climate change and impacts in the 21st century. CD-ROM publication 481508018, Bilthoven, the Netherlands.
IPCC, 2001. Climate Change 2001: Mitigation. Cambridge University Press, Cambridge, UK.
Joos, F., Plattner, G.-K., Stocker, T.F., Marchal, O. and Schmittner, A., 1999. Global warming and marine carbon cycle feedbacks on future atmospheric CO2. Science, 284: 464-467.
Manne, A.S. and Richels, R.G., 2001. An alternative approach to establishing trade-offs among greenhouse gases. Nature, 410: 675-677.
Meinshausen, M., 2005. On the Risk to Overshoot 2°C, Scientific Symposium "Avoiding Dangerous Climate Change", Met Office, Exeter, United Kingdom.
Meinshausen, M., Hare, W.L., Wigley, T.M.L., van Vuuren, D.P., den Elzen, M.G.J and Swart, R., 2004. Multi-gas emission pathways to meet climate targets. Climatic change (submitted).
Meyer, A., 2000. Contraction & Convergence. The global solution to climate change. Schumacher Briefings, 5. Green Books, Bristol, UK.
Morita, T., Nakicenovic, N. and Robinson, John, 2000. Overview of mitigation scenarios for global climate stabilization based on new IPCC emission scenarios (SRES). Environmental Economics and Policy Studies, 3: 65-88.
Murphy, J.M., Sexton, D.M.H., Barnett, D.N., Jones, G.S., Webb, M.J., Collins, M. and Stainforth, D.A, 2004. Quantification of modelling uncertainties in a large ensemble of climate change simulations. Nature, 430: 768-772.
Nakicenovic, N. and Riahi, K., 2003. Model runs with MESSAGE in the Context of the Further Development of the Kyoto-Protocol, WBGU - German Advisory Council on Global Change, Berlin.
Paltsev, S., Reilly, J., Jacoby, H., Ellerman, A.D. and Tay, K.H., 2003. Emissions Trading to Reduce Greenhouse Gas Emissions in the United States:The McCain-Lieberman Proposal. Report No. 97, Massachusetts Institute of Technology, Cambridge, MA.
Raper, S. C. B. and Cubasch, U., 1996. Emulation of the results from a coupled general circulation model using a simple climate model. Geophysical Research Letters, 23(10): 1107-1110.
Reilly, J., Prinn, R.G., Harnisch, J., Fitzmaurice, J., Jacoby, H., Kicklighter, D., Stone, P., Sokolov, A. and C., Wang., 1999. Multi-gas Assessment of the Kyoto Protocol. Nature, 401(6753): 549-555.
Richels, R., Manne, A. and Wigley, T.M.L., 2004. Moving beyond concentrations: the challenge of limiting temperature change. Working-Paper 04-11, AEI-Brookings Joint Center for Regulatory Studies.
Schaefer, D. O., Godwin, D. and Harnisch, J., 2004. Estimating future emissions and potential reductions of HFCs, PFCs and SF6. Energy Journal (in press).

Schimel, D., Grubb, M., Joos, F., Kaufmann, R. , Moss, R. , Ogana, W. , Richels, R. and Wigley, T. M. L, 1997. Stabilization of Atmospheric Greenhouse Gases: Physical, Biological and Socio-Economic Implications. ISBN 92-9169-102-X, IPCC, Geneva.
Smith, J., Schnellnhubner, H.-J. and Mirza, M.Q.M., 2001. Vulnerability to climate change and reasons for concern: a synthesis. In: J.J. McCarthy, O.F. Canziani, N.A. Leary, D.J. Dokken and K.S. White (Editors), Climate Change 2001: Impacts, Adaptation, and Vulnerability. Cambridge University Press, Cambridge, UK.
Stott, P.A., Stone, D.A. and Allen, M.R., 2004. Human contribution to the European heatwave of 2003. Nature, 432: 610-614.
Swart, R., Berk, M., Janssen, M., Kreileman, E. and Leemans, R., 1998. The safe landing analysis: risks and trade-offs in climate change. In: J. Alcamo, R. Leemans and E. Kreileman (Editors), Global change scenarios of the 21st century. Results from the IMAGE 2.1 model. Elseviers Science, London, pp. 193-218.
Swart, R., Mitchell, J., Morita, T. and Raper, S., 2002. Stabilisation scenarios for climate impact assessment. Global Environmental Change, 12(3): 155-165.
Tol, R.S.J., 1999. The marginal Cost of greenhouse gas emissions. Energy Journal, 20(1): 61-81.
van Vuuren, D.P., de Vries, H.J.M., Eickhout, B. and Kram, T., 2004a. Responses to Technology and Taxes in a Simulated World. Energy Economics, 26(579-601).
van Vuuren, D.P., den Elzen, M.G.J. and Berk, M.M., 2002. An evaluation of the level of ambition and implications of the Bush Climate Change Initiative. Climate Policy, 2: 293-301.
van Vuuren, D.P., den Elzen, M.G.J., Berk, M.M., Lucas, P., Eickhout, B., Eerens, H. and Oostenrijk, R, 2003. Regional costs and benefits of alternative post-Kyoto climate regimes. RIVM-report 728001025, National Institute for Public Health and the Environment, Bilthoven, the Netherlands.
van Vuuren, D.P., Eickhout, B., Lucas, P.L. and den Elzen, M.G.J., 2004b. Long-term multi-gas scenarios to stabilise radiative forcing - exploring costs and benefits within an integrated assessment framework. Energy Journal (accepted).
van Vuuren, D.P., Weyant, J.P. and DelaChesnaye, F. C., 2005. Mult-gas scenarios to stabilise radiative forcing. Energy Economics (submitted).
White-House, 2002. Executive Summary of Bush Climate Change Initiative.
Wigley, T. M. L, 2003. MAGICC/SCENGEN 4.1: Technical Manual, UCAR - Climate and Global Dynamics Division, Boulder, CO.
Wigley, T. M. L. and Raper, S. C. B., 2001. Interpretation of high projections for global-mean warming. Science, 293(5529): 451-454.
Wigley, T. M. L. and Raper, S. C. B., 2002. Reasons for larger warming projections in the IPCC Third Assessment Report. Journal of Climate, 15(20): 2945-2952.
Wigley, T. M. L., Richels, R. and Edmonds, J., submitted. Overshoot Pathways to CO2 stabilization in a multi-gas context. In: M.E. Schlesinger and J.P. Weyant (Editors), Human Induced Climate Change: An Interdisciplinary Perspective. Cambridge University Press, Cambridge, UK.
Wigley, T.M.L., Richels, R. and Edmonds, J.A., 1996. Economic and environmental choices in the stabilisation of CO_2 concentrations: choosing the 'right' emissions pathway. Nature, 379: 240-243.

Appendix A Description of the emission pathways calculation

The driver parameterized global CO_2-equivalent emission pathway is defined by sections of constant yearly emission reductions (R_I (initial 2010 value), R_X, R_Y and R_Z) and years (X_1, X_2, Y_3, Y_4 and Z_5) at which the reduction rates change, as indicated in Figure A.1. A parameterization based on three periods of approximately constant reduction rates allows us to match a stabilization profile reasonably well. Note that the effective emission reduction rates will be different from the preset rates due to (a) smoothing of emissions profiles and (b) lower bounds for some gases' reductions, which affect lower emission pathways. These lower bounds can result if a certain baseline and target emission path is chosen, which emission gap is not fully covered by the chosen MAC curves. As well, the maximally reducible amount of N_2O and CH_4 emissions after 2100 has been fixed at 75% of 2100 emissions, which can lead to a gap in preset and effective reduction paths after 2100 for lower concentration pathways.

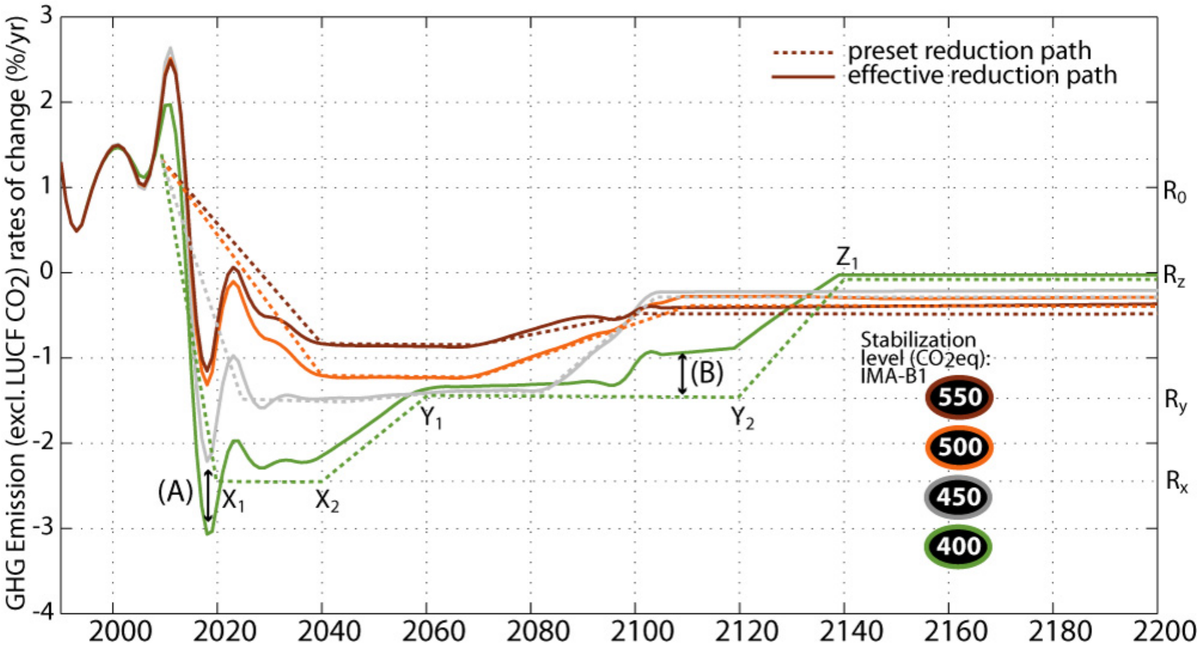


Figure A.1 The preset driver parameterized global CO_2-equivalent emission pathway (dotted), defined by sections of constant yearly emission reductions (R_I (initial 2010 value), R_X, R_Y and R_Z) and years at years (X_1, X_2, Y_3, Y_4 and Z_5) at which the yearly reduction changes. Effective reduction paths might differ (solid lines - see text). The plotted emission pathways lead to a stabilization of radiative forcing. It is possible to create peaking emission paths that would continue at R_x emission reduction rates.

The calculation of parameterized emission pathway aimed at concentration stabilization is done in two steps:

1. First, calculate the parameter R_X for a parameterized emission pathway (dotted line in Figure A.1) leading to a concentration peaking in a certain year, using the iterative procedure described in Chapter 2. Here, we need to make assumptions about the

initial rate R_0 and years X_1, which are based on expert knowledge from existing mitigation scenarios;[24]

2. Second, calculate the remaining parameters $X_2, R_z, Y_1, Y_2, R_y, Z_1, R_z$ for a parameterized emission pathway (solid dotted in Figure A.1), leading to a concentration stabilization in a certain year.

[24] Only for the emission pathway peaking at 480ppm CO_2eq, do we also need to make assumptions about the initial rate R_Y and years X_2 and Y_3, which are again based on information from the lower range of mitigation scenarios in the literature.

Appendix B Source of information on marginal abatement costs

Table B.1: Source of information on marginal abatement costs for the default scenario (adapted from van Vuuren et al., 2004b)

Emission category (Non-CO_2 gases)	*Source of information on marginal abatement costs*	*Reduction potential of main sources (2010)*	*Assumed annual increase of potential*
CH_4 and N_2O from agricultural sources	DeAngelo et al. (2004) and Graus et al. (2004) for development of potential in 2010-2050 period	N_2O soil: 7% CH_4 animals: 7% CH_4 rice: 20%[*] CH_4 manure : 17%	3.9% up to 2050 3.9% up to 2050 1.5% up to 2050 2.4% up to 2050; 0.4% 2050-2100 [x]
CH_4 and N_2O emissions from industrial and energy-related sources	Delhotal et al. (2004)	CH_4 total : 65% N_2O process : 90-95%	0.4% [x]
CH_4 and N_2O emissions (no MAC curves available)	This study	Maximum reduction (compared baseline) of 35% in 2040 [x x]	0.4% [x]
Halocarbons	Schaefer et al. (2004); this study	2010: around 40% 2100: 95% in 2100 [vv]	
Emission category (CO_2)	*Source of information on marginal abatement costs*	*Reduction potential of main sources*	*Assumed annual increase of potential*
CO_2 from energy use and production	Time-dependent MACs of TIMER (van Vuuren et al., 2004a) [vvv]	2010: Around 50% 2100: Around 80%	- [x]
Sinks	Based on IMAGE calculations (Graveland et al., 2002)	Potential increases to 400 MtC annually in 2050	-
Forest management	Conservative assumptions based on the extension of the Marrakesh Accords as described in van Vuuren et al. (2003).	Total amount of 135 MtC-eq. annually is assumed	-

* In DeAngelo et al. (2004) a reduction of 38% is given. This number has been scaled down for 2010 on the basis of Graus et al. (2004).

v Here, van Vuuren et al. (2004b) assumed no reductions.

v v Here, van Vuuren et al. assumed a 0.4% annual increase.

vvv Here, Van Vuuren et al. assumed a time-dependent MACs iterating between FAIR and TIMER.

x CPI + tech baseline scenario assumes a 2.0% annual increase of potential for non-CO_2 emissions, and a 0.2% additional technological improvement for CO_2 emissions from energy use and production.

x x CPI + tech baseline scenario assumes a 80% reduction in 2040.

Appendix C Global greenhouse gas emissions of the pathways presented

This appendix presents the emissions underlying the default pathways presented for stabilization at 550, 450 and 400 ppm CO_2-equivalent concentrations.

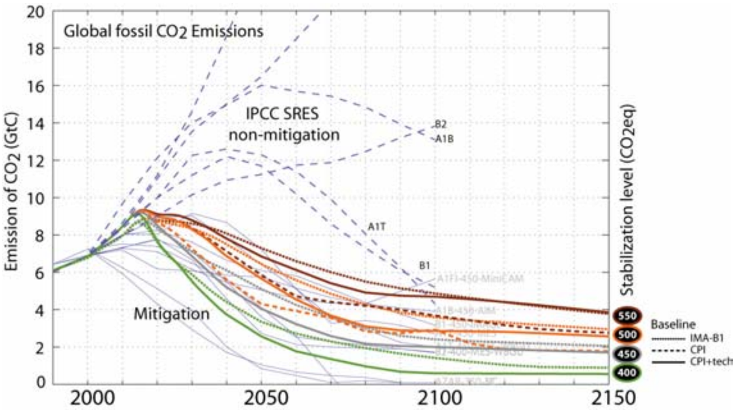


Figure C.1 Global fossil CO_2 emissions. For comparison, the emission implications of the IPCC-SRES non-mitigation scenarios (grey dotted lines) and a range of SRES mitigation scenario (grey solid lines) are also plotted.

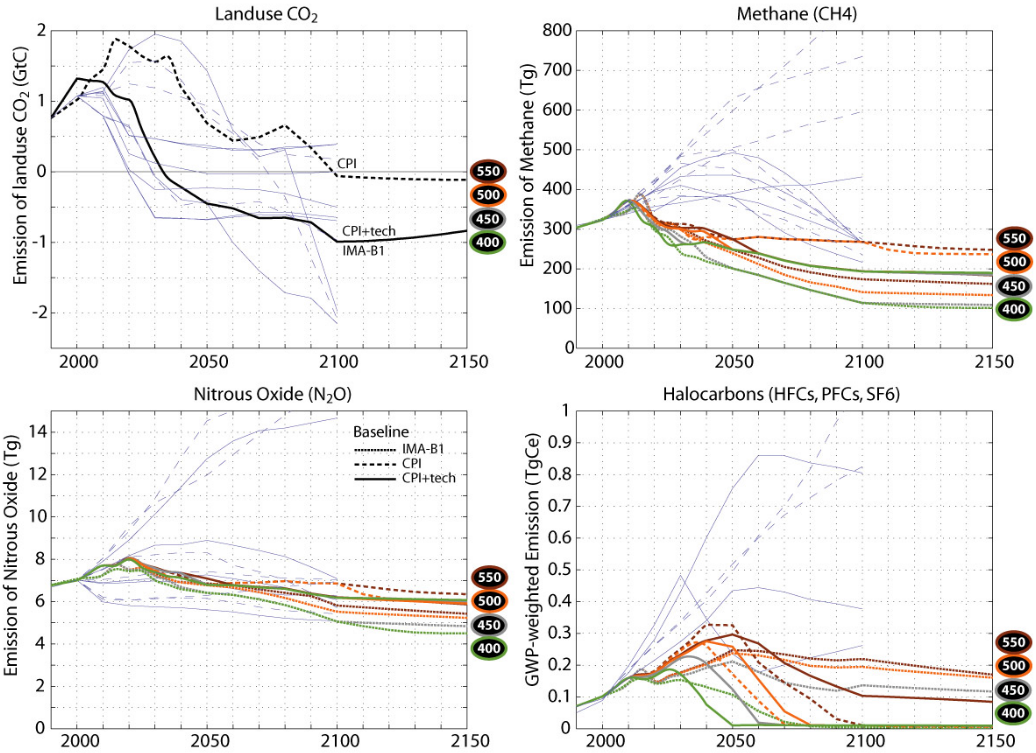


Figure C.2 Global landuse CO_2, methane, nitrous oxide and halocarbon emissions. For comparison, the emission implications of the IPCC-SRES non-mitigation scenarios (grey dotted lines) and a range of SRES mitigation scenario (grey solid lines) are also plotted.

Appendix D Comparison with IMAGE 2.2 multi-gas emission pathways

This Appendix compares the emission pathways presented here with the two earlier IMAGE multi-gas emission pathways, leading to a long-term stabilization at 550 and 650 ppm CO_2-eq. (hereafter referred to as the IMAGE S550e and S650e pathways) (Eickhout et al., 2003). The IMAGE pathways have been used within the EU DG Environment project 'Greenhouse gas reduction pathways in the UNFCC post-Kyoto process up to 2025' (see Criqui et al., 2003). Table D.1 summarizes the differences between the two studies.

Table D.1 Differences between the earlier IMAGE multi-gas emission pathways (Eickhout et al., 2003) and the emission pathways presented in this study

Differences	**Eickhout et al. (2003)**	**This study**
Definition profiles		
CO_2-eq. concentration stabilization level	550 and 650 ppm in 2100 and 2150	400, 450, 500 and 550 ppm in 2250, 2250, 2200 and 2100
Final CO_2 concentration level	450 and 550 ppm CO_2-only*	350-375, 400-425, 440-475 and 475-500 ppm CO_2-only, respectively.**
Including overshoot	No overshoot	No overshoot for 550ppm CO_2-eq. Overshoot or peaking at 480, 500 and 525 ppm for stabilization pathways at 400, 450 and 500 ppm, respectively.
Definition CO_2-equivalent concentration	Based on radiative forcing of the *six Kyoto* greenhouse gases (CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6).	Based on radiative forcing of *all* greenhouse gases (incl. the CFCs, HCFCs), tropospheric ozone and aerosols (Schimel et al., 1997).
Baseline assumptions		
LUCF CO_2 emissions	CO_2 emissions including CO_2 fertilization effect.	CO_2 emissions not including CO_2 fertilization effect (as feedbacks included in used climate model MAGICC)
Baseline scenario	CPI scenario	CPI, CPI+tech and B1 scenario
Models used		
Terrestrial carbon cycle model	Geographical explicit carbon cycle model (IMAGE 2.2)	Global terrestrial carbon cycle model MAGICC 4.1 model
Oceanic carbon cycle model	ocean mixed-layer pulse response function of ocean model (Joos et al., 1999)	MAGICC 4.1
Atmospheric chemistry	IPCC-TAR methodology	IPCC-TAR methodology
Climate model	Climate model of MAGICC 3.0	Climate model of MAGICC 4.1
Methodology		
Methodology for the calculation of emission pathways	CO_2 – For the period from 2012-2040 we assume a linearly increasing reduction rate. From 2040, onwards, we use the inverse CO_2 concentration calculations of Enting et al. (1994). Non-CO_2 – Non-CO_2 is responsible for a further 100 ppm, and based on assumptions about emission reduction rates (expert judgement).	Calculates mixes of greenhouse gas emission reductions for a given global emission pathway under a least-costs approach based on iterative process (for more details see Chapter 2).

* A result of the inverse CO_2 concentration calculations (methodology)
** Outcome of the calculations

As mentioned earlier, this study focuses more on the lower CO_2-equivalent concentration stabilization levels (400, 450, 500 and 550 ppm CO_2-eq.), therefore the only CO_2-eq. concentration stabilization level, analysed in both studies, is the 550 ppm CO_2-eq. level, which we use for the basis of our comparison.

Comparison of the IMAGE S550e and FAIRSIMCAP S550e-CPI pathway (excl. LUCF CO_2 emissions)

Definition of the CO_2-equivalent concentration

One of the more important differences between the two studies is the definition of CO_2-equivalent concentration levels. Where Eickhout et al. only included the six Kyoto greenhouses gases in the definition, in this study we included all human-induced greenhouse gases, tropospheric ozone and aerosols, following the IPCC definition (see Schimel et al., 1997). The effect of the both definitions on the CO_2-equivalent concentration is illustrated for the IMAGE S550e pathway and our emission pathway at 550 ppm CO_2-eq. for the CPI scenario (hereafter known as FAIRSIMCAP S550e-CPI pathway in Figure D.1. Both studies use the same CPI scenario.

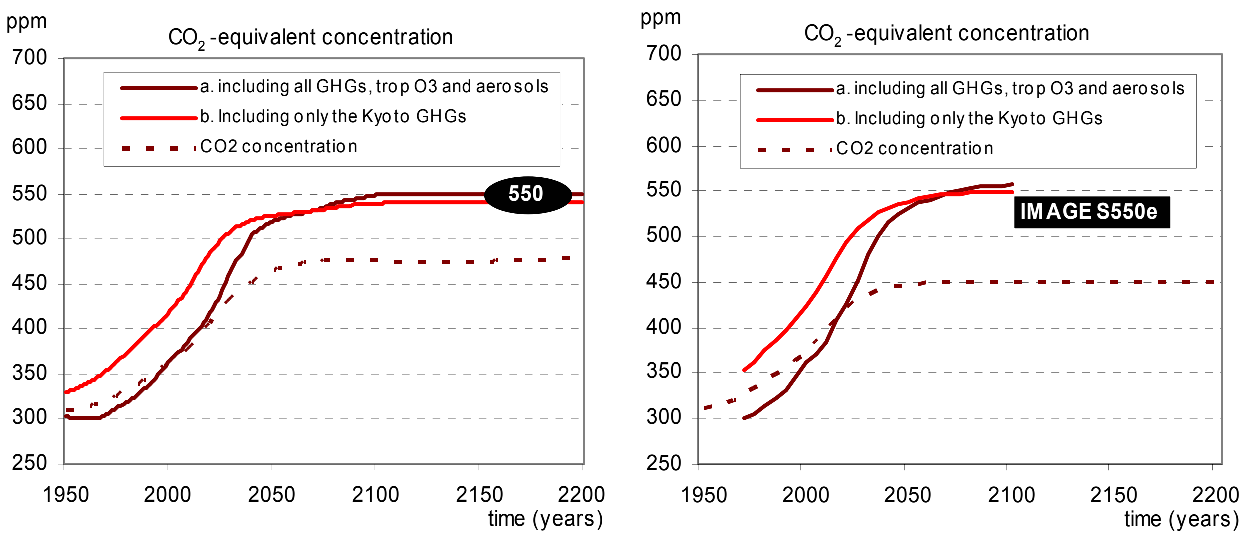
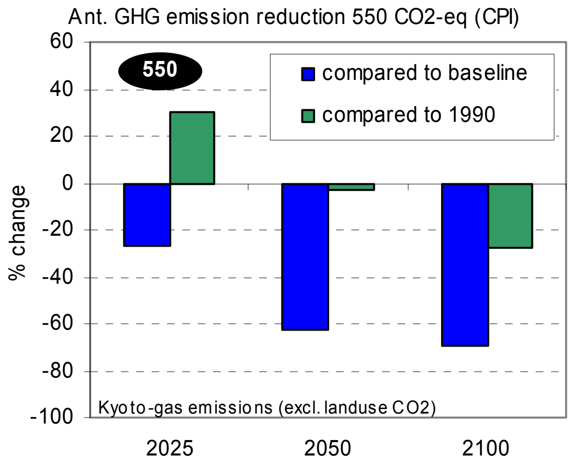


Figure D.1 The CO_2-equivalent concentration for the two definitions for the emission pathway at 550 ppm CO_2-eq. for the CPI scenario (FAIRSIMCAP S550e-CPI, left) and IMAGE S550e pathways (right). The CO_2-equivalent concentrations are defined on the basis of the radiative forcing of: a. all greenhouse gases, tropospheric ozone and aerosols (Schimel et al., 1997), as assumed in this study; and b. only Kyoto greenhouse gases, as assumed in Eickhout et al. (2003). Note, for comparison, also the depiction of CO_2 concentration (dashed line) for the emission pathways.

By including all greenhouse gases, tropospheric ozone and aerosols, the CO_2-equivalent concentration is presently lower because of the assumed cooling effect of the aerosols, which is larger than the assumed warming effect of tropospheric ozone. The difference between the two CO_2-equivalent concentration definitions will disappear in future projections because of the expected mitigation strategies for aerosol emission (directly for reasons for human health and acidification and indirectly as a synergetic effect of climate policies). Therefore the impact of different definitions of CO_2-equivalent concentration has a minor effect on the final emission pathway for the 550 ppm CO_2-eq. concentration level.

However, the use of the definition has a major impact, in combination with the allowed overshoot of concentrations, on the emission pathways for the lower CO_2-eq. concentration levels, i.e. 400, 450 and 500 ppm CO_2-eq. With the definition of the inclusion of only the Kyoto gases as in Eickhout et al., these levels seem to be out of reach, as for example, the 500 ppm CO_2-eq. level is already reached around 2025. By including all greenhouse gases, tropospheric ozone and aerosols in the CO_2-equivalent concentration, these lower concentration targets are possible.

Methods used
The major remaining difference between both studies comes from the different methodological approaches. The global emissions and the resulting reductions for the IMAGE S550e and FAIRSIMCAP S550e-CPI pathways are depicted in Figure D.2. This Figure clearly show that the IMAGE S550e pathway leads to lower emissions of the Kyoto gases (excluding LUCF CO_2) for the period 2025-2045, but at the longer term (after 2050) the differences between the emissions of both profiles becomes less. More specifically, in 2025 the emissions of the IMAGE S550e pathway are about 22% above 1990 levels, whereas for the FAIRSIMCAP S550e-CPI pathway emissions are about 30% above 1990 levels.



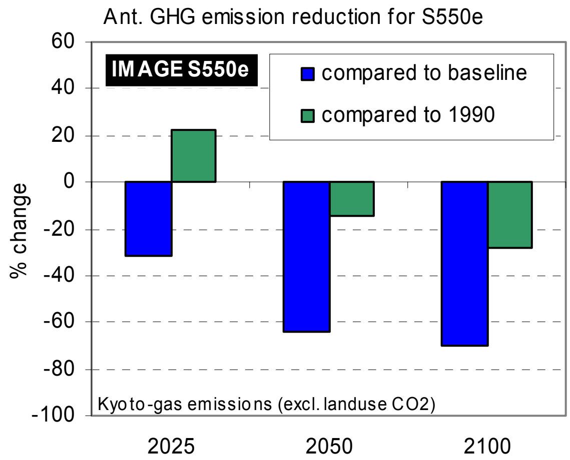


Figure D.2 Global emission reduction efforts (excluding LUCF CO_2 emissions) for the FAIRSIMCAP S550e-CPI pathway (left) and for the IMAGE S550e profile (right).

Eickhout et al. predefined for the IMAGE S550e pathway a 450 ppm CO_2 only concentration level. The other Kyoto gases are allowed to account for the remaining 100 ppm CO_2-eq. In this study the 'cost-optimal' allocation methodology for every 5 year segment of the emission path leads in the short terms (till 2025) to more non-CO_2 reductions, and therefore higher CO_2 concentrations, i.e. at 475-500 ppm CO_2. Note again that it is not possible to judge from the applied methods, which emission pathway is closer to a 'cost-optimal' emission pathway over time that dynamically accounts for induced technological progress, learning effects and system inertia. These differences in the final CO_2 concentrations evidently lead to lower CO_2 emissions and higher non-CO_2 emissions for the IMAGE S550e profile. This result is in line with the cost-optimal implementation of the allowed global emission pathway in van Vuuren et al. (2003; 2004b). The difference in CO_2 and non-CO_2 contribution to the 550ppm CO_2-eq. level impact the conclusions on the emission allowances in three ways (as also mentioned in Eickhout et al., 2003).

1. *Less flexibility for the IMAGE S550e profile* – The current CO_2 concentration is already approximately 380 ppm, and this has increased rapidly at a speed of about 30 ppm CO_2 over the past 20 years. Without action, the CPI baseline surpasses the 450 ppm target as early as 2030. Not allowing overshoot of the 450 ppm CO_2 target

implies that the rate of increase needs to be reduced quite drastically within this 30 years time frame and, obviously, the amount of flexibility is constraint, leading to lower CO_2 emissions on the short-term; of course, this may be compensated by less emission reduction hereafter.

2. *Fast response of non-CO_2 reductions for this study* – The early non-CO_2 reductions, in this study lower the CO_2-equivalent concentrations directly (Hansen et al., 2000; Eickhout et al., 2003; Meinshausen et al., 2004; Wigley et al., submitted). This, in turn, allows CO_2 emissions required to match the final CO_2-equivalent concentration profile, to be higher, and the same holds for the overall emissions (see Figure D.2).

3. *Slightly enhanced CO_2 fertilization effect for this study* – Another factor relates to the terrestrial CO_2 fertilization feedback. More specifically, at higher CO_2 concentration levels, plants absorb more CO_2, providing a negative feedback that tends to slow down the growth of atmospheric CO_2. The CO_2 concentration levels for the FAIRSIMCAP S550e-CPI pathway are higher, leading to a higher CO_2 fertilization effect. This additional uptake of CO_2 by the terrestrial vegetation allows for a modest additional space of CO_2-eq. emissions.

Figure D.2 also indicates that the reductions are even less for 550 ppm CO_2-eq. pathways for the other scenarios (B1 and CPI+tech) (i.e. the FAIRSIMCAP S550e-CPI+tech and S550e-B1 pathways), mainly because these scenarios assume lower LUCF CO_2 emissions, and thus the allowed emissions of the Kyoto gases (excl. LUCF CO_2) may be higher.

Comparison of the IMAGE S550e and FAIRSIMCAP S550e-CPI pathway (incl. LUCF CO_2 emissions)

IMAGE's climate model core is built on MAGICC, but IMAGE's the terrestrial and ocean carbon cycle models differ from those of MAGICC. This is the main reason why we now include a LUCF CO_2 emissions trajectory excluding the CO_2 fertilization effect, otherwise we would double count this fertilization effect, by accounting this in the calculated terrestrial carbon uptake of the MAGIC model, and in the assumed LUCF CO_2 emissions. The LUCF CO_2 emissions trajectory for the IMAGE S550e pathway, leads to a much higher sink after 2050 compared to the CPI one (depicted in Figure C.2) , i.e. already surpassing the zero emission by 2050, and finally in 2100, it becomes about -0.8 GtC/year.

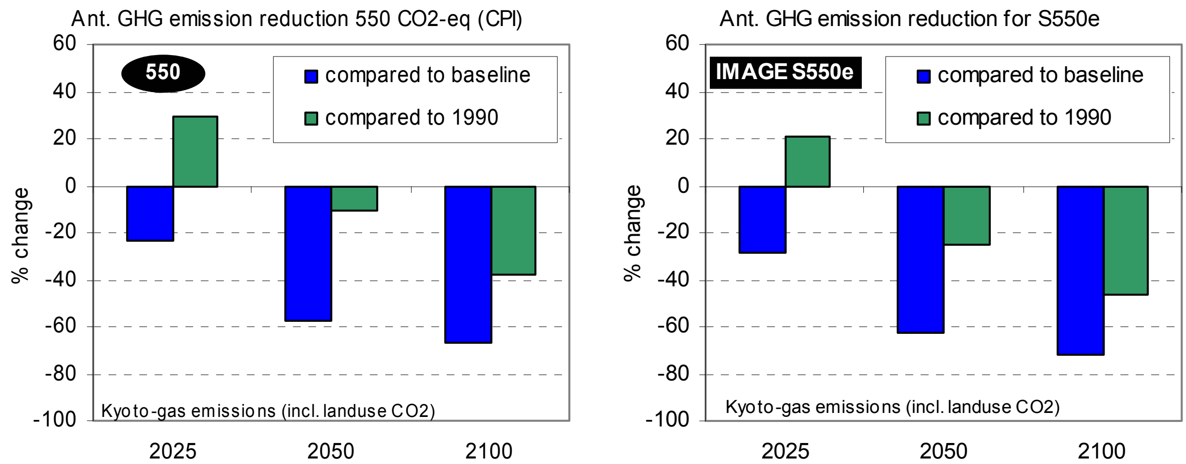


Figure D.3 Same as Figure D.2, but now including LUCF CO_2 emissions

In the following, greenhouse gas emissions including the LUCF CO_2 are compared for the IMAGE S550e and FAIRSIMCAP S550e-CPI pathways. Figure D.3 shows that the inclusion of the LUCF CO_2 emissions for our FAIRSIMCAP emission pathways leads to fewer differences among them. This is because the FAIRSIMCAP S550e-CPI pathway's lower emissions (excl. LUCF CO_2 emissions) compared to pathways based on the CPI+tech and B1 baseline, are now combined with CPI's higher LUCF CO_2 emissions.

Finally, comparing Figures D.2 and D.3 shows that for the IMAGE S550e pathway the inclusion of the LUCF CO_2 emissions leads to much lower emissions, and higher reductions on the long-term. As aforementioned, this difference is partially reasoned by the differences in definition of CO_2-equivalence.