# Long-term multi-gas scenarios to stabilise radiative forcing – Exploring costs and benefits within an integrated assessment framework.

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## *Abstract*

This paper presents a set of multi-gas mitigation scenarios that aim for stabilisation of greenhouse gas radiative forcing in 2150 at levels from 3.7 to 5.3 W/m$^2$. At the moment, non-$CO_2$ gasses (methane, nitrous oxide, PFCs, HFCs and $SF_6$) contribute to about a quarter of the global emissions. The analysis shows that including the these non-$CO_2$ gases in mitigation analysis is crucial in the formulation of a cost-effective response. For stabilisation at 4.5 W/m$^2$, a multi-gas approach leads to 40% lower costs than an approach that would focus at $CO_2$-only. Within the assumptions used in this study, the non-$CO_2$ gasses contribution to total reduction is very large under less stringent targets (up to 60%), but declines under stringent targets. Improving knowledge on how future reduction potential for non-$CO_2$ gasses could develop is in this context a crucial research question. Including non-$CO_2$ gasses also allows for meeting more stringent stabilisation targets. While stabilising at low radiative forcing (3.7 W/m$^2$) obviously leads to larger environmental benefits than the 4.5 W/m$^2$ case (temperature increase in 2100 are 1.9 and 2.3°C, respectively), costs to reach that target are also higher (0.80% and 0.34% of GDP in 2100, respectively).

## 1. Introduction

Increasing atmospheric concentrations of carbon dioxide ($CO_2$) are, by far, the most important driving force of the enhanced greenhouse effect. In that context, most mitigation studies so far have concentrated on this gas only. At the same time, however, human activities cause emissions of several other greenhouse gases (GHGs) exists, including methane ($CH_4$), nitrous oxide ($N_2O$) and fluorinated and chlorinated hydrocarbons (halocarbons). In order to 'stabilise greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system' (UNFCCC 1992) also these gases need to be accounted for. In 1997, policy-makers acknowledged this by formulating the Kyoto targets in terms of a 'basket' of greenhouse gases[1] (allowing full substitution among these gases), thus making a multi-gas abatement strategy operational. Interestingly, most studies on the implications of a multi-gas strategy are more recent. An important reason is that consistent information on reduction potential for the non-$CO_2$ gases has been lacking. Available studies exploring the impacts of including non-$CO_2$ gases in the analysis of the Kyoto Protocol nevertheless find that major cost reductions can be obtained through the relatively cheap abatement options for some of the non-$CO_2$ gases and (more generally) the increase in flexibility (Hayhoe et al. 1999; Reilly et al. 1999; Blok et al. 2001; Lucas et al. 2002). Multi-gas studies on long-term stabilization targets indicate similar conclusions (e.g. Tol (1999), Jensen and Thelle (2001), Manne and Richels (2001), Van Vuuren et al. (2003), den Elzen et al. (2004)) or indicate important advantages in terms of avoiding climate impacts (Hansen et al. 2000). 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), Fuglestvedt et al. (2003), O'Neill (2003)).

For 'CO$_2$-only' stabilization, available information now allows for a reasonably good understanding of mitigation potential and the associated range of costs across a wide range of climate targets (as a function of a wide range of assumptions and modeling approaches) (see Hourcade and Shukla (2001)). A similar situation certainly does not exist for multi-gas stabilisation, as the number of individual studies is still rather low, methodologies have not been compared and studies have hardly assessed multiple stabilisation targets. The context of a large modeling comparison study (EMF- 21) and the data that has been collected in this context on marginal abatement costs for non-CO$_2$ (Kyoto) gases now provide an opportunity for change. In this paper, we will develop a set of mitigation scenarios that aim to stabilise radiative forcing of greenhouse gases using the IMAGE 2.2 Integrated Assessment model in combination with the climate-policy model, FAIR 2.0 (for a description of both models see Section 2). The analysis focuses on two crucial questions:

1. What are the differences in abatement costs and environmental impacts between a long-term multi-gas mitigation strategy (including all Kyoto gasses) and a CO$_2$-only strategy aiming for a similar climate stabilisation target?
2. How do the mitigation efforts, abatement costs and environmental impacts differ for multi-gas mitigation scenarios that aim for less and more stringent stabilisation targets?

To answer these questions, three methodological questions directly arise: 1) how to define the stabilisation target for a multi-gas stabilisation scenario; 2) how to allow for substitution among the different greenhouse gases; and 3) how to incorporate abatement of non-CO$_2$ gases into the modeling framework. The third question will be dealt with in our analysis, while the first two questions will be discussed here.

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[1] The gasses, from now on referred to as 'Kyoto' gas are CO$_2$, CH$_4$, N$_2$O, PFCs, HFCs and SF$_6$. CFCs and HCFCs have not been covered by the Kyoto protocol as their consumption has been dealt with in the context of

Regarding the first methodological question, long-term $CO_2$-only stabilision studies generally explored the environmental and economic implications of stabilising the $CO_2$ concentration (ranging from 450-750 ppmv) (EMF-16 1999; Hourcade and Shukla 2001; Swart et al. 2002). For multi-gas studies, one would need a similar long-term climate target but now integrating the different gases (accounting, for instance, their different radiative properties and atmospheric lifetimes). In general, selecting such a target early in the cause-effect chain from human activities to climate change impacts (e.g. emissions) increases the certainty of required reduction measures, but decreases the certainty on climate impacts. Selecting a climate target further down the cause-effect chain (e.g. temperature change, or even to be avoided climate impacts) increases certainty on impacts, but decreases certainty on required reduction measures (UNFCCC 2002). In fact, uncertainties increase most (either way) in the step from radiative forcing to temperature change due to the large uncertainty range for climate sensitivity (Matthews and van Ypersele 2003). Analogy with the $CO_2$ concentration suggests formulating targets in terms of radiative forcing, which is equivalent to the concentrations of the different gases weighted for their radiative properties. The advantage of choosing radiative forcing targets over temperature targets is that the calculation of radiative forcing does not depend on climate sensitivity, which is the major uncertain factor in the cause-effect chain. The downside is, of course, that a wide range of temperature impacts are possible for the same radiative forcing level. Given the fact that this study concentrates on comparing changes in abatement action, radiative forcing targets have been chosen. In these targets, we have included the forcing of the 'Kyoto' gases, but also those of CFCs (including their indirect radiative effect), tropospheric ozone, sulphur dioxide and other aerosols. As shown in this article (see Table 5), the contribution of the non-Kyoto radiative agents (mentioned in the list

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treaties on ozone depleting substances.

above) tend to cancel each other out at the long-term (2100) in the stabilisation scenarios. As the central long-term climate target for our analysis, we have chosen stabilisation at 4.5 $W/m^2$ in 2150, with 3.7 and 5.3 $W/m^2$ as alternative targets[2]. A radiative forcing target of 4.5 $W/m^2$ more or less equates to a $CO_2$ concentration at 550 ppmv (the standard case in most earlier work), assuming 1 $W/m^2$ additional forcing for the non-$CO_2$ gases (Wigley and Raper 2001).

For the second methodological question, a measure is needed in which the emissions of different greenhouse gases with different atmospheric lifetimes and different radiative properties can be compared. Ideally, such a measure would allow for substitution among different gases (in order to achieve cost reductions) but ensures equivalence in climate impact. Fuglestvedt at al. (2003) provide a comprehensive overview of the different methods that have been proposed, and the advantages and disadvantages of using them. One of these, $CO_2$-equivalent emissions based on the Global Warming Potentials (GWP), has been adopted in most current climate policies, such as the Kyoto Protocol, and US climate policy (White-House 2002). Despite the continuous scientific debate on the use of GWPs (particularly as they do not account for economic dimension of the problem and are based on a rather arbitrary time horizon), the concept is mostly regarded as convenient and to date no alternative measure has attained a comparable status. In fact, O'Neill (2003) and Person et al. (2004) have argued that the disadvantages of GWPs are likely to be outweighed by their strong points. In this paper, we will use the 100 year GWPs (Ramaswamy 2001) to substitute among the different gases. The mitigation analysis covers the group of Kyoto greenhouse gasses.

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[2] Radiative forcing can also be expressed by the equivalent $CO_2$ concentration that would result in a similar forcing. The three radiative forcing levels explored here, 3.6, 4.5 and 5.3 W/m2, correspond to an equivalent $CO_2$ concentration of 550, 650 and 750 ppmv $CO_2$-eq., respectively.

Thus, to answer our two focal questions, five different scenarios have been developed, i.e. the baseline scenario, a scenarios that stabilise radiative forcing at 4.5 W/m$^2$ in 2150 using a multi-gas approach, and a scenario that mitigates '$CO_2$-only' using the $CO_2$-equivalent emissions of the multi-gas scenario as a gap[3], and two multi-gas scenarios stabilizing the radiative forcing at 5.3 W/m$^2$ in 2150 and 3.7 W/m$^2$ in 2100. In addition to these scenarios, sensitivity cases have been explored – in particular, on technology assumptions for the abatement potential of the non-$CO_2$ gases. In the next section, we present the overall methodology that has been used for this analysis. Section 3 discusses the results for the baseline. Section 4 presents the analysis on the differences between a $CO_2$-only and multigas approach (focal question 1), while section 5 presents the analysis for various stabilisation targets (focal question 2). In section 6, we show the results of the sensitivity analysis that has been performed. The final section draws up several conclusions.

## 2. Methodology

### *2.1 General methodology*

In our methodology we used the IMAGE 2.2 Integrated Assessment model (IMAGE-team 2001), the TIMER 1.0 energy model (which is part of the IMAGE 2.2 framework) (de Vries et al. 2002) and the FAIR 2.0 climate policy model (den Elzen and Lucas 2003). The IMAGE 2.2 model is an integrated assessment model, consisting of a set of linked and integrated models that together describe important elements of the long-term dynamics of global environmental change, such as agriculture and energy use, atmospheric emissions of greenhouse gases and air pollutants, climate change, land-use change and environmental impacts. The global energy model, TIMER, as part of the IMAGE model, describes the

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[3] To indicate the link between the multi-gas and $CO_2$-only run, the latter is referred to as 4.5 W/m$^2$ $CO_2$-only stabilisation. Note that using a similar $CO_2$-equivalent emissions trajectory for the $CO_2$-only scenario does not

primary and secondary demand and production of energy and the related emissions of greenhouse gasses and regional air pollutants. Finally, FAIR is a policy decision-support tool developed to explore and evaluate the environmental and abatement costs implications of various international climate regimes for differentiation of future commitments for meeting long-term climate targets. In this study, only the (multi-gas) abatement costs model of FAIR is used.

The analysis consists of five major steps:

1. Using the IMAGE and IMAGE/TIMER models to construct the baseline scenario, i.e. potential greenhouse gas emissions in the absence of climate policies (see Section 2.2), with both models providing information on the potential costs of reducing emissions from different sources.
2. Employing, in addition, the IMAGE model to develop the global $CO_2$-equivalent emission profiles, leading to a stabilization of the GHG concentration at a radiative forcing of 3.7, 4.5 and 5.3 $W/m^2$ (see Section 2.3).
3. Using the abatement costs sub-model of FAIR to distribute the global emission reduction objective (i.e. difference between the global baseline scenario and global emissions profile) over the different regions, gases and sources following a least-cost approach on the basis of Marginal Abatement Cost (MAC) curves. The model includes a set of endogenously MACs (energy and sinks $CO_2$ by TIMER or IMAGE) and exogenously determined MACs of the EMF 21 project (non- $CO_2$) (see Section 3.4).
4. Forwarding the international marginal price for carbon emissions from energy and industrial sources, and the required abatements for the non-$CO_2$ gases, to the IMAGE/TIMER model to determine the changes in emission levels.

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necessarily lead to a similar radiative forcing stabilisation as the multi-gas scenario (4.5 $W/m^2$).

5. Finally, assessing the climate impacts using the IMAGE 2.2 climate model.

In step 3, the FAIR model splits the global emission reduction objective among the different gases and sources in following a least-cost approach taking full advantage of flexibility in reduction among different regions and substitution among gases and emission sources using 100-year GWP indices. The calculated marginal price of reduction can be interpreted as an international permit price (as in emission trading) or as a carbon-equivalent tax level (as it is applied in the energy model – see step 4). The tax level induces changes in the energy model, such as fuel substitution, energy savings and application of zero-carbon energy options. In the analysis neither the tax nor the permit price represents specific policy instruments proposed to implement the potential emission reductions. Instead, the marginal price of reduction (referred to as marginal price in the rest of this article) should be interpreted as a metric of the required level of policy action to induce the kind of changes needed to reach the radiative forcing target assuming cost-optimal implementation of available options.

The modeling framework as used in this study has a hybrid approach with respect to the use of MAC curves. For agricultural sources, a pure MAC approach is used - in which the current price of reducing one unit of $CO_2$-equivalent emissions determines the reduction rate of one specific source. For all energy-related sources, a mixed approach is used, in which first the marginal price applied in the energy system and end-of-pipe measures (based on MACs) are determined; subsequently, these are fed into the energy model. The energy model takes care of the interactions that result from the greenhouse gas constraint. For instance, changes in energy production as a result of reducing $CO_2$ emissions will also reduce methane emissions emitted from energy production and transport. Using this hybrid MAC approach has the advantage of great transparency and flexibility. However, the approach also faces a number of limitations. First of all, we do not model direct linkages to the overall economy; and as a result we calculate abatement costs but no impacts on GDP or utility losses. Furthermore, using the MAC curves methodology for agricultural emissions will not lead to structural changes of the system, resulting in unaffected agricultural production levels. Finally, for the interactions between the MAC-based approach and the energy model, only one iteration is made, which would preferably repeated a number of times to better incorporate the path dependency in the energy sector (see also section 2.3).

An essential element of the modeling framework is that it concentrates on a system dynamics description of physical entities and flows, and their relationships. This means that the drivers of emission changes in the model are those that also drive emissions in the real world such as number of animals and the feed consumed, fertiliser application, harvested areas and energy production rather monetary proxys for the drivers (as used often in general computable equilibrium models). Using the IMAGE model also allows us to calculate consequences of mitigation action in terms of atmospheric changes and climate impacts as well. This remained of this section concentrates on three crucial steps in the analysis, i.e. 1) the description of land-use related non-$CO_2$ emissions, 2) the marginal abatement costs for enhancement of carbon sequestration by forests (sinks) and 3) the incorporation of marginal abatement curves in our analysis.

### *2.2 Emissions in IMAGE 2.2*

In IMAGE 2.2, both energy and land-use emissions are calculated on the basis of multiplying (changes in) physical activity levels with (changes in) emissions factors (emissions = activity level x emission factor). The focus on physical activity levels (instead of monetary drivers used in many other models) has the advantage of a more comprehensive coverage of relevant dynamics for each individual driver, such as saturation (e.g. for many agricultural drivers) and linkages. The total set of gases and compounds comprising the emission calculations are:

- greenhouse gases covered by the Kyoto Protocol ($CO_2$,$CH_4$, $N_2O$, HFCs, PFCs and $SF_6$)
- ozone precursors ($NO_x$, CO, NMVOC)
- other important substances for radiative forcing (CFCs, aerosols)
- acidifying compounds ($SO_2$)

For the calibration period (1970-1995) both emission factors and activity levels are determined on the basis of available data sources, i.e. in particular FAO (agriculture, (FAO 1999)), IEA (energy, (IEA 2000)) and EDGAR (emissions (Olivier and Berdowski 2001)). Appendix 1 provides an overview of the agricultural emission sources, and the activity drivers used within the model. In the scenario period, both the activity levels and emission factors change over time. For the emission factors, it is (in general) assumed that the higher emission factors in less-industrialised countries slowly evolve to the emission factors in industrialised countries. For industrialised countries, trajectories are followed on the basis of historical rates of change – and assumed possible improvements (determined by the scenario context). Concentrating on the non-$CO_2$ gasses $CH_4$ and $N_2O$, their emissions mostly originate from agricultural activities (50% and 90%, respectively). In IMAGE, these activities are influenced by population growth, increases in per capita caloric intake, dietary practices, and agricultural production methods and yields. The largest source, for example, $CH_4$ emissions from animals (enteric fermentation) depend on the number of cattle (which is a function of meat demand, trade and animal size) and an animal-dependent emission factor. The second large source, $CH_4$ emissions from rice fields are based on the harvested areas of irrigated, rainfed and deepwater rice and regional emission factors. It should be noted that for the baseline emissions of the halocarbons, no independent modeling was done, but exogenously set scenarios are used from the IPCC SRES A1b scenario (Fenhann 2000).

### *2.3 Development of stabilisation profiles in terms of $CO_2$-equivalent emissions*

A set of global emission profiles has been developed that lead to stabilizing greenhouse gas forcing at 3.7, 4.5 and 5.3 $W/m^2$. These profiles are determined in terms of $CO_2$-equivalent emissions and used as caps for the cost-optimal implementation of reduction measures. The method for developing the profiles and the results are described in detail in (Eickhout et al. 2003). The profiles are based on three phases. First, until 2012, existing climate change policies are implemented - in particular - the Kyoto targets for most Annex-I countries and the Bush Climate Action Plan for the USA (see (White-House 2002)). All other regions follow the baseline. 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) and similar reduction rates for non-$CO_2$ gases that result in stabilisation of radiative forcing in 2150. We did not allow for overshooting the specific stabilization target - which implies that to reach the 3.7 $W/m^2$ target, rather steep reductions are required early on in the scenario. For the other two stabilization levels, much more flexibility in the timing of emission reduction is allowed; the profiles chosen should be regarded as being representative of medium reduction paths. As shown by Eickhout et al. (2003), emissions of different gases can be reasonably well substituted under these profiles, still leading to stabilisation of radiative forcing.

### *2.4 Determining the cost-optimal implementation of reduction measures*

The required mitigation action to reach the different stabilisation profiles is analyzed using the abatement cost model of FAIR 2.0 (den Elzen and Lucas 2003). The abatement cost model determines the cost-optimal implementation of the required global reductions over the different gases, sources and regions, using aggregated permit demand and supply curves. The permit demand and supply curves are derived from reduction costs curves on the basis of the same methodology as applied by Ellerman and Decaux (1998). For the non-$CO_2$ GHG emissions, MAC curves from EMF-21 (see Table 1) are used; these are based on detailed abatement options. For the energy and industry-related $CO_2$ emissions, response curves from the TIMER energy system model (Van Vuuren et al. 2004) are used, including technological developments, learning effects and system inertia.[4]

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 to be taken in the absence of climate policy ('frozen emission factors' (see Table 1 for the relevant references). Therefore, the following steps were made before the MACs were used in the costs calculations (see Figure 2):

- The MAC curves were translated into relative reductions from the original baseline and projected on our own baseline to create curves consistent with this scenario.
- Improvements in emission factors under the baseline scenario (representing mitigation measures implemented for other reasons than climate policy) were subtracted from the MACs in order to avoid double counting[5]. This baseline correction removed most of the negative costs parts of the EMF-21 curves. Remaining negative costs options in the EMF-21 were set at zero costs.

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[4] In order to capture the role of path dependency in the emission reductions, a large number of response curves have been calculated assuming a linear increase of the permit price after the first commitment period and the final value in the evaluation year. The response curves are converted into MAC curves to be used in FAIR. Under the baseline, regional differences in pay-back times for energy-efficiency investments are used to introduce differences in energy efficiency levels among regions. It is assumed in the mitigation cases that the high carbon prices and the emergence of an international permit market are assumed to lead to converging pay-back times, with full convergence at 300 US$ per tC-eq (Van Vuuren et al. 2003).

[5] This was done by determining the relative reduction of the relevant IMAGE emission factor (%), and subtracting this percentage from the low-cost side of the MAC.

- Increases in the abatements potential due to technology progress and removal of implementation barriers were accounted for by multiplying the MAC curves by a technological improvement rate.

A crucial uncertainty here is the rate at which the MAC curves move out in time. Unfortunately, little information is available on the possible improvement of the MAC curves after 2020. In addition to further development of existing technologies and development of new technologies, reduction of implementation barriers for current mitigation measures represent an important factor increasing abatement potential in time. Processes that decrease such barriers include time (overcoming limited capital turnover), changes in farming systems (from small scale, subsistence, farming systems to larger, commercial systems), increases in investment opportunities and development of systems that pool small-scale reduction options in order to reduce the transaction costs. Graus et al. (2004) indicate, on the basis of the detailed technology information underlying the EMF-21, that removal of implementation barriers could lead to an increase of global reduction potential for $N_2O$ emissions from 7% in 2010 (EMF-21) to 32% in 2050, for $CH_4$ emissions from enteric fermentation from 7% to 32%, for $CH_4$ emissions from manure from 17% to 44% and for $CH_4$ emissions from rice cultivation from 20% to 37% in 2050. Their numbers have been used to calibrate the rate of changes in MAC curves for these sources. For other non-$CO_2$ emission sources, long-term emission reduction potential could in theory be estimated in a similar way. However, such studies are still lacking. Instead, other technology development processes can be taken as a reference. For instance, the reductions in $CO_2$ emission in the energy model TIMER increase by about 1-2% annualy in the first 20 years after introduction of a carbon tax mostly as a result of overcoming inertia. After that period, the rate of increases is 0.5-1.0%, dominated by technological progress dynamics (Van Vuuren et al. 2004). Another example is the experienced efficiency improvement of end-use technology over the last 30 years (0.5-1.5% per year) (Schipper et al. 1997). Based on these numbers, we have assumed a relatively conservative value of an increasing potential (at constant costs) for all other non-$CO_2$ MACs of 0.4% per year.

### *2.5 Incorporating sinks estimates based on the IMAGE 2.2 model*

Several studies have looked into the costs and potential of carbon sequestration and generally found a potential ranging from hundreds of MtC-s up to 1-2 GtC annually, at costs ranging from $10-$200 US$ per ton stored (Kauppi and Sedjo 2001). These studies also indicate that the estimates strongly depend on the baseline scenario: for instance, how much agricultural land will become available for reforestration; how much deforestration occurs? To capture this baseline dependency, we have developed as set of marginal abatement cost curves for forestry (afforestration or reforestration) in the context of the IMAGE 2.2 model using the baseline of this study (see section 3). The sinks potential is determined at a 0.5 x 0.5 degree grid, fully taking into account changes in land-use and climatic conditions. We do not capture carbon sequestration specifically on degraded lands.

To determine the potential for reforestation, we first determine future land-use for food, feed, timber and biofuels. In IMAGE, the demand for these products is driven by population size, dietary preferences, income and trade. Yield changes in the agricultural sector subsequently determines how much land is required. As population growth slows down and agricultural yields further improve, land tends to become available that is no longer used for other purposes. The IMAGE model subsequently determines how much carbon can potentially be sequestered in that area. This, however, needs to be corrected for the amount of carbon that would be sequestered by regrowing natural vegetation in this area anyway. This is captured by the concept of Surplus Potential Productivity (SPP), which represents the net C sequestration by the plantation minus that of the original vegetation (see Figure 3). The carbon plantations are assumed to be implemented only in areas that 1) have a positive SPP and 2) have no other use for a 50-year period given the baseline. The net annual C sequestration is calculated as a mean during a 50-year period and aggregated from the grid level to the level of the IMAGE regions[6]. The carbon supply curves form the basis of the sink MAC curves by taking into account grid-level land costs, forest establishment costs, and operation and maintenance costs. The costs are based on the literature overview provided by IPCC (IPCC 1996). For, operation and maintenance costs a reference value for Western Europe of 95 US$ per hectare is used and varied for the other regions on the basis of per capita income. The overall annual potential sink derived in this way amounts in 2050 to about 1.5 GtC. However, the potential sink area is reduced by a factor to represent implementation barriers We have assumed that these barriers cause a reduction of the area through an implementation degree of 10% in 2010 and 30% in 2030 and onward (see also Graveland et al. (2002)).

The result of our approach is a changing MAC for each region over time and based on a detailed land-use assessment, with each point in the MAC representing a grid cell with a positive SPP (see Figure 4; the 4 regions shown are selected as examples). The potential of OECD regions (like Western Europe) is mostly influenced by increases in agricultural yields and the assumed management of carbon plantations. For some low-income regions (like South America) the availability of excess agricultural land around the middle of the century plays a major role, leading to great increase in carbon sequestration potentials.

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[6] All model calculations are performed at the level of 17 IMAGE regions or at the 0.5 x 0.5 grid (environmental variables and land-use). The IMAGE regions are Canada, USA, Central America, South America, Northern Africa, Western Africa, Eastern Africa, Southern Africa, Western Europe, Central Europe, FSU, Middle East, South Asia, East Asia, South-East Asia, Oceania, Japan.

## 3. The Common Poles IMAGE baseline

In our analysis we used the Common Poles IMAGE (CPI) baseline scenario (see also van Vuuren et al. (2003)). The scenario is based on the existing POLES model reference scenario (Criqui and Kouvaritakis (2000)) and the IMAGE IPCC SRES A1b and B2 baseline scenarios (IMAGE-team 2001). This scenario assumes a continued process of globalisation, medium technology, development and strong dependence on fossil fuels. Economic growth is near the historic average, with average per capita global growth at 2.1% in the early parts of the scenario - slowly declining to 1.4% in 2100. As growth is higher in low-income regions than in high-income regions, the relative gap between the regions is partially closed. The main exception is formed by Sub-Saharan Africa, where lack of stability and institutional capacity slow downs economic growth for the first 2-3 decades (and also in latter periods, this region stays significantly behind other regions). The assumptions for population are based on the UN medium projections up to 2030. For the period of 2030-2100, the UN long-term medium projection was used, as implemented for the IMAGE B2 scenario (IMAGE-team 2001). In this population scenario the global population stabilises at a level of 9.5 billion by 2100.

With the projected increase in population and income, primary energy use continues to grow in almost all regions. Worldwide, primary energy use increases by about 75% in 1995-2025 and by another 40% in the 2025-2050 period, with almost all of this growth occurring in non-Annex I regions. Oil continues to be the most important energy carrier until 2040, with its demand mainly driven by the transport sector. After 2040, both natural gas and coal take over this position worldwide, with particularly gas becoming the dominant energy carrier (natural gas is used mainly in the electric power section and stationary energy sectors). The actual mix, obviously, strongly differs with the region – with some regions relying on natural gas to fuel their electric power sector and others on coal.

As a result, energy-related carbon dioxide emissions increase sharply from 6.3 GtC in 2000 to 14.9 GtC in 2050, then level off to reach 15.4 GtC in 2100 (see Table 3) and continue to be the major source of GHG emissions. After 2050, stabilising population levels also slow down further growth in carbon dioxide emissions. In terms of land-use change, worldwide, population growth and shifts to more luxurious diets lead to an additional need for agricultural land in the first half of century, despite improvements in agricultural production. Later, further productivity gains result in a surplus of agricultural land, in particular, land in high-income regions that can be converted into forest areas. As a result, carbon dioxide emissions from land-use increase slightly between 1995 and 2040, but decrease afterwards. Most of the land-use related emissions originate in developing regions, in particular, due to population growth that leads to a higher agricultural demand and hence deforestation. The rate of deforestation in each region is also a good proxy for the amount of land that becomes available for carbon plantations (see Section 2.5). Table 4 depicts the deforestation rate in each region.

Table 3 also shows that total $CH_4$ and $N_2O$ emissions increase up to 2050, after which they remain more-or-less constant. Over the century, their contribution in total greenhouse gases drops from 23% to 18%, as their growth rate is slower than that of $CO_2$. This is caused by the fact that most land-use-related drivers of these emissions have strong saturation tendencies. For $CH_4$, only emissions from animal husbandry, gas production and landfills are likely to grow rapidly, in the absence of climate policies. For coal and oil production, changes in production levels and capture of methane for economic and safety reasons reduces $CH_4$ emissions. Wetland rice emissions remain more-or-less constant as not much expansion occurs in wetland rice cultivation and yields improve. For $N_2O$, only growing fertiliser use is expected to lead to increasing $N_2O$ emissions. Halocarbons (chlorinated and fluorinated gases) form by far the fastest growing category of emissions. The reasons for their increase include rapid growth rates of some emitting industries (semi-conductors, electricity production) and replacement of ozone-depleting substances by HFCs. It should be noted that despite the rapid increases, emissions in absolute terms remain relatively small compared to other sources.

Changes also occur in terms of the regional emissions. For all sources, emissions from non-Annex I countries grow considerably faster than those from Annex I countries. Looking at $CO_2$ emissions only, the share of emissions from Annex-I countries declines from 60% in 2000 to 20% in 2100. For all greenhouse gas emissions, the share of non-Annex I countries is already lower, i.e. nearly 50% in 2000. Here, as well, the share of Annex I countries declines to 20% in 2100.

The projection of IMAGE 2.2 are model based, but seem to compare well to scenarios that have been developed on the basis of specific country projections such as the recent scenario from EPA (Scheele and Kruger 2004). For the short-term period up to 2020, global methane emission increase by 33% in the EPA scenario between 2000 and 2020, and by 36% in the IMAGE CPI scenario. For $N_2O$, these numbers are 32% and 29%, respectively. For the fluorinated gases, both scenarios finally indicate an increase of nearly 120% in 2020 in terms of $CO_2$-equivalent emissions.

## 4. Stabilising radiative forcing at 4.5 W/m$^2$: Multi-gas versus $CO_2$-only

### *4.1 Emissions reductions and cost*

In order to reach the selected emission profile that leads to stabilisation of the greenhouse gas radiative forcing at 4.5 W/m$^2$, greenhouse gas emissions (measured in terms of $CO_2$-equivalents) under the multi-gas scenario need to be reduced by about 15% in 2025, 35% in 2050 and 60% in 2100 in comparison to the baseline emissions. The same equivalent emission profile was used for the $CO_2$-only run. Figure 5 compares the $CO_2$-only and multi-gas emission scenarios that have been developed under this stabilization target. It can be seen that for the $CO_2$-only scenario a small part of the emission reductions are, in fact, achieved through reduction of methane, as the systemic changes in the energy system, induced by putting a price on carbon, also reduces these emissions. $CO_2$ emissions are reduced by about 80% in 2100 compared to baseline.

In the Multi-gas scenario, less stringent reductions of $CO_2$ are obviously required (around 60% in 2100), although the figure also shows that still by far the largest contribution comes from reductions of $CO_2$ emissions. It should be noted that the reduction rates are not distributed evenly across the different gases and the contribution of different gasses changes sharply over time. For the Kyoto period, the majority of reductions can cost-optimally be achieved by reductions for the non-$CO_2$ gases and by using sinks. Only 10% of the reductions would be obtained from reducing energy-related $CO_2$ emissions (see also Lucas et al., (2002)). The disproportional contribution of non-$CO_2$ abatement at low prices is caused mainly by relatively low-cost abatement options that have been identified for these gases (e.g. reducing methane emissions from energy production and $N_2O$ emissions from adipic and acidic acid industries).

After 2015 the share of the non-$CO_2$ emissions in total reductions is slowly reduced. In part, this shifts simply reflects that non-$CO_2$ represents only a fifth or so of total greenhouse gas emissions, and that reduction becomes more proportional to the emissions. In addition, however, it also reflects the underlying reduction potential estimates. A large number of non-$CO_2$ emission sources have a limited (identified) abatement potential (such as $N_2O$ emissions from fertiliser application or $CH_4$ emissions from enteric fermentation). There are, at least in theory, other options to reduce these emissions that have not been accounted for in the abatement potential use such as changes in consumption patterns (e.g. a reduction of meat consumption) or radical changes in production patterns (bio-engineering). In contrast, other sources can be reduced substantially (sometimes by a combination of changes in energy use and end-of-pipe measures such as $CH_4$ emissions from energy production, which are reduced by 50-70%). The total abatement potential for non-$CO_2$ gases after 2050 is virtually exhausted. As a result, by the end of the century, the reductions for $CO_2$ are slightly higher than the average emission reductions. Overall, emissions need to be reduced by 60% in 2100, while the reduction of $CO_2$ is nearly 65%. For $CH_4$, relatively large reductions are obtained for landfills and production of coal, oil and gas (see also Table 2). The latter are not only due to end-of-pipe measures but also include the impact of more systemic changes in the energy system. Overall, $CH_4$ emissions are reduced by approximately 40% in 2050 and 45% in 2100. For $N_2O$, the most substantial reductions are achieved from the production of acidic and adipic acid (up to 70% reduction). For fertiliser use, some small reductions occur, but these are mostly offset by increases in emissions from agricultural lands due to biofuel production. For most $N_2O$ sources, no marginal abatement curves have been derived. Furthermore, emissions of the halocarbons are reduced by 65% for the total group, which is the maximum obtainable potential. Finally, the maximum amount of carbon sequestration for sinks per year is achieved by 2050, i.e. 0.4 GtC annually.

The marginal costs associated with these changes are presented in Figure 6. In both scenarios, the increase in marginal price follows a rather smooth path over most of the century. These costs range, however, from 310 US$/tCeq in 2100 for the multi-gas variant and 580 US$/tCeq for the $CO_2$-only scenario (nearly a factor 2 difference). These numbers are 138 and 175 US$/tCeq, respectively, in 2050 (30% difference). Two important reasons for the differences in marginal cost levels between the multi-gas and $CO_2$-only scenario exist. The first reason is that, early on in the scenario, the least-cost approach selects the relatively cheap emission reduction options, mainly exists for non-$CO_2$ sources. The second reason is that, in particular by the end of scenario period, the marginal costs of reducing $CO_2$ further has become so high that including more abatement potential (by including the non-$CO_2$ sources) substantially decreases the marginal costs. As a result, the difference in marginal costs is large early in the scenario (in 2010, 6 US$/tC-eq versus 30 US$/tC-eq or a factor 5) and by the end of the century (nearly a factor 2). Halfway the scenario, however, the impact on marginal costs is smaller. In terms of fraction of GDP, total abatement costs for both scenarios are 0.38% and 0.58% of world GDP in 2100. Here, the impact by the end of the century is less pronounced.

### *4.2 Climate impacts*

Despite the fact that both the multi-gas and the $CO_2$-only scenario have the same $CO_2$ equivalent emissions, the scenarios do not lead to exactly the same climate outcomes. While the multi-gas scenarios stabilises radiative forcing at 4.5 $W/m^2$, the 2100 radiative forcing of the $CO_2$-only scenario is already 4.9 $W/m^2$. The increase in global mean temperature in 2100 is 2.3°C for the multi-gas scenario and 2.5°C for the $CO_2$-only scenario. There are several reasons for this difference. First of all, emission reductions for $CH_4$ (in the multi-gas scenario) result in a faster reduction in GHG radiative forcing (due to its shorter lifetime) than for $CO_2$.

As a result, temperature increase is somewhat lower throughout the century. Secondly, the $CO_2$ concentration of the $CO_2$-only scenario is somewhat lower than for the multi-gas strategy, which implies less absorption of $CO_2$ by oceans and the biosphere. Thirdly, reducing $CO_2$ by means of systemic changes in the energy system leads to several other emission reductions, among which a reduction of sulphur emissions from the energy system (leading to higher temperature change as sulphur aerosols have a net cooling effect) and ozone precursors (leading to lower temperature change by reducing ozone concentrations). Sygna et al. (2002) have shown that by extending the scenario further into the future (e.g. 2300), the situation could shifts and the $CO_2$-only scenario might have the lowest temperature increase. In fact, we found a similar result by exploratively extending our results beyond 2100. The results shows that substition among different greenhouse gases using their (100 year) GWPs does not lead to exactly similar climate outcomes in 2100. The differences, however, are relatively small.

## 5. Stabilising radiative forcing at different levels

### *5.1 Emission reductions and cost*

Several researchers have established the cost increases as a result of a series of increasingly tight concentration targets for $CO_2$ (see Hourcade and Shukla (2001)). Comparing these cost levels to the possible climate impacts associated with these levels allows stakeholders to assess (to some degree) the advantages and disadvantages of stabilising $CO_2$ concentration at different concentration levels. Given the results of the previous section, which showed that including non-$CO_2$ gases can lead to major cost reductions, it seems useful to redo such an analysis on the basis of a multi-gas approach for different levels of radiative forcing. Here, two additional scenarios are assessed, i.e. 3.7 and 5.3 $W/m^2$. Figure 8 shows the accompanying scenarios and marginal price levels for stabilising radiative forcing at these levels.

For this 5.3 W/m$^2$ stabilisation scenario, the marginal price increases more or less linearly to a level of 100 US$/tCeq and remains constant thereafter, leading to a reduction of greenhouse gas emissions of 40% in 2100. $CO_2$ is reduced at a similar rate to the total greenhouse gases. The halocarbons are reduced more than proportionally (65%), while $CH_4$ (40%) and $N_2O$ (14%) are reduced less than proportional. For the most ambitious climate target (3.7 W/m$^2$) a different situation exists. First of all, emission reductions need to take place early in the scenario period in order to avoid an overshoot of the radiative forcing target. Moreover, in order to achieve the target, total 2100 emissions will need to be reduced by 75%. This implies that the amount of abatement potential for the non-$CO_2$ gases is crucial. Under our standard assumption, the carbon price needs to rise sharply, in order to avoid an overshoot of the radiative forcing level early in the scenario. After 2050, the carbon price increases more slowly. The fact that the marginal price is considerably higher than for the 4.5 W/m$^2$ scenario can be explained by the exponential form of the global MAC curve with rapidly increasing prices for the higher emissions reductions. By far, the most reductions come from $CO_2$, which is reduced by 80% in 2100 (compared to 75% for total greenhouse gases). Reductions of methane amount to 55%.

For the 3.7 W/m$^2$ scenario abatement costs per unit of GDP increases very rapidly from 2010 to 2040 to a maximum level of 1.5% of global GDP, after which the ratio gradually decreases to 0.8-0.9%. For the 4.5 W/m$^2$ scenario, the relative costs increase gradually and stabilises after 2070 at 0.4% of GDP. For the 5.3 W/m$^2$ stabilisation scenario, finally, costs reach a level of about 0.1% of GDP. It should be noted, however, that in all cases the cost levels as mentioned are subject to considerable uncertainty (as indicated in section 6).

In terms of reductions among the different gases, the three scenarios more-or-less confirm the trend already found for the 4.5 W/m$^2$ scenario (Figure 9). For the less stringent climate target a larger share of reductions is achieved through reductions of non-$CO_2$ gases than the average reduction, while for the more stringent target, $CO_2$ emissions need to be reduced more than the average reduction, as abatement options for the other gases have been exhausted. The radiative forcing of the different scenarios reflects the changes in terms of emission reductions. However, a few other important observations can be made. First, in terms of radiative forcing, the halocarbons become a considerable forcing agent by the end-of-the century (7% of total radiative forcing), surpassing as a group the contribution of $N_2O$. Secondly, $N_2O$ itself only represents a relatively small contribution to forcing, but given the lack of identified reduction options, its contribution is hardly increased for more ambitious scenarios. Third, in addition to the contributions of the Kyoto gases, there are also a number of other forcing agents – including tropospheric ozone, sulphur aerosols (negative forcing) and other aerosols. The contribution of the latter is very uncertain – and in the current IMAGE model represents only a small net negative forcing. The forcing of tropospheric ozone and sulphur aerosols, however, might still be in the order of a third of the $N_2O$ forcing. Interestingly, both ozone and sulphur aerosols are coupled to the reduction of $CO_2$ emissions. While reducing the net cooling effect of $SO_2$ leads to a higher temperatures of about 0.1 degree in 2100, the net reduction of ozone-forcing, in turn, leads to lower temperatures and offsets the sulphur impact on this time scale. This is, however, not true across the century, as the sulphur–carbon coupling tends to occur earlier than that the carbon and ozone precursor coupling.

### *5.2 Climate impacts*

The three multi-gas scenarios analysed here lead to clearly different temperature increases in 2100 (see Figure 10). Using the medium value for climate sensitivity (2.5 $W/m^2$), the 5.3 $W/m^2$ scenario leads to an increase of 2.6°C in 2100 over pre-industrial levels, i.e. 0.6°C less than in the baseline scenario. The 3.7 $W/m^2$ scenario, in contrast, leads to a 1.9°C increase. It should be noted that the EU has formulated as its objective of climate policy to limit global mean temperature increase to a maximum of 2.0°C warming. The 3.7 $W/m^2$ wouldjust be able to meet that target in 2100, but unless radiative forcing would be reduced after 2100, global mean temperature would increase further to an equilibrium level of about 2.3°C. The 4.5 $W/m^2$ stabilisation scenario takes an intermediate position.

Another proxy for the risk of adverse impacts from climate change is the rate of temperature change. In this analysis, we have not specifically targeted for meeting any rate of change target, although the resulting rates can still be assessed. Figure 10 shows that for the baseline scenario, the rate of temperature change is around 0.25°C per decade for the whole of the century. In the mitigation scenarios the rate of temperature increase drops to below a rate of 0.2°C per decade. For the 4.5 $W/m^2$ and 5.3 $W/m^2$ scenarios this occurs around 2060, and for the 3.7 W/m2 scenario in 2040. By the end of the century, rates of temperature increase are 0.05°C per decade for the 3.7 and 4.5 $W/m^2$ scenarios and just below 0.15°C per decade for the 5.3 $W/m^2$ scenario. In the early decades, however, the mitigation scenarios hardly do better than the baseline. The reason is that in the mitigation scenarios changes in the energy system to reduce $CO_2$ emissions also lead to a reduction in sulphur-cooling (as already emphasised by Wigley (1991)). This occurs in particular in those scenarios that concentrate on $CO_2$ reduction. The multi-gas 4.5 W/m2 and 5.3 W/m2 scenarios, in fact, both show a lower rate of temperature increase between 2020 and 2040 than the baseline as a result of more than proportional reduction of methane emissions. This indicates that there might indeed be a possibility of meeting a rate of change target in the 2000-2040 period in the context of long-term stabilisation scenarios, by emphasising non-$CO_2$ emission reductions, partly in order to offset the decreased aerosol cooling effect. Such scenarios are close to the proposed 'alternative' mitigation scenario by Hansen et al. (2000). However, whether such type of policies are realistically achievable is questionable, given for instance the limitation to reductions of non-$CO_2$ gasses (see earlier in the article) which will require extensive reductions of $CO_2$ sooner or later, but also the inertia in negotiation processes.

## 6. Discussion and sensitivity analysis

Many studies indicated the uncertainties that influence the results of the mitigation analysis in terms of abatement action and costs (Hourcade and Shukla 2001; Morita and Robinson 2001). In this section, we will explore some of the uncertainties that are important for our results for non-$CO_2$ gasses after 2010. The sensitivity of our results against these will be explored below. Other crucial uncertainties that impact costs include the assumptions on technology development for $CO_2$ abatement potential, the timing of mitigation action and the formation of an effective coalition to implement climate policy. As these, however, have been covered elsewhere (see for instance den Elzen et al (2004) and van Vuuren et al. (2004), we will not discuss them here. We will pay some attention to the role of using GWPs in our analysis. Moreover, we will discuss the impact of the uncertainty on climate sensitivity on the climate results.

### *Sensitivity to the baseline scenario*

The emission levels assumed in the baseline scenario directly determine the reductions that are required to reach the emission profile for stabilisation. In addition, the scenario assumptions also indirectly influence the abatement potential, in particular, assumptions related to costs of different technologies. Finally, the economic assumptions obviously influence the relative cost measures such as GDP losses or abatement costs as percentage of GDP. Figure 11 shows that the consequences of using a different baseline for global abatement costs and the contribution of non-$CO_2$ gasses in total emission reduction. In our analysis, we have used the IPCC SRES A1b and B2 scenarios as implemented by IMAGE 2.2 (IMAGE-team 2001) instead of the CPI baseline used so-far. The Figure shows that this has a very strong influence on costs. In case of the A1b scenario (a high economic growth scenario) rapidly rising emissions (in the absence of climate policy) imply that reaching a profile that leads to stabilisation at 4.5 $W/m^2$ requires strongly increasing costs levels during the first half of the century. In the second half, however, the relative costs to GDP decrease as continuing GDP growth offset costs increases and population decreases (assumed under this scenario) lead to decreasing baseline emissions anyway. In the B2 scenario (a medium growth scenarios with relatively low emissions), in contrast, costs develop much smoother as a result of a smaller gap between the baseline and the emission target. By the end of century, in both alternative scenarios, the baseline emissions levels are lower those of the CPI baseline. This leads to a smaller reduction obligation, resulting in a higher share of non-$CO_2$ gasses in total abatement and lower costs.

### *Sensitivity to the potential to reduce non-$CO_2$ emissions and their costs*

The rate at which the potential for non-$CO_2$ emission reductions develops after 2010 is a crucial uncertainty for the analysis performed here. Therefore, we explored two alternative scenarios, assuming no improvement in the total potential after 2010 and a faster improvement rate of 1% per year. In addition, a model run was performed in which the EMF-21 MAC curves for non-$CO_2$ gasses were totally replaced by those from the GECS project (the GECS project also developed global MAC curves for non-$CO_2$ gasses, see Criqui (2002)). The analysis shows that these (relatively small) changes in the rate of increase of the reduction potential (certainly within the range of likely assumptions, see the discussion in Section 2.4) can have considerable influences on the outcome. The sensitivity run assuming faster technology development for non-$CO_2$ gas reduction potential indicates a drop of relative costs to GDP from 0.34% to 0.30% in 2100. At the same time, the share of non-$CO_2$ gasses in total emission reduction increases from 19% to over 25%. The run with no further improvement in the abatement potential obviously shows the opposite, with costs increasing to 0.40% of GDP. Replacing the EMF-21 set of MAC curves by the alternative GECS curves increases the overall costs level. So-far no detailed source-by-source comparison between the GECS and EMF-21 curves was made. The most important factor that leads to lower costs in case of EMF-21 than for the GECS curves is the fact that former also covers several agricultural sources.

It should finally be noted that a several non-$CO_2$ emission sources, no MAC curces are available (e.g. $N_2O$ emissions from crop residues and animal waste). These emission in total cover about 0.5 GtC. In our analysis, we consequently assumed that no abatement can be obtained for them. The question whether abatement options (either technical options or via consumption changes) can be identified that are able to reduce the emissions from these sources in the future form a major uncertainty (and would reduce costs further compared to $CO_2$-only strategies).

*The use of GWPs to subtitute among different gases*

In the introduction, some of the critique that has been brought forward against the use of GWPs as a metric for substitution has been discussed (e.g. their arbitrary time period, their dependency on the specific situation (atmosphere composition) and the assumed possibility to separate the economic and physical dimensions of climate policy). It was concluded, however, that today no alternative measure has attained a comparable status, and that several authors have argued that the shortcomings and costs are likely to be outweighed by the strengths (that is, to conveniently allow for development of multi-gas strategies). Although no specific analysis has been performed, the use of GWPs is a important assumption in our analysis. It was found for the extreme case of including no non-$CO_2$ abatement versus the multi-gas strategy (for the 4.5 $W/m^2$ stabilisation scenario) in reaching a profile defined on the basis of 100 year GWPs leads to some differences in terms of radiative forcing and temperature change. These differences, however, are relatively small, and the scenarios will converge more after 2100. The main difference occurs in the first half of the century. In fact, one could argue that using GWPs has an additional advantage of not focussing on one particular target only (here a long-term stabilisation target), but also leads to considerable reductions of $CH_4$ early in the scenario period. Postponing this abatement (as would be suggested by flexible optimalisation) would lead to much higher rates of temperature in the 2000-2020 period as a result of additional changes in the energy sector, and associated reductions in sulphur cooling.

*Uncertainties influencing the temperature outcomes*

There are a number of critical uncertainties in the climate system that determine the temperature outcomes of the scenarios. Important uncertainties include the uncertainties associated with the carbon cycle, the radiative forcing of various agents, land-use change (impacting both the carbon cycle and the albedo), climate sensitivity and the ocean-heat uptake. A key uncertainties is the climate sensitivity (Matthews and van Ypersele 2003). In our analysis, a climate sensitivity of 2.5°C has been used, which is the medium estimate provided by IPCC (Cubash and Meehl 2001). If instead, climate sensitivity is varied across the range of 1.5-4.5°C (Cubash and Meehl 2001), the 2100 temperature increase for stabilisation at 4.5 W/m$^2$ changes from 2.3 °C (compared to pre-industrial) to a range from 1.5 – 3.5 °C. For stabilisation at 3.7 W/m$^2$, the 1.9 °C changes into a range from 1.3– 3.0 °C. This large range in climate outcomes represents a major challenge in decision-making. It is important to note the difference indicated in Table 5 between the 2100 temperature increase and the equilibrium temperature. Stabilising radiative forcing implies that a substantial further temperature increase is still to come after 2100 (e.g. 4.5 W/m$^2$ leads to a 2100 temperature increase of 2.3 °C, but an equilibrium temperature increase of 3.0 °C). A considerable share of that difference can actually be avoided, by not only stabilising radiative forcing, but by actually reducing radiative forcing after the peak level has been reached. So-far, not many (so-called) peaking scenarios have been explored, but they are likely to form part of a cost-effective long-term strategy to limit global temperature increase.

## 7. Conclusions

In this analysis, one baseline scenario and three multi-gas scenarios for stabilising radiative forcing at 3.7, 4.5 and 5.3 W/m$^2$ were developed. In addition, one scenario was developed with the same equivalent emission profile as the 4.5 W/m$^2$ multi-gas scenario, but now focussing reductions on $CO_2$-only. In the multi-gas stabilisation scenarios substitution among the different greenhouse gases was based on the marginal abatement costs and 100-year GWPs. The following conclusions can be drawn from the analysis:

*Simple trend extrapolation does not suffice in developing non-$CO_2$ emissions scenarios: each source is driven by specific dynamic activity levels. While total $CH_4$ and $N_2O$ emissions are projected to increase, their contribution in total emissions is likely to decline. Land-use related $CO_2$ emissions are expected to peak in the first half of the century and decline thereafter.*

Each source of greenhouse emissions is driven by a complex web of drivers, including activity changes, technological changes and environmental policies. To describe these changes properly, it is necessary to specify how these drivers are likely to develop in the future in an integrated way. Emissions of most of the non-$CO_2$ gases are coupled strongly with agricultural activities, which are likely to show strong saturation tendencies over the next century (as population growth slows down, and productivity continues to improve). As a result, the contribution of $CH_4$ is likely to decline from 19% to 15%, while the contribution from $N_2O$ remains constant at 4%. For $CH_4$, only emissions from animal husbandry, gas production and landfills are likely to grow rapidly in the absence of climate policies. In contrast, emissions of the halocarbons are likely to experience rapid growth rates but remain limited to 5% of total emissions in 2100. Finally, $CO_2$ emissions from deforestation are likely to peak before 2050 and decline thereafter. Factors that contribute to lower deforestation emissions are increasing scarcity of forests, slower population growth and further increases in agricultural productivity.

*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). Later in the scenario period, the contribution of most gases becomes more proportional to their share in baseline emissions.*

For most of the non-$CO_2$ gases, relatively cheap reduction options exist to reduce part of their emissions. A multi-gas approach using 100-year GWPs chooses to use these options for the non-$CO_2$ gases (which, in general, have high GWP values) as a crucial part of a cost-effective policy in the near term. As a result, the contribution of $CO_2$ in the first two decades is limited to only 10-20% of total reductions, while the contribution of non-$CO_2$ gasses is 50-60% and sinks cover about 20-30% of the reductions. However, as overall, global reduction targets become increasingly tight with time, the lion's share of reductions needs to come from $CO_2$. A factor that contributes to this, is that the current knowledge on abatement options for non-$CO_2$ gases for several sources only allows for reductions in the order of 20% of emissions (see further). This is, in particular, the case for hard-to-abate sources such as enteric fermentation and fertiliser application.

*While the contribution of non-$CO_2$ gases in the mitigation scenarios remains limited to 20-30% by the end of the century, the impact of including non-$CO_2$ gases on total costs can be very large. In other words 'what flexibility' is very important in reducing costs.*
In order to stabilise radiative forcing at 4.5 $W/m^2$, the marginal costs in 2100 of a multi-gas scenario is a factor of 2 lower than for the $CO_2$-only scenario. There are two important reasons for this. First of all, early in the scenario period the multi-gas approach strongly benefits from the low-cost non-$CO_2$ reduction options. Secondly, by the end of the scenario period, the reductions achieved by non-$CO_2$ abatement measures avoid the most expensive options for $CO_2$ that need to be taken for the $CO_2$-only scenario.

*Including non-$CO_2$ gases allows for meeting more stringent climate targets, while the role of non-$CO_2$ in total abatement is dependent on the radiative forcing stabilsiation target.* In this study, three different scenarios aiming for stabilisation of radiative forcing at 5.3, 4.5 and 3.7

$W/m^2$ were developed. In terms of the share in total emission reductions, the non-$CO_2$ gases play a major role in the 5.3 $W/m^2$ stabilisation scenario (their radiative forcing is reduced from more than 1.6 $W/m^2$ in the baseline to 1.0 $W/m^2$ in the stabilisation scenario). For more stringent targets, reductions of $CO_2$ will become more and more important. In the 3.7 $W/m^2$ scenario, for instance, more than 80% of the emissions reductions come from $CO_2$. The reduction potential for $N_2O$ is seriously constrained; as a result of this, the emissions of this gas hardly depends on the stabilisation target.

*The contribution of other forcing agents – such as ozone and sulphur - are also impacted by the mitigation scenarios, even if policies do not target them deliberately. The reduced negative forcing from sulphur aerosols increases total radiative forcing, while the reduced forcing from ozone might compensate this effect.*

The emissions from $SO_2$ (causing the formation of sulphur aerosols) and $NO_x$ and VOC (the main precursors of ozone formations) all stem mainly from combustion of fossil fuels. The systematic changes in the energy sector induced by climate policies also reduce the emissions of these gases. As a result, both the negative forcing from sulphur and the positive forcing from tropospheric ozone seriously decreases for more stringent stabilisation scenarios. The impact on ozone forcing seems in the long term to offset the impact on sulphur. In the first few decades, however, the impacts on sulphur forcing are considerably larger than those on ozone resulting in a relatively rapid rate of temperature increase (due to larger sulphur emissions and a more than proportional impact on the use of coal).

*The development of the abatement potential and reduction costs for non-$CO_2$ gases in the future represents a crucial uncertainty for current assessments on mitigation scenarios.*

The information on non-$CO_2$ abatement options and their costs have been inventoried for EMF-21 for mainly 2010, and over a limited cost range of 0 to 200 US$/tCeq. After 2010, the abatement potential of most gases is likely to increase as a result of technological development and the reduction of implementation barriers. The rate at which these trends will evolve, however, are highly uncertain. Under the current implementation the cheap parts of the non-$CO_2$ MACs tend to get exhausted before the middle of the century in scenarios aiming to stabilise at 4.5 $W/m^2$ or below. This is reflected in the rapid drop in the share of the non-$CO_2$ gases in total reductions over time. It will be crucial to extend research on non-$CO_2$ emission reduction options beyond 2010. Questions are whether there are physical or economic barriers to reduce the non-$CO_2$ gases further; or whether technological development is likely to lead major increases in the current abatement potential. We have assessed the impact of technology development in a series of sensitivity runs, showing the large impacts on the marginal price and overall costs.

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Figure 1: Overview of the modeling approach used.

Figure 2: Incorporation of Marginal Abatement Curves in FAIR 2.0.

Figure 3: Schematic representation of the calculation of the Surplus Potential Productivity (SPP).

Figure 4: Sinks MAC curves for four regions in 2010 (left) and 2050 (right).

Figure 5: Contribution of gases in total emission reduction over time ($CO_2$ only (left) versus multi-gas (right)).

Figure 6: Global abatement costs as % of GDP (left) and marginal reduction costs (right).

Figure 7: Climate impacts of stabilising radiative forcing at 4.5 $W/m^2$, multi-gas vs. $CO_2$ only.

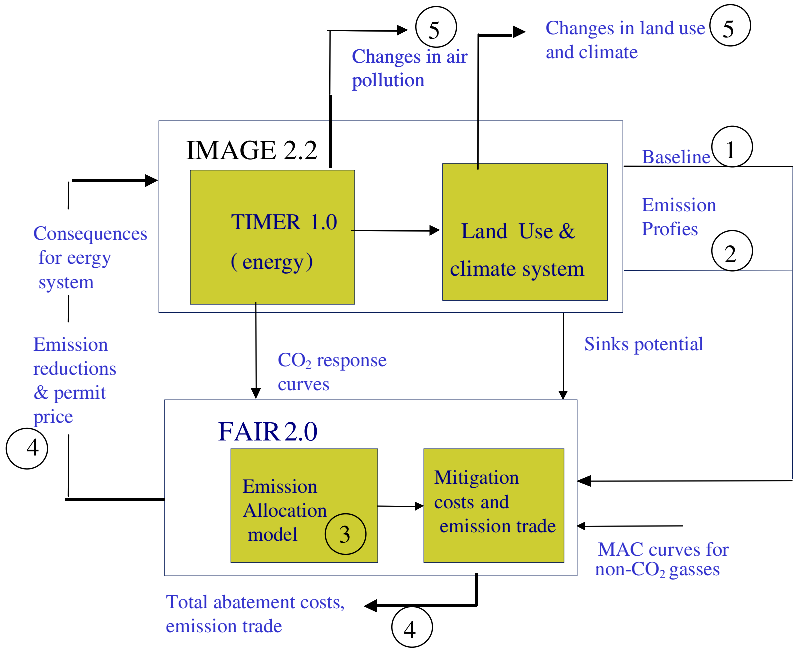
Figure 8: Stabilisation of radiative forcing at 3.7 $W/m^2$, 4.5 and 5.3 $W/m^2$; greenhouse gas emissions (left), marginal reduction costs (middle) and global abatement costs as % GDP (right).

Figure 9: $CO_2$ equivalent emissions (left) and radiative forcing (right) in 2100 for stabilisation at 3.7, 4.5 and 5.3 $W/m^2$.

Figure 10: Global mean temperature change compared to pre-industrial levels (left) and decadel temperature increase (right) for the different scenarios analysed.

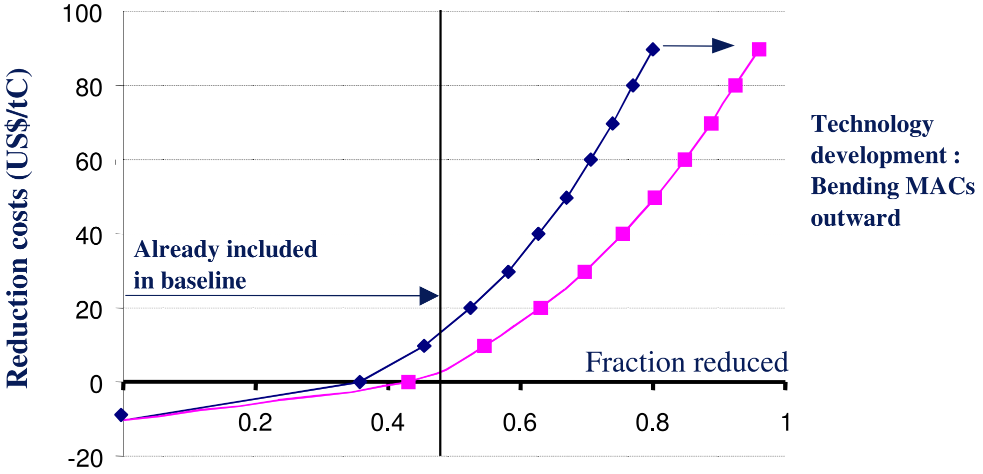
Figure 11: Results of sensitivity tests for baseline and assumptions of rate of increase of of non-$CO_2$ reduction potential, stabilisation at 4.5 $W/m^2$ (left marginal costs; right contribution of non-$CO_2$ gasses).

**Figure 1: Overview of the modeling approach used.**



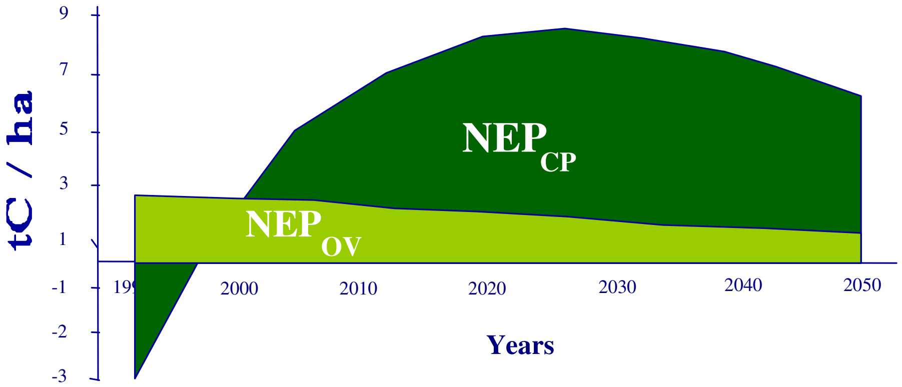
Note: numbers in Figure refer to the 5 major modeling steps discussed in the methodology section (2.1).

**Figure 2: Incorporation of Marginal Abatement Curves in FAIR 2.0.**



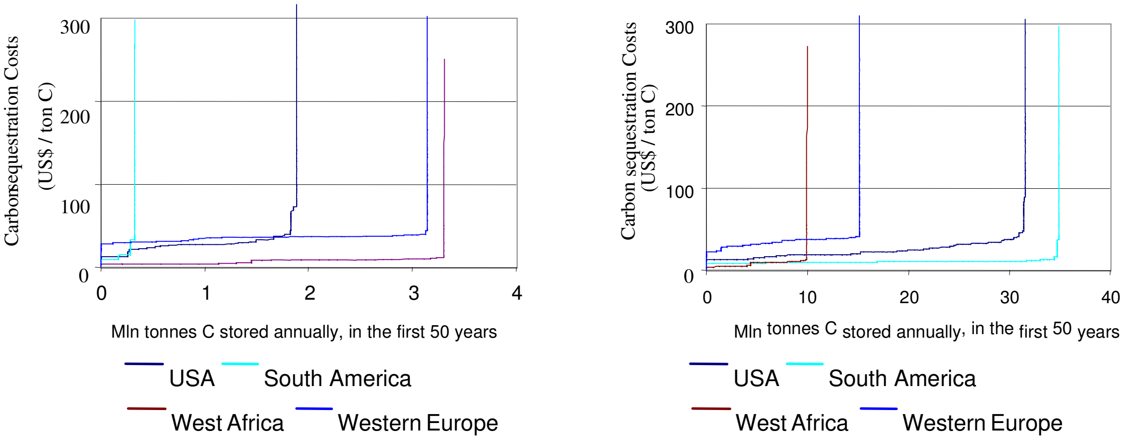
Note: The marginal abatement curves are corrected for the improvements are already assumed in the baseline scenario, and bend outward in time as result of technology development,

**Figure 3: Schematic representation of the calculation of the Surplus Potential Productivity (SPP).**



Note: Surplus Potential Productivity (SPP) is defined as the difference between the NEP for the carbon plantation (CP) and that for the situation in the baseline scenario (original vegetation, OV). The negative NEP for the carbon plantation in the initial years is the result of decomposition of litter and soil organic matter following clearing of the original vegetation.

**Figure 4: Sinks MAC curves for four regions in 2010 (left) and 2050 (right).**



Note: Calculations are performed at the level of 17 world regions. Here, four regions are shown to indicate the different changes as a function of time for different regions.

**Figure 5: Contribution of gases in total emission reduction over time, 4.5 W/m$^2$ stabilisation (CO$_2$ only (left) versus multi-gas (right)).**

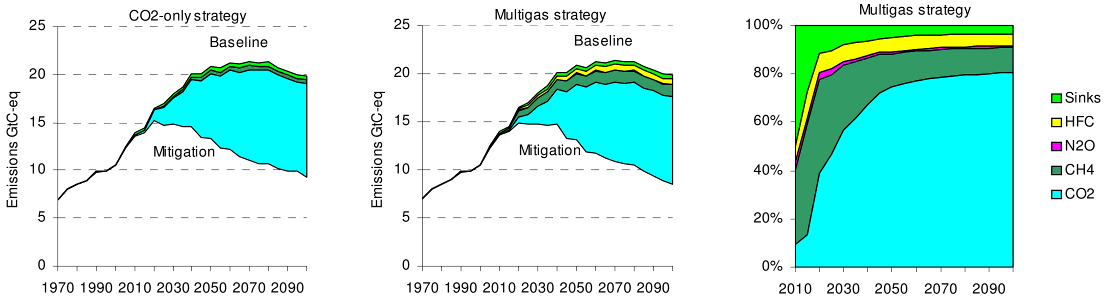


**Figure 6: Global abatement costs as % of GDP (left) and marginal reduction costs (right).**

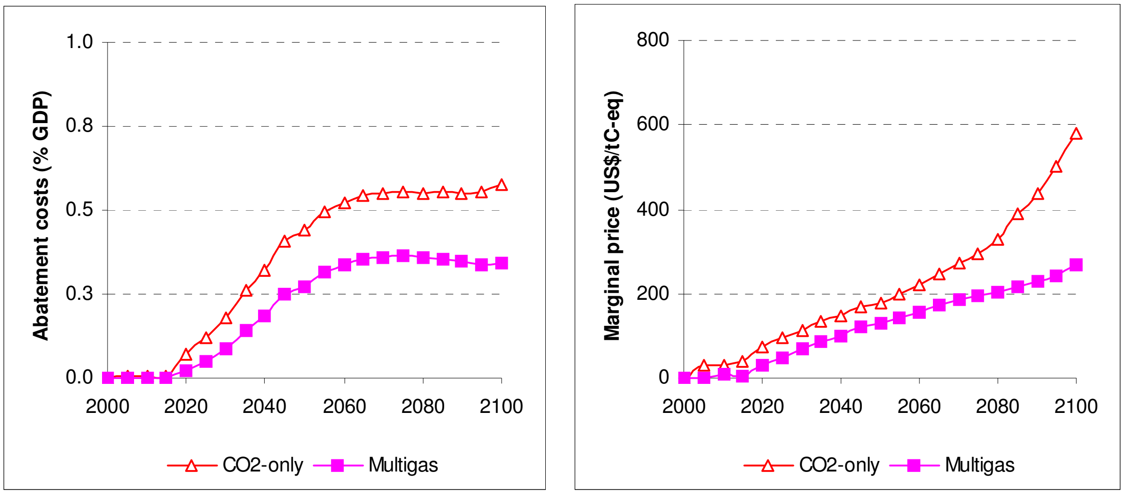
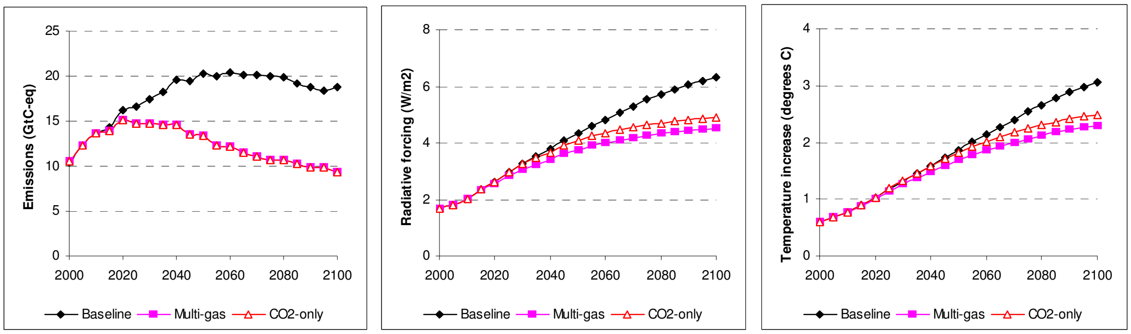


**Figure 7: Climate impacts of stabilising radiative forcing at 4.5 W/m$^2$, multi-gas vs. CO$_2$ only.**



(Note: A climate sensitivity of 2.5°C has been assumed).

**Figure 8: Stabilisation of radiative forcing at 3.7 W/m$^2$, 4.5 and 5.3 W/m$^2$; greenhouse gas emissions (left), marginal reduction costs (middle) and global abatement costs as % GDP (right).**

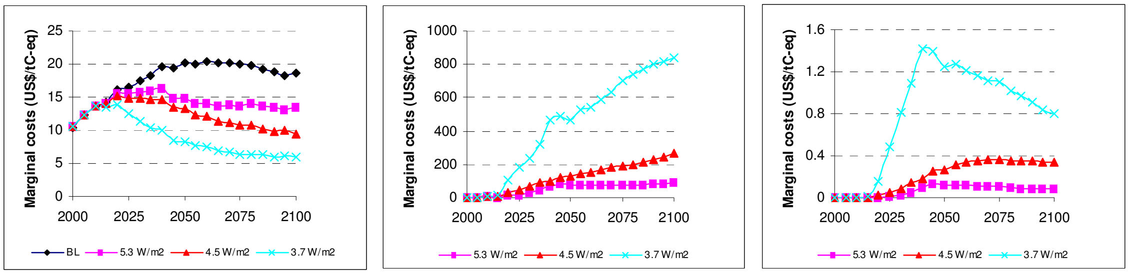
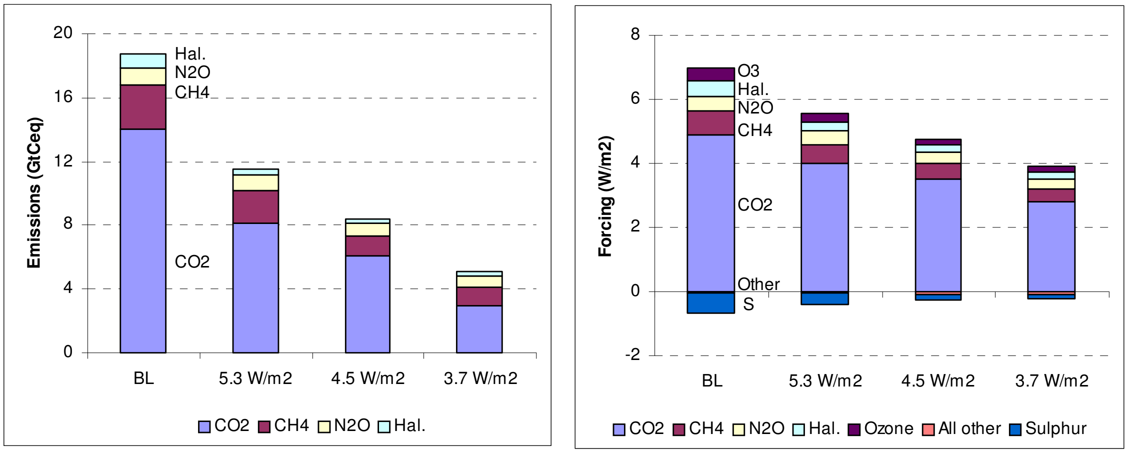


**Figure 9: $CO_2$ equivalent emissions (left) and radiative forcing (right) in 2100 for stabilisation at 3.7, 4.5 and 5.3 $W/m^2$.**



Note: ‘Hal.’ = halocarbons as covered by the Kyoto protocol. All other captures additional forcing of water, stratospheric ozone and aerosols.

**Figure 10: Global mean temperature change compared to pre-industrial levels (left) and decadel temperature increase (right) for the different scenarios analysed.**

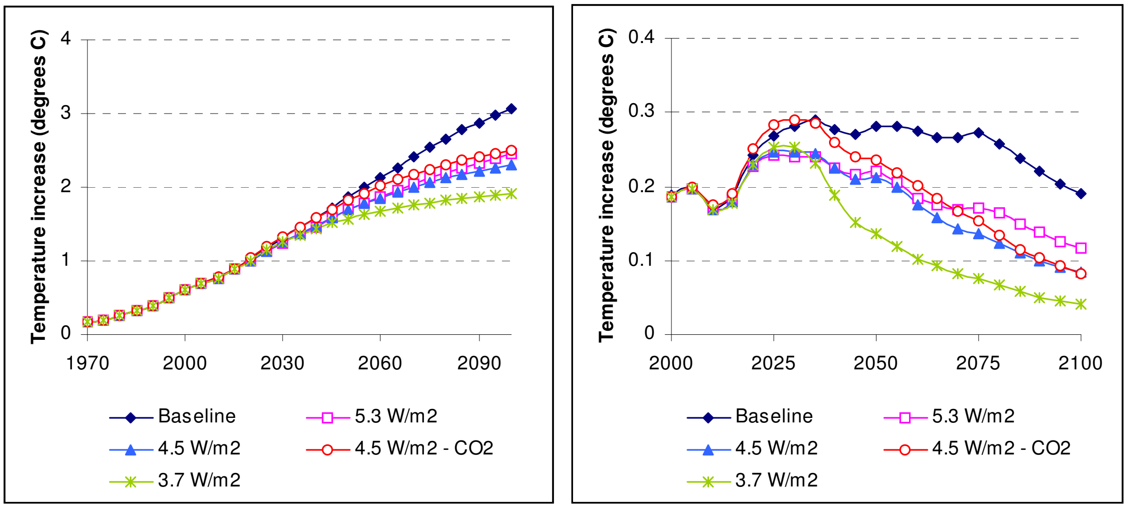


**Figure 11: Results of sensitivity tests for baseline and assumptions of rate of increase of of non-$CO_2$ reduction potential, stabilisation at 4.5 $W/m^2$ (left marginal costs; right contribution of non-$CO_2$ gasses).**

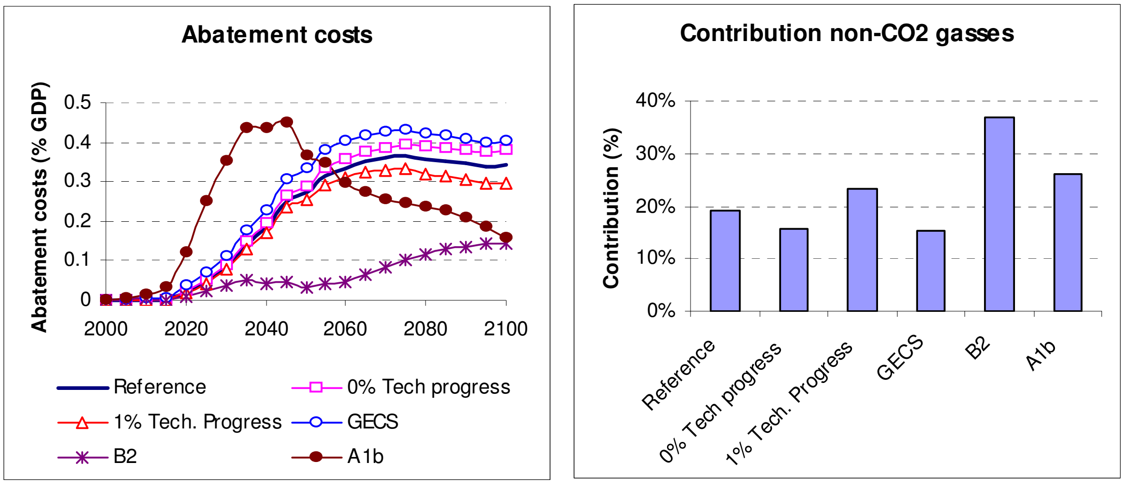


Table 1: Source of information on marginal abatement costs

| *Emission category (Non-$CO_2$ gasses)* | *Source of information on marginal abatement costs* | *Reduction potential of main sources (2010)* | *Assumed annual increase of potential* |
|---|---|---|---|
| CH4 and N2O from agricultural sources | (DeAngelo et al. 2004) and (Graus et al. 2004) for development of potential in 2010-2050 period. | $N_2O$ soil: 7% | 3.9% until 2050 |
| | | $CH_4$ animals: 7% | 3.9% until 2050 |
| | | $CH_4$ rice: 20%[*] | 1.5% until 2050 |
| | | $CH_4$ manure : 17% | 2.4% until 2050;<br>0.4% 2050-2100 |
| CH4 and N2O emissions from industrial and energy-related sources | (Delhotal et al. 2004) (*) | $CH_4$ total : 65%<br>$N_2O$ process : 90-95% | 0.4% |
| Halocarbons | (Schaefer et al. 2004) | Total reduction of 40% | 0.4% |
| *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 iterating between FAIR and TIMER (Van Vuuren et al. 2004) | 2010: Around 50%<br>2100: Around 80% | - |
| Sinks | Based on IMAGE calculations (Graveland et al. 2002) | Potential increases to 0.4 GtC annually in 2050 | - |
| Forest management | Conservative assumptions based on the extension of the Marrakesh Accords as described in (Van Vuuren et al. 2003) | A total amount of 135 MtC-eq annualy is assumed. | - |

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[*] 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).

*Table 2: Main driving forces of the CPI baseline by regions*

| | Population (in mill.) | | | Per Capita Income (in PPP €1995 per year)[7] | | | Per Capita Income (growth rates) | |
|---|---|---|---|---|---|---|---|---|
| | 1995 | 2025 | 2050 | 1995 | 2025 | 2050 | 1995-2025 | 2025-2050 |
| Canada & USA | 296 | 362 | 391 | 25604 | 42520 | 55757 | 1.7% | 1.1% |
| Enlarged EU | 505 | 499 | 450 | 17128 | 34534 | 50107 | 2.4% | 1.5% |
| CIS | 293 | 298 | 273 | 1747 | 5323 | 14750 | 3.8% | 4.2% |
| Oceania | 28 | 40 | 46 | 15469 | 30054 | 43397 | 2.2% | 1.5% |
| Japan | 125 | 121 | 111 | 41052 | 65270 | 90424 | 1.6% | 1.3% |
| Latin America | 476 | 690 | 800 | 3591 | 6779 | 12144 | 2.1% | 2.4% |
| Africa | 719 | 1346 | 1831 | 613 | 873 | 1761 | 1.2% | 2.8% |
| ME & Turkey | 219 | 378 | 483 | 3282 | 6371 | 12577 | 2.2% | 2.8% |
| South Asia | 1245 | 1865 | 2160 | 356 | 1560 | 4060 | 5.0% | 3.9% |
| SE & E Asia | 1798 | 2293 | 2439 | 1392 | 7404 | 16930 | 5.7% | 3.4% |
| World | 5706 | 7891 | 8984 | 4931 | 9052 | 14413 | 2.0% | 1.9% |

*Source: IMAGE 2.2*

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[7] GDP levels of different countries are normally compared on the basis of conversion to a common currency (mostly US$) 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). In this article, we have usually used PPP-based GDP estimates, but where required, MER-based estimates for comparison are used.

*Table 3: Emissions under the CPI baseline and the 4.5 W/m$^2$ multi-gas stabilisation scenario*

| | CPI-baseline | | | | | | *Multi-gas 4.5 W/m$^2$ stabilization scenario* | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Emissions (in GtC-eq) | | | Share in emissions (%) | | | Emissions (in GtC-eq) | | | *Change compared to baseline (%)* | | |
| Gases and sources | 2000 | 2050 | 2100 | *2000* | *2050* | *2100* | 2000 | 2050 | 2100 | *2000* | *2050* | *2100* |
| **CO2** | | | | | | | | | | | | |
| Energy | 6.29 | 14.93 | 15.35 | *81%* | *93%* | *101%* | 6.29 | 9.15 | 5.51 | *100%* | *61%* | *36%* |
| Process | 0.44 | 0.56 | 0.38 | *6%* | *3%* | *3%* | 0.44 | 0.39 | 0.17 | *100%* | *70%* | *44%* |
| Land-use | 1.02 | 0.62 | -0.58 | *13%* | *4%* | *-4%* | 1.00 | 0.28 | -0.66 | *100%* | *-91%* | *39%* |
| | 7.74 | 16.12 | 15.15 | *100%* | *100%* | *100%* | 7.72 | 9.83 | 5.02 | *100%* | *65%* | *36%* |
| **CH4** | | | | | | | | | | | | |
| Landfills | 0.19 | 0.47 | 0.46 | *10%* | *16%* | *17%* | 0.19 | 0.10 | 0.00 | *100%* | *22%* | *0%* |
| Sewage | 0.18 | 0.27 | 0.28 | *10%* | *9%* | *10%* | 0.18 | 0.27 | 0.28 | *100%* | *100%* | *100%* |
| Wetland rice | 0.20 | 0.20 | 0.18 | *10%* | *7%* | *6%* | 0.20 | 0.15 | 0.08 | *100%* | *72%* | *46%* |
| Animals | 0.60 | 0.90 | 1.06 | *31%* | *30%* | *38%* | 0.60 | 0.83 | 0.90 | *100%* | *92%* | *85%* |
| Other land-use | 0.15 | 0.15 | 0.10 | *8%* | *5%* | *4%* | 0.15 | 0.13 | 0.09 | *101%* | *86%* | *88%* |
| Coal production | 0.20 | 0.30 | 0.22 | *10%* | *10%* | *8%* | 0.20 | 0.08 | 0.02 | *100%* | *28%* | *7%* |
| Oil production | 0.05 | 0.06 | 0.01 | *3%* | *2%* | *0%* | 0.05 | 0.04 | 0.00 | *100%* | *68%* | *46%* |
| Gas production | 0.31 | 0.60 | 0.42 | *16%* | *20%* | *15%* | 0.31 | 0.19 | 0.13 | *100%* | *31%* | *32%* |
| Other energy | 0.03 | 0.04 | 0.03 | *1%* | *1%* | *1%* | 0.03 | 0.03 | 0.01 | *100%* | *77%* | *17%* |
| Process emissions | 0.01 | 0.01 | 0.00 | *0%* | *0%* | *0%* | 0.01 | 0.00 | 0.00 | *100%* | *61%* | *58%* |
| | 1.91 | 3.00 | 2.77 | *100%* | *100%* | *100%* | 1.91 | 1.82 | 1.52 | *100%* | *61%* | *55%* |
| **N2O** | | | | | | | | | | | | |
| Animal waste | 0.15 | 0.16 | 0.16 | *33%* | *25%* | *23%* | 0.15 | 0.10 | 0.10 | *100%* | *65%* | *65%* |
| Fertilizer | 0.17 | 0.29 | 0.33 | *38%* | *45%* | *49%* | 0.17 | 0.24 | 0.27 | *100%* | *82%* | *82%* |
| Domestic sewage | 0.02 | 0.03 | 0.03 | *5%* | *5%* | *5%* | 0.02 | 0.02 | 0.02 | *100%* | *65%* | *65%* |
| Crop residues | 0.01 | 0.04 | 0.05 | *3%* | *6%* | *7%* | 0.01 | 0.04 | 0.05 | *100%* | *100%* | *101%* |
| Biological N fixation | 0.01 | 0.02 | 0.03 | *3%* | *4%* | *4%* | 0.01 | 0.02 | 0.03 | *100%* | *100%* | *101%* |
| Other land-use | 0.03 | 0.04 | 0.02 | *6%* | *7%* | *3%* | 0.03 | 0.04 | 0.02 | *103%* | *92%* | *104%* |
| Energy | 0.02 | 0.03 | 0.04 | *4%* | *5%* | *5%* | 0.02 | 0.02 | 0.02 | *100%* | *58%* | *62%* |
| Process | 0.04 | 0.02 | 0.02 | *8%* | *4%* | *4%* | 0.04 | 0.01 | 0.01 | *100%* | *29%* | *28%* |
| | 0.44 | 0.64 | 0.68 | *100%* | *100%* | *100%* | 0.44 | 0.48 | 0.52 | *100%* | *76%* | *77%* |
| **All gases** | | | | | | | | | | | | |
| CO2 | 7.74 | 16.12 | 15.15 | *76%* | *78%* | *78%* | 7.72 | 9.83 | 5.02 | *100%* | *65%* | *36%* |
| CH4 | 1.91 | 3.00 | 2.77 | *19%* | *15%* | *14%* | 1.91 | 1.82 | 1.52 | *100%* | *61%* | *55%* |
| N2O | 0.44 | 0.64 | 0.68 | *4%* | *3%* | *3%* | 0.44 | 0.48 | 0.52 | *100%* | *76%* | *77%* |
| HFC | 0.07 | 0.601 | 0.675 | *1%* | *3%* | *3%* | 0.07 | 0.258 | 0.237 | *100%* | *43%* | *35%* |
| PFC&SF6 | 0.069 | 0.193 | 0.195 | *1%* | *1%* | *1%* | 0.069 | 0.083 | 0.068 | *100%* | *43%* | *35%* |
| **Total** | **10.17** | **19.62** | **18.34** | ***100%*** | ***100%*** | ***100%*** | **10.20** | **12.47** | **7.36** | ***100%*** | ***64%*** | ***40%*** |

Table 4: Deforestation rates in million ha per year (negative values imply growth of forest area)

| | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Canada | -4.80 | -0.62 | 0.19 | -2.00 | -2.75 | 0.16 | 1.06 | -0.01 | -0.03 | 0.02 | -0.25 |
| USA | -1.65 | -0.66 | -0.64 | -0.44 | -0.46 | -0.11 | 0.53 | -0.06 | 0.08 | -0.06 | -0.01 |
| Latin America | -3.70 | 5.53 | 2.37 | 1.95 | -1.58 | -1.80 | 2.59 | 2.19 | 4.34 | 3.49 | 2.31 |
| Europe | -1.74 | -0.95 | -1.20 | -0.96 | -0.50 | 0.01 | 0.36 | -0.09 | 0.19 | -0.04 | -0.01 |
| CIS | -13.65 | 2.53 | -3.09 | -4.22 | -3.55 | -3.27 | -1.74 | 0.83 | 0.99 | 0.15 | 0.32 |
| East Asia (incl. China) | 4.10 | -2.20 | -5.08 | -5.27 | -4.42 | -4.91 | -0.99 | -0.03 | -0.20 | -0.32 | 7.32 |
| South Asia (incl. India) | -1.38 | 5.64 | 2.86 | -0.25 | 0.01 | 0.07 | 0.12 | -0.50 | -0.50 | -0.34 | 0.00 |
| Oceania | 3.38 | -0.33 | 0.36 | 1.55 | -0.67 | -0.88 | 0.31 | 0.49 | 1.43 | 0.49 | -0.06 |
| Asia-Pacific | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Africa | 0.25 | 21.07 | 24.19 | 9.03 | 13.10 | 7.84 | 0.82 | -9.74 | -15.32 | -10.10 | -2.96 |
| World | -22.23 | 34.72 | 25.73 | 2.70 | 1.87 | 0.46 | 4.95 | -5.66 | -7.35 | -7.57 | 5.88 |

## Table 5: Main characteristics of the 3 multi-gas stabilization scenarios

| | Stablisation | | Forcing | | | Concentration | | Temperature increase | |
|---|---|---|---|---|---|---|---|---|---|
| | 2150 | | 2100 | | | 2100 | | 2100 | Equilibrium |
| | W/m$^2$ | $CO_2$-eq conc. | CO2 forcing | Other Kyoto gas forcing | Other forcing | $CO_2$-eq conc | $CO_2$ conc. | | |
| 1 | 3.7 | 550 | 2.73 | 0.90 | -0.03 | 550 | 470 | 1.9 | 2.5 |
| 2 | 4.5 | 650 | 3.55 | 0.90 | -0.08 | 635 | 540 | 2.3 | 3.0 |
| 3 | 5.3 | 750 | 4.01 | 1.03 | -0.12 | 715 | 610 | 2.6 | 3.6 |
| Baseline | | | 4.88 | 1.58 | -0.16 | 936 | 696 | 3.1 | |

## Appendix A: Description of land-use related emissions

The table below describes the key assumptions in land-use related emissions in IMAGE 2.2.

| *Source* | *Key activity level* | *Emission factors and other assumptions* |
|---|---|---|
| Biomass burning (deforestation) (CH4, CO, N2O, NOx, NMVOC SO2) | Land use change/deforestation | Based on the quantity of C burnt during deforestation (as indicated by the carbon stock model) |
| Savanna burning (CH4, CO, N2O, NOx, NMVOC) | Area of savanna | Based on the quantity of C burnt in savannas (fixed carbon flux per unit area) |
| Agricultural residue burning (CH4, CO, N2O, NOx, NMVOC, SO2) | Crop areas | Based on the crop, fraction above-ground residues and burning fraction based on (Bouwman et al. 1997), (Smil 1999); (EPA 1994) and emission factors from (IPCC 1997) |
| Landfills (CH4) | Urban population | Coupled to urban population + exogenous emission factor for $CH_4$ treatment |
| Domestic sewage treatment (CH4, N2O) | Human population | Coupled to total human population, and a GDP dependent treatment factor |
| Wetland rice fields (CH4) | Area of wetland rice fields | Based on harvested areas of irrigated, rainfed and deepwater rice (FAO 1999) Regional emission factors based on (Neue 1997). |
| Animals (CH4) | Number of animals | Cattle: feed intake (cattle) according to (Alcamo et al. 1998). Other animals: animal populations; emission factors from (IPCC 1997). |
| Animal waste (CH4, N2O) | Number of animals. | Emission factors from (IPCC 1997). |
| Arable land (N2O,NOx) | Agricultural land area | N2O: Based on N-fertilizer use, use of N-fixing crops (pulses, soybeans), and crop residue incorporation. Emission factors and general procedure from (IPCC 1997).<br>NOx: N fertilizer use (synthetic fertilizer + animal manure); emission factor from (Veldkamp and Keller 1997). Crop residue incorporation as for N2O |
| Indirect sources (N2O) from surface water and goundwater caused by N leaching from soils | Agricultural land area | Based on use of synthetic N fertilizers and animal manure N and population according to (IPCC 1997). |
| Land-clearing effects (N2O, NOx) | Land use change/deforestation | Based on forest clearing rates (deforestation) plus post-clearing for N2O emission rates according to (Kreileman and Bouwman 1994). |
| Aquatic sources (CH4, CO, N2O, SO2) | Constant | Based on IPCC (CH4, CO); (N2O); oceanic DMS (IPCC 1995) |
| Natural wetlands (CH4) | Constant | Constant; global emission based on (IPCC 2001). |
| Soils under natural vegetation (N2O, NOx) | Area of different vegetation types | N2O: Based on NPP, soil fertility index, monthly mean temperature and soil moisture, soil type, (Modified from (Bouwman et al. 1993); (Kreileman and Bouwman 1994).<br>NOx: based on the areas of biomes; emission factors for biomes from (Davidson and Kingerlee 1997). These emission factors include canopy reduction factors to describe absorption of NOx by plant leaves. |
| Natural vegetation (NMVOC) | Area of different vegetation types | Emission from (Guenther et al. 1995). |
| Other natural sources (CH4, CO, NOx, SO2) | Constant | Constant, based on (IPCC 1995); includes CH4 from termites and CH4 hydrates, CO from plants and wildfires, NOx from lightning, SO2 from natural sources (volcanoes) |