

Long-Term Multi-Gas Scenarios to Stabilise Radiative Forcing – Exploring Costs and Benefits Within an Integrated Assessment Framework

D.P. van Vuuren†, B. Eickhout*, P.L. Lucas* and M.G.J. den Elzen**

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/m². At the moment, non-CO₂ gasses (methane, nitrous oxide, PFCs, HFCs and SF₆) contribute to about a quarter of the global emissions. The analysis shows that including these non-CO₂ gasses in mitigation analysis is crucial in formulating a cost-effective response. For stabilisation at 4.5 W/m², a multi-gas approach leads to 40% lower costs than an approach that would focus at CO₂-only. Within the assumptions used in this study, the non-CO₂ gasses contribution to total reduction is very large under less stringent targets (up to 60%), but declines under stringent targets. While stabilising at 3.7 W/m² obviously leads to larger environmental benefits than the 4.5 W/m² case (temperature increase in 2100 are 1.9 and 2.3°C, respectively), the costs of the lower target are higher (0.80% and 0.34% of GDP in 2100, respectively). Improving knowledge on how future reduction potential for non-CO₂ gasses could develop is shown to be a crucial research question.

1. INTRODUCTION

Increasing atmospheric concentrations of carbon dioxide (CO₂) 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), including methane (CH₄), nitrous oxide (N₂O) and fluorinated and chlorinated hydrocarbons (halocarbons, HFC, PFC, SF₆). In order to 'stabilise greenhouse gas concentrations in the atmosphere at a level

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* Netherlands Environment Assessment Agency (MNP/RIVM), PO Box 303, 3720 BA Bilthoven, The Netherlands.

† Corresponding author: D.P. van Vuuren. Email: Detlef.van.Vuuren@mnp.nl.

that would prevent dangerous anthropogenic interference with the climate system' (UNFCCC 1992) these gases need to be accounted for as well. In 1997, policy-makers acknowledged this by formulating the Kyoto targets in terms of a 'basket' of greenhouse gases¹ (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-CO₂ gases has been lacking. Available studies exploring the impacts of including non-CO₂ gases nevertheless find important advantages in terms of reduction of costs and in terms of avoiding climate impacts.

For 'CO₂-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-CO₂ (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 CO₂-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-CO₂ gases into the modeling framework. The third question will be dealt with in our analysis, while the first two questions will be discussed here.

Regarding the first methodological question, long-term CO₂-only stabilisation studies generally explored the environmental and economic implications of stabilising the CO₂ concentration (ranging from 450-750 ppmv) (EMF-16 1999;

1. The gasses, from now on referred to as 'Kyoto' gasses are CO₂, CH₄, N₂O, PFCs, HFCs and SF₆. CFCs and HCFCs have not been covered by the Kyoto protocol as their consumption has been dealt with in the context of treaties on ozone depleting substances.

Hourcade and Shukla 2001; Swart et al. 2002). For multi-gas studies, one could use 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). Analogy with the CO₂ 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 (Matthews and van Ypersele 2003). 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 3), the contribution of the non-Kyoto radiative agents (mentioned in the list 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/m² in 2150, with 3.7 and 5.3 W/m² as alternative targets². A radiative forcing target of 4.5 W/m² more or less equates to a CO₂ concentration at 550 ppmv (the standard case in most earlier work), assuming 1 W/m² additional forcing for the non-CO₂ 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. Fuglestedt et 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, CO₂-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 explicitly specify for economic dimension of the problem and are based on a rather arbitrary time horizon), the concept is

2. Radiative forcing can also be expressed by the equivalent CO₂ 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 CO₂ concentration of 550, 650 and 750 ppmv CO₂-eq., respectively.

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.

Thus, to answer our two focal questions, five different scenarios have been developed, i.e. the baseline scenario, a scenario that stabilizes radiative forcing at 4.5 W/m^2 in 2150 using a multi-gas approach, a scenario that mitigates 'CO₂-only' using the CO₂-equivalent emissions of the multi-gas 4.5 W/m^2 scenario as a gap³, 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-CO₂ 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 CO₂-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 2005). 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 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.

3. To indicate the link between the multi-gas and CO₂-only run, the latter is referred to as 4.5 W/m^2 CO₂-only stabilisation. Note that using a similar CO₂-equivalent emissions trajectory for the CO₂-only scenario does not necessarily lead to a similar radiative forcing stabilisation as the multi-gas scenario (4.5 W/m^2).

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 CO₂-equivalent emission profiles, leading to a stabilization of the GHG concentration at a radiative forcing of 3.7, 4.5 and 5.3 W/m² (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 CO₂ derived from by TIMER or IMAGE) and exogenously determined MACs of the EMF 21 project (non-CO₂) (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-CO₂ gases, to the IMAGE/TIMER model to determine the changes in emission levels.
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 CO₂-equivalent emissions determines the reduction rate of one specific source. For all energy-related sources, a mixed approach is used, in which first MAC curves are derived in the energy model; next, the marginal price (based on MACs) are determined;

and finally these are fed back 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 CO₂ emissions will also reduce methane emissions emitted from energy production and transport. Using this hybrid MAC approach has the advantage of 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 be 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, fertilizer application, harvested areas and energy production rather than monetary proxies 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. The remainder of this section concentrates on crucial steps in the analysis, i.e. 1) the description non-CO₂ emissions, 2) the development of stabilisation profiles, 3) the determination of the cost-optimal implementation of reduction measures and 4) the incorporation of estimates for carbon sequestration by forests (sinks) into the model.

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 (CO₂, CH₄, N₂O, HFCs, PFCs and SF₆)
- ozone precursors (NO_x, CO, NMVOC)
- other important substances for radiative forcing (CFCs, aerosols)
- acidifying compounds (SO₂)

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. The supplementary information to this paper⁴ 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-CO₂ gasses CH₄ and N₂O, 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, CH₄ emissions from animals (enteric fermentation) depends 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, CH₄ emissions from rice fields is 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 CO₂-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/m². These profiles are determined in terms of CO₂-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 CO₂ concentration calculations of Enting et al. (1994) and similar reduction rates for non-CO₂ 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/m² 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 reductions is allowed; the profiles chosen should be regarded

4. Supplementary Information on this paper is available from the EMF-website.

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 2005). 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 cost curves on the basis of the same methodology as applied by Ellerman and Decaux (1998). For the non-CO₂ 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 CO₂ emissions, response curves from the TIMER energy system model (Van Vuuren et al. 2004) are used, including technological developments, learning effects and system inertia.⁵

The non-CO₂ 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 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 counting⁶. 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.
- 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.

5. 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).

6. 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.

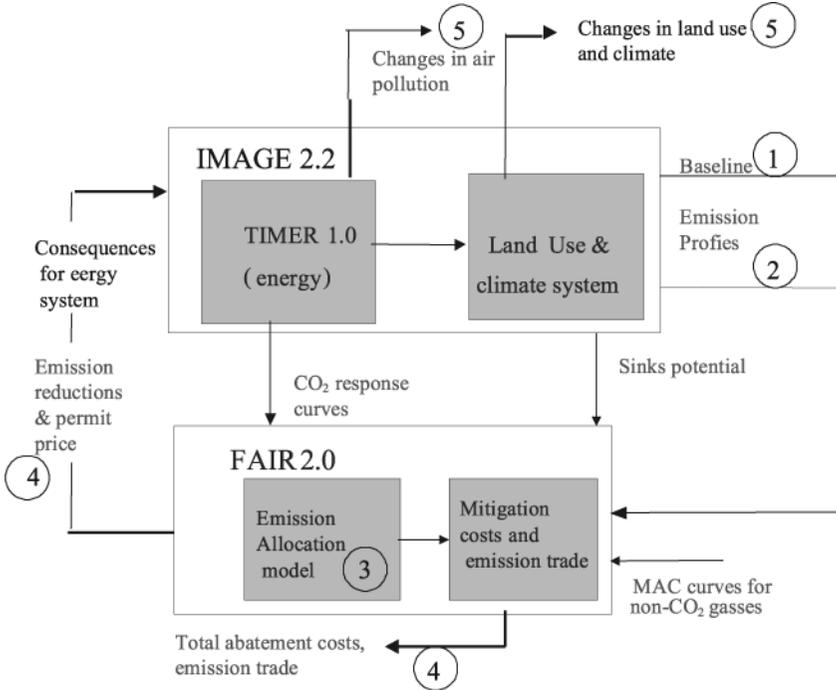
Table 1. Source of Information on Marginal Abatement Costs

<i>Emission category (Non-CO₂ gasses)</i>	<i>Source of information on marginal abatement costs</i>	<i>Reduction potential of main sources (2010)</i>	<i>Assumed annual increase of potential</i>
CH ₄ and N ₂ O from agricultural sources	DeAngelo et al. (2006) and Graus et al. (2004) for development of potential in 2010-2050 period.	N ₂ O soil: 7% CH ₄ animals: 7% CH ₄ rice: 20%* CH ₄ manure : 17%	3.9% until 2050 3.9% until 2050 1.5% until 2050 2.4% until 2050; 0.4% 2050-2100
CH ₄ and N ₂ O emissions from industrial and energy-related sources	Delhotal et al. (2006) (*)	CH ₄ total : 65% N ₂ O process : 90-95%	0.4%
Halocarbons	Schaefer et al. (2006)	Total reduction of 40%	0.4%
<i>Emission category (CO₂)</i>	<i>Source of information on marginal abatement costs</i>	<i>Reduction potential of main sources</i>	<i>Assumed annual increase of potential</i>
CO ₂ from energy use and production	Time-dependent MACs iterating between FAIR and TIMER (Van Vuuren et al. 2004)	2010: Around 50% 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 annually is assumed.	—

* In DeAngelo et al. (2006) a reduction of 38% is given. This number has been scaled down for 2010 on the basis of Graus et al. (2004).

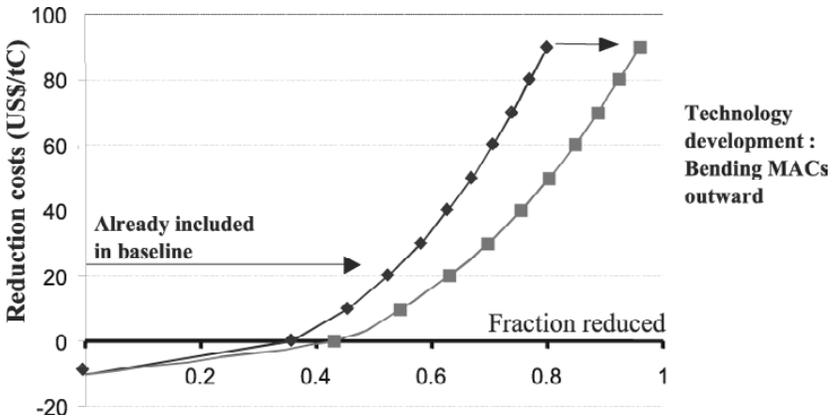
A crucial uncertainty here is the rate at which the MAC curves move out in time. Unfortunately, little information is available on the possible improvement of the MAC curves after 2020. In addition to further development of existing technologies and development of new technologies, reduction of implementation 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 data, that removal of implementation barriers could lead to an increase of

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 already assumed in the baseline scenario, and bend outward in time as result of technology development.

global reduction potential for N₂O emissions from fertiliser use from 7% in 2010 (EMF-21) to 32% in 2050, for CH₄ emissions from enteric fermentation from 7% to 32%, for CH₄ emissions from manure from 17% to 44% and for CH₄ 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-CO₂ 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 CO₂ emission in the energy model TIMER increase by about 1-2% annually 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-CO₂ 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 reforestation; how much deforestation occurs? To capture this baseline dependency, we have developed a set of marginal abatement cost curves for forestry (afforestation or reforestation) 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 regions⁷. 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 (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 the total potential to 10% in 2010 and 30% in 2030 and onward (see also Graveland et al. 2002).

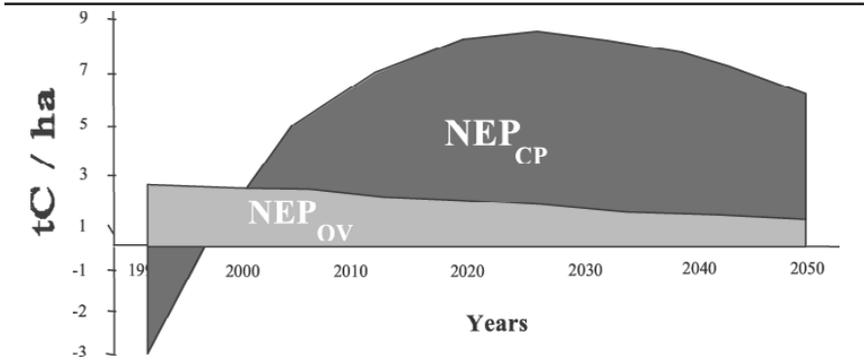
The result of our approach is a changing MAC for each region over time based on a detailed land-use assessment, with each point in the MAC representing a grid cell with a positive SPP (see Figure 4; the 4 regions shown are selected as examples). The potential of OECD regions (like Western Europe) is 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.

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.

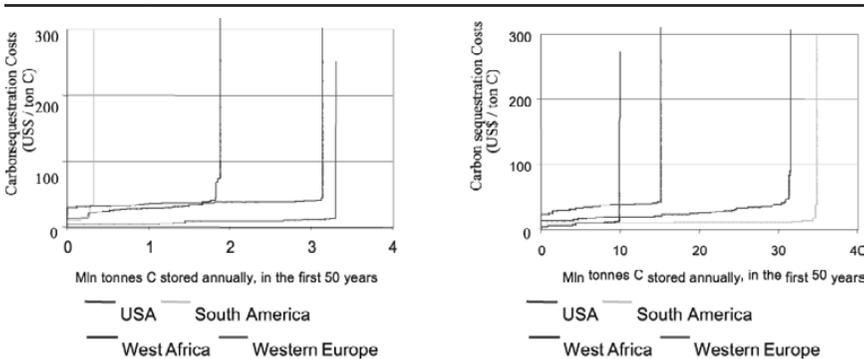
7. All model calculations are performed at the level of 17 IMAGE regions or at the 0.5 x 0.5 grid (environmental variables and land-use). The IMAGE regions are Canada, USA, Central America, South America, Northern Africa, Western Africa, Eastern Africa, Southern Africa, Western Europe, Central Europe,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

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.

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 among regions – 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 2 and Supplementary Information) 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 meat and poultry in people's 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 plantation.

Total CH₄ and N₂O emissions increase up to 2050, after which they remain more-or-less constant (Table 2). Over the century, their contribution in total greenhouse gases drops from 23% to 18%, as their growth rate is slower than that of CO₂. This is caused by the fact that most land-use-related drivers of these emissions have strong saturation tendencies. For CH₄, 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 CH₄ emissions. Wetland rice emissions remain more-or-less constant as not much expansion occurs in wetland rice cultivation and yields improve. For N₂O, only growing fertiliser use is expected to lead to increasing N₂O 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 CO₂ 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 projections 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 2006). 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.

Table 2. Emissions Under the CPI Baseline and the 4.5 W/m² Multi-gas Stabilisation Scenario

	CPI-baseline						<i>Multi-gas 4.5 W/m² stabilization scenario</i>					
	Emissions (in GtC-eq)			Share in emissions (%)			Emissions (in GtC-eq)			<i>Change compared to baseline (%)</i>		
Gases	2000	2050	2100	2000	2050	2100	2000	2050	2100	2000	2050	2100
CO ₂	7.74	16.12	15.15	76%	78%	78%	7.72	9.83	5.02	100%	65%	36%
CH ₄	1.91	3.00	2.77	19%	15%	14%	1.91	1.82	1.52	100%	61%	55%
N ₂ O	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												
&SF ₆	0.069	0.193	0.195	1%	1%	1%	0.069	0.083	0.068	100%	43%	35%

Detailed information of the sources per gas is included in the supplementary information which is available from the EMF-website.

For N₂O, 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 CO₂-equivalent emissions.

4. STABILISING RADIATIVE FORCING AT 4.5 W/M²: MULTI-GAS VERSUS CO₂-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/m², greenhouse gas emissions (measured in terms of CO₂-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 CO₂-only run. Figure 5 compares the CO₂-only and multi-gas emission scenarios that have been developed under this stabilization target. It can be seen that for the CO₂-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. CO₂ emissions are reduced by about 80% in 2100 compared to baseline.

In the Multi-gas scenario, less stringent reductions of CO₂ are obviously required (around 60% in 2100), although the figure also shows that still by far the largest contribution comes from reductions of CO₂ 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 (Table 2; Figure 5). For the Kyoto period, the majority of reductions can cost-optimally be achieved by reductions for the non-CO₂ gases and by using sinks. Only 10% of the reductions

would be obtained from reducing energy-related CO₂ emissions (see also Lucas et al., (2005)). The disproportional contribution of non-CO₂ 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 N₂O emissions from adipic and acrylic acid industries).

After 2015 the share of the non-CO₂ emissions in total reductions is slowly reduced. In part, this shift simply reflects that non-CO₂ 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-CO₂ emission sources have a limited (identified) abatement potential (such as N₂O emissions from fertiliser application or CH₄ 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 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 CH₄ emissions from energy production, which are reduced by 50-70%). The total abatement potential for non-CO₂ gases after 2050 is virtually exhausted. As a result, by the end of the century, the reductions for CO₂ are slightly higher than the average emission reductions. Overall, total greenhouse gas emissions are reduced by 60% in 2100, while the reduction of CO₂ is nearly 65%. For CH₄, relatively large reductions are obtained for landfills and production of coal, oil and gas. 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, CH₄ emissions are reduced by approximately 40% in 2050 and 45% in 2100. For N₂O, the most substantial reductions are achieved from the production of acrylic 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 N₂O sources, no marginal abatement curves were available and emissions simply follow the baseline. Emissions of the halocarbons are reduced by 65% for the total group. Finally, the maximum amount of carbon sequestration for sinks 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 CO₂-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 CO₂-only scenario exist. The first reason is that, early on in the scenario. The least-cost approach selects the relatively cheap emission reduction options which mainly consists of reductions in non-CO₂ sources. The second reason is that by the end of scenario period, the marginal costs of reducing CO₂ further has become so high that including more abatement

Figure 5. Contribution of Gases in Total Emission Reduction Over Time (CO₂ Only (left) versus Multi-gas (right))

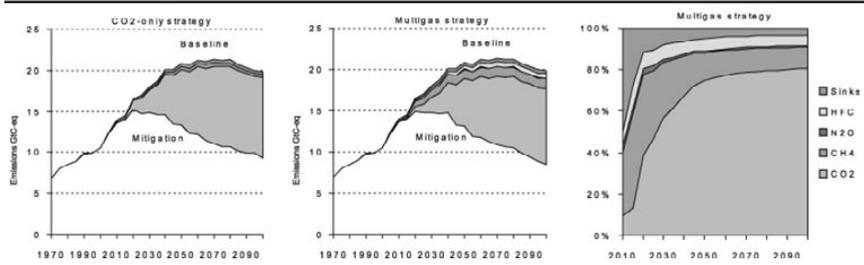
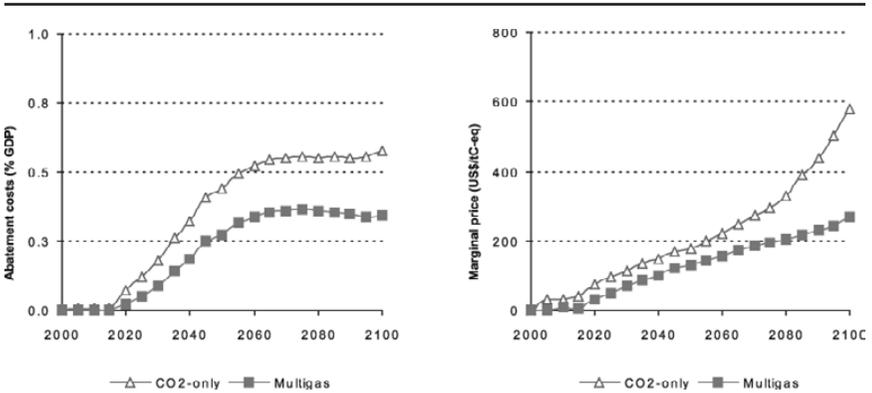


Figure 6. Global Abatement Costs as % of GDP (left) and Marginal Reduction Costs (right)



potential (by including the non-CO₂ sources) substantially decreases the marginal costs. As a result, the difference in marginal costs is large early in the scenario (in 2010, 6 US\$/tCeq versus 30 US\$/tCeq 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 CO₂-only scenario have the same CO₂ 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/m², the 2100 radiative forcing of the CO₂-only scenario is already 4.9 W/m². The increase in global mean temperature in 2100 is 2.3°C for the multi-gas scenario and 2.5°C for the CO₂-only scenario. There are several reasons for this difference. First of all, emission reductions for CH₄ (in the multi-gas scenario) result in a

faster reduction in GHG radiative forcing (due to its shorter lifetime) than for CO₂. As a result, temperature increase is somewhat lower throughout the century. Secondly, the CO₂ concentration of the CO₂-only scenario is somewhat lower than for the multi-gas strategy, which implies less absorption of CO₂ by oceans and the biosphere. Thirdly, reducing CO₂ 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 shift and the CO₂-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 substitution 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.

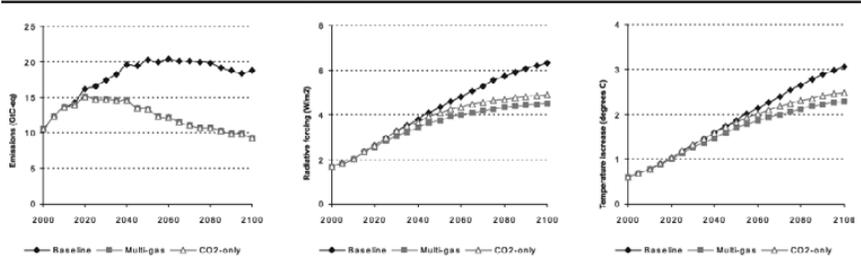
5. STABILISING RADIATIVE FORCING AT DIFFERENT LEVELS

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 CO₂ (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 CO₂ concentration at different concentration levels. Given the results of the previous section, which showed that including non-CO₂ 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/m². Figure 8 shows the accompanying scenarios and marginal price levels for stabilising radiative forcing at these levels. Table 3 shows some of the main results for greenhouse gas emissions and temperature change.

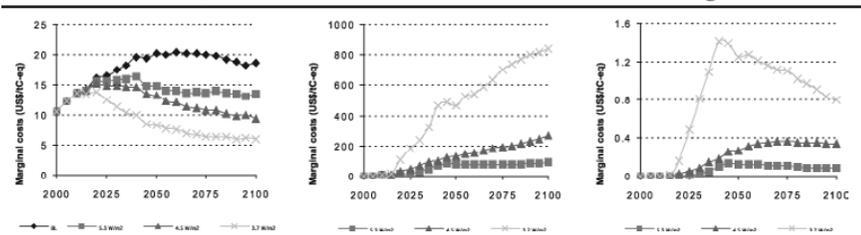
For this 5.3 W/m² stabilisation scenario, the marginal price increases more or less linearly to a level of 100 US\$/tCeq and remains constant thereafter, leading to a reduction of greenhouse gas emissions of 40% in 2100. CO₂ is reduced at a similar rate to the total greenhouse gases. The halocarbons are reduced more than proportionally (65%), while CH₄ (40%) and N₂O (14%) are reduced less than proportional. For the most ambitious climate target (3.7 W/m²) 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-CO₂ 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

Figure 7. Climate Impacts of Stabilising Radiative Forcing at 4.5 W/m², Multi-gas vs. CO₂ Only



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

Figure 8. Stabilisation of Radiative Forcing at 3.7 W/m², 4.5 and 5.3 W/m²; Greenhouse Gas Emissions (left), Marginal Reduction Costs (middle) and Global Abatement Costs as % GDP (right)



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/m² 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 CO₂, 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/m² stabilisation 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/m² scenario, the relative costs increase gradually and stabilises after 2070 at 0.4% of GDP. For the 5.3 W/m² 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 reported here 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/m² scenario (Figure 9). For the less stringent climate target a larger share of reductions is achieved through reductions of non-CO₂ gases than the average reduction, while for the more stringent target, CO₂ emissions need to be reduced more than the average reduction, as

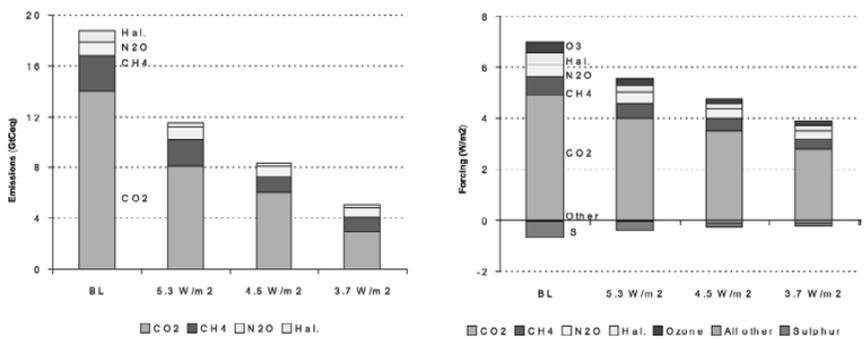
abatement options for the other gases have been exhausted. The radiative forcing of the different scenarios reflects the changes in terms of emission reductions. However, a few other important observations can be made. First, in terms of radiative forcing, the halocarbons become a considerable forcing 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 and Table 3). 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 would just be able to meet that target in 2100 for a medium climate sensitivity value, but unless radiative forcing is 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.

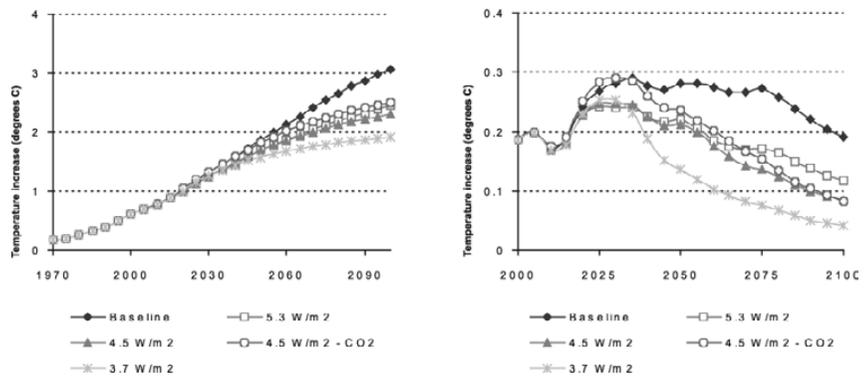
Another proxy for the risk of adverse impacts from climate change is the rate of temperature change. In this analysis, we have not specifically targeted for meeting any rate of change target, although the resulting rates can still be assessed. Figure 10 shows that for the baseline scenario, the rate 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/m^2 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

Figure 9. CO₂ Equivalent Emissions (left) and Radiative Forcing (right) in 2100 for Stabilisation at 3.7, 4.5 and 5.3 W/m²



Note: 'Hal.' = halocarbons as covered by the Kyoto protocol. 'Other' other captures additional forcing of water, stratospheric ozone and aerosols. 'S' represents the net forcing from sulphur aerosols.

Figure 10. Global Mean Temperature Change Compared to Pre-Industrial Levels (left) and Decadal Temperature Increase (right) for the Different Scenarios Analysed



mitigation scenarios changes in the energy system to reduce CO₂ 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 CO₂ reduction. The multi-gas 4.5 W/m² and 5.3 W/m² scenarios, 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-CO₂ emission reductions, partly in order to offset the decreased aerosol cooling

Table 3. Main Characteristics of the 3 Multi-gas Stabilization Scenarios

	Stabilisation		Forcing			Concentration		Temperature increase	
	2150		2100			2100	2100	Equilibrium	
	CO ₂ -eq conc. (W/m ²)	CO ₂ forcing (ppm)	Other Kyoto gas forcing (W/m ²)	Other conc (W/m ²)	CO ₂ -eq conc. (ppm)	CO ₂ (ppm)	(ppm)	(ppm)	(ppm)
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	

effect. Such scenarios are close to the proposed 'alternative' mitigation scenario by Hansen et al. (2000). However, whether such policies are realistically achievable is questionable, given for instance the limitations to reductions of the non-CO₂ gasses (see above) which will require extensive reductions of CO₂ sooner or later, but also the inertia in the negotiation processes.

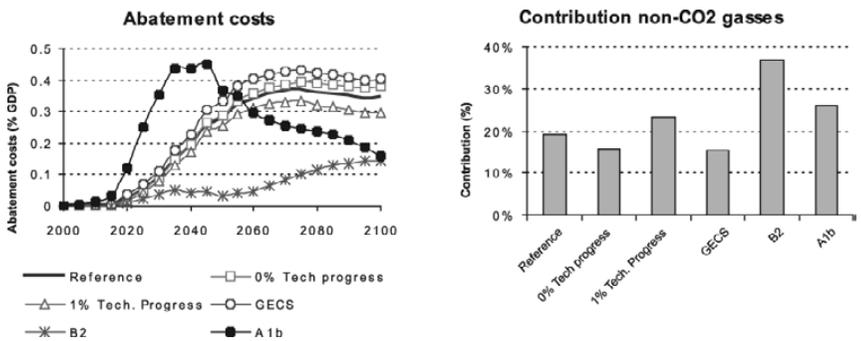
6. DISCUSSION AND SENSITIVITY ANALYSIS

Many studies identify 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-CO₂ 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 CO₂ 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 2005 and van Vuuren et al. 2004), we will not discuss them here. Instead, we will pay some attention to the role of using GWPs in our analysis. Moreover, we will discuss the impact of the uncertainty about climate sensitivity on the climate results. Finally, in the previous section we noted that the lowest of the stabilization targets (3.7 W/m²) has only a small chance of limiting global mean temperature increase to 2°C compared to pre-industrial levels. This is, however, the official target of climate policy for the EU. Moreover, several studies indicated that considerable climate change impacts may already occur at global mean temperature increase of 2°C (see IPCC 2001). In this context, we will briefly discuss whether alternative scenarios could be developed that have a higher chance of meeting such target; and in particular the type of assumptions needed to develop them.

6.1 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-CO₂ 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/m² 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 (the population decrease assumed under this scenario leads to decreasing baseline emissions). In the B2 scenario (a medium growth scenario 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-CO₂ gasses in total abatement and lower costs.

Figure 11. Results of Sensitivity Tests for Baseline and Assumptions of Rate of Increase of Non-CO₂ Reduction Potential, Stabilisation at 4.5 W/m² (left marginal costs; right contribution of non-CO₂ gasses in 2100)



6.2 Sensitivity to the Potential to Reduce Non-CO₂ Emissions and Their Costs

The rate at which the potential for non-CO₂ 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-CO₂ gasses were totally replaced by those from the GECS project (the GECS project also developed global MAC curves for non-CO₂ 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 influence on the outcome. The sensitivity run assuming faster technology development for non-CO₂ 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-CO₂ 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 for several non-CO₂ emission sources, no MAC curves are available (e.g. N₂O emissions from crop residues and animal waste). These emissions in total cover about 0.5 GtC. In our analysis, we consequently assumed that no abatement can be obtained for them. Whether abatement options (either technical options or via consumption changes) can be reduce emissions from these sources in the future is a major uncertainty (and one whose resolution would reduce costs further compared to CO₂-only strategies).

6.3 The Use of GWPs to Substitute 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-CO₂ abatement versus the multi-gas strategy (for the 4.5 W/m² 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 CH₄ early in the scenario period. Postponing this abatement (as would be suggested by flexible optimization) 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.

6.4 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 uncertainty 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/m² changes from 2.3°C (compared to pre-industrial) to a range from 1.5 – 3.5°C. For stabilisation at 3.7 W/m², 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 3 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/m² 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.

6.5 Stabilising at Lower Level of Radiative Forcing: Is it Possible?

As indicated above, the stabilization scenarios discussed in this study have only a small chance of limiting global mean temperature to 2°C compared to pre-industrial levels, the official target of EU Climate Policy. Based on a range of probability distribution functions for climate sensitivity published in literature, Meinshausen (2005) shows that this chance varies between 0–30% (for a 2.5°C target, the probability range would change to 10–55%). This obviously begs the question: What it would take to increase the chances of meeting a 2°C target? Meinshausen (2005) indicates that stabilization at 2.6 W/m² or 2.0 W/m² could

significantly increase the probability to 20-70% or 45-95%, respectively. Would it be possible to reach such radiative forcing level?

Den Elzen and Meinshausen (2005) explored this question by developing emissions pathways using the FAIR/SimCap modeling framework – starting off from the same Marginal Abatement Cost curves as discussed in Section 2. Their analysis led to two conclusions. First, in order to meet these lower radiative forcing levels, a temporary overshoot of the target level cannot be avoided. The total radiative forcing in IMAGE in 2000 is 1.7 W/m^2 (based on the Kyoto greenhouse gases, but also CFCs, sulphur, ozone, BC/OC). Under the CPI baseline, a 2.0 W/m^2 target would already be exceeded around 2010 and the 2.6 W/m^2 target around 2020. Given all inertia, emission pathways aiming for these targets can simply not avoid to first overshoot, then start to return to the target in the second half of the century, and to finally reach the target after 2150. Such pathways still would be able to avoid most of the equilibrium temperature increase that would occur after reaching a peak in radiative forcing. Second, Den Elzen and Meinshausen (2005) also found that the emission reduction potentials in the modeling framework that are used in this study so-far are insufficient to finally reach such stabilization levels.

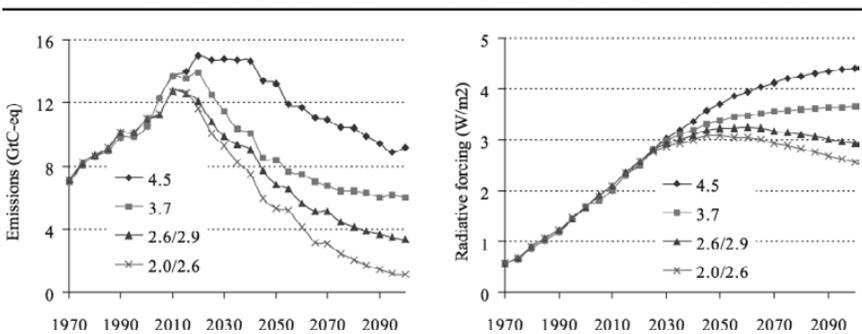
Thus, the next question is whether it is possible to extend the number of reduction options in the modeling framework so that it can meet low stabilization targets, based on a realistic assessment of existing literature? Van Vuuren et al. (in prep.) have looked into this question and describe in detail how new literature on mitigation options can be interpreted to derive more optimistic assumptions for the total mitigation potential. Here, we briefly summarize the more technology-optimistic assumptions that are made in order to meet low level stabilization targets. These assumptions are indicative of the required level of additional actions that need to be taken compared to the mitigation actions already described in this paper.

- a) In reducing CO_2 emissions from energy use, more reduction potential is needed. Hoogwijk (2004) re-estimated the potential for bioenergy. The total potential that can be produced on abandoned agriculture land and part of natural grass and savanna areas would be in the range from 200 to 800 EJ – and around 400-450 EJ for scenarios assumptions as used in this study (the potential used here is around 300 EJ). For, carbon capture and storage (CCS) power plants new studies (Hendriks et al. 2004; IPCC 2005) indicate that costs for CCS plants compared to conventional plants could be reduced to 10-15 dollar per MWh – making the option a very attractive one to reduce emissions power production and large industrial sources. Moreover, adding hydrogen as final energy carrier (in particular the transport sector) introduces the ability to produce hydrogen from zero or very low emissions sources under ambitious climate policies (e.g. coal in combination with CCS). This introduces the option to reduce transport emissions at relatively low additional costs. Finally, Hoogwijk (2004) also provided estimates of the potential and costs for producing wind and solar power - indicating a joint potential that, if combined with

- either biomass, nuclear power or CCS could reduce power sector greenhouse gas emissions to virtually zero.
- Secondly, Lucas et al. (in prep.) performed an extensive survey of the maximum achievable reduction potentials for non-CO₂ gas sources. By assuming these potential, instead of the more conservative estimates used here extends the technical potential to about 70% of 2100 non-CO₂ emissions.
 - The estimates for carbon sequestration potential by carbon plantations are subject to considerable uncertainty (see Section 2). The potential has been re-estimated by van Vuuren et al. (in prep.): 1) allowing a higher implementation factor (40%), 2) being somewhat more optimistic (based on literature) on the additional growth of managed tree plantations compared to natural forest, and 3) assuming a harvest cycle of sinks with timber used to replace normal timber production (and related deforestation). This increased the annual potential to 2.0 - 2.5 GtC.
 - The introduction of the combination of bio-energy and carbon capture and storage (BECCS) in the electric power sector and the production of hydrogen can play an important role in reducing emissions in case of ambitious climate policy scenarios (Azar et al. in press). This energy technology in fact absorbs CO₂ from the atmosphere in the growth cycle of biomass which is stored underground creating net negative emissions per unit of energy consumption. The electric power production costs of this option may be in the order of 85\$/MWh around 2030.

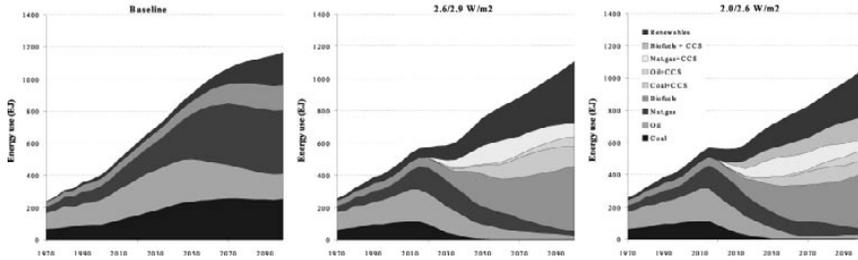
On the basis of the options discussed under a-c, it was found possible to develop a technically feasible scenario that would peak radiative forcing at 3.2

Figure 12. Comparison of Two of the Stabilization Scenarios Developed in This Study (4.5 and 3.7 W/m² Stabilization Scenarios) to Two Alternative Cases That Aim for Stabilization at Lower Levels



Note: For the low level stabilization scenarios (2.6/2.9 W/m² and 2.0/2.6 W/m²) both the final stabilization target (first number) and 2100 forcing (second number) is indicated.

Figure 13. Indication of primary Energy Use for 3 Scenarios: The CPI Baseline, the 2.6/2.9 W/m² Stabilization Scenario and the 2.0/2.6 W/m² Stabilization Scenario



W/m² – and to return to 2.9 W/m² in 2100. The emissions of this scenario and the resulting radiative forcing levels are depicted in Figure 12. The energy system associated with this scenario is shown in Figure 13. The pathway depicted by Den Elzen and Meinshausen (2005) for stabilization at 2.0 W/m² could only be achieved by adding the additional assumptions under (d.) (BECCS). In that case, it was possible to develop a scenario that peaked radiative forcing at 3.1 W/m² and to return to 2.6 W/m² by 2100.

In terms of marginal costs, the scenarios developed by Van Vuuren et al. (in prep.) have carbon prices comparable to the prices discussed earlier for the 3.7 W/m² stabilization scenario. This comparison, however, is not very meaningful as the technology base between these scenarios are very different – which causes the relatively low marginal costs in the scenarios of Van Vuuren et al. (in prep.) (We have added the scenarios here to discuss the technical feasibility of these low level concentration scenarios.) In terms of total abatement costs, these two ambitious scenarios have certainly much higher costs than the ones discussed in this paper given the fact that the emissions to be avoided are considerably higher and early abatement is necessary. The net present value of the abatement costs of the scenarios discussed in this paper, using a 5% discount rate, are 0.5, 1.4 and 7.0 Trillion US\$, for respectively the 5.3, 4.5 and 3.7 W/m² stabilisation scenario (which are medium estimates compared to the EMF-16 values as quoted in Hourcade and Shukla (2001) on the basis of their CO₂ concentration). The corresponding values of the two more ambitious scenarios are 10.2 and 16 Trillion US\$, for the scenarios with a 2100 radiative forcing of 2.9 and 2.6 W/m² respectively.

Figure 12 shows that emissions are reduced to about 3.3 GtC-eq in 2100 for the scenario with a 2100 radiative forcing of 2.9 W/m² with reductions being roughly proportional across the different gases. Under the 2.6 W/m² 2100 radiative forcing level, emissions are reduced further to 1 GtC-eq. in 2100 as a result of extensive use of the BECCS option. In fact, CO₂ emissions go even slightly negative. The extensive use of BECCS in this scenario can be seen in

Figure 13. The energy system is changed significantly in the two low stabilization scenarios: either by using less energy – and by important changes in energy supply. Overall, this discussion on alternative scenarios shows that low radiative forcing stabilization scenarios are technically feasible – but have very large implication for the world energy system.

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/m² were developed. In addition, one scenario was developed with the same equivalent emission profile as the 4.5 W/m² multi-gas scenario, but now focussing reductions on CO₂-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-CO₂ emissions scenarios: each source is driven by specific dynamic activity levels. While total CH₄ and N₂O emissions are projected to increase, their contribution in total emissions is likely to decline. Land-use related CO₂ 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-CO₂ 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 CH₄ is likely to decline from 19% to 15%, while the contribution from N₂O remains constant at 4%. For CH₄, 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, CO₂ 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-CO₂ 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-CO₂ 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-CO₂ 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 CO₂ in the first two decades is limited to only 10-20% of total reductions, while the contribution of non-CO₂ 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 CO₂. A factor that contributes to this result, is that the current knowledge on abatement options for non-CO₂ 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-CO₂ gases in the mitigation scenarios remains limited to 20-30% by the end of the century, the impact of including non-CO₂ 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/m², the marginal costs in 2100 of a multi-gas scenario is a factor of 2 lower than for the CO₂-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-CO₂ reduction options. Secondly, by the end of the scenario period, the reductions achieved by non-CO₂ abatement measures avoid the most expensive options for CO₂ that need to be taken for the CO₂-only scenario.

Including non-CO₂ gases allows for meeting more stringent climate targets, while the role of non-CO₂ in total abatement is dependent on the radiative forcing stabilisation target.

In this study, three different scenarios aiming for stabilisation of radiative forcing at 5.3, 4.5 and 3.7 W/m² were developed. In terms of the share in total emission reductions, the non-CO₂ gases play a major role in the 5.3 W/m² stabilisation scenario (their radiative forcing is reduced from more than 1.6 W/m² in the baseline to 1.0 W/m² in the stabilisation scenario). For more stringent targets, reductions of CO₂ will become more and more important. In the 3.7 W/m² scenario, for instance, more than 80% of the emissions reductions come from CO₂. The reduction potential for N₂O is seriously constrained; as a result of this, the emissions of this gas hardly do not depend significantly on the stabilization 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 SO₂ (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 abatement potential and reduction costs for non-CO₂ gases in the future represents a crucial uncertainty for current assessments on mitigation scenarios.

The information on non-CO₂ abatement options and their costs have been inventoried for EMF-21 mainly for 2010, and over a limited cost range of 0 to 200 US\$/tCe_q. After 2010, the abatement potential of most gases is likely to increase as a result of technological progress 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-CO₂ MACs tend to get exhausted before the middle of the century in scenarios aiming to stabilise at 4.5 W/m² or below. This is reflected in the rapid drop in the share of the non-CO₂ gases in total reductions over time. It will be crucial to extend research on non-CO₂ emission reduction options beyond 2010. Questions are whether there are physical or economic barriers to reduce the non-CO₂ gases further; or whether technological development is likely to lead to 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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