The Role of Non-CO_2 Greenhouse Gases in Climate Change Mitigation: Long-term scenarios for the 21st century

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Abstract

The non-CO_2 greenhouse gases have so far jointly contributed around 40 percent to overall global warming. In this paper we examine the role of these gases in meeting long-term climate change targets. For this purpose, we develop mitigation scenarios aimed at achieving long-term stabilization of global radiative forcing at 4.5 W/m^2 as compared to pre-industrial times. We use the MESSAGE model for a thorough bottom-up representation of the various greenhouse gases and the corresponding mitigation technologies. This approach endogenizes energy feedback effects from mitigation of non-CO_2 gases and takes into account the interplay and side benefits that exist across GHGs. We analyze two mitigation scenarios - one allowing only for CO_2 mitigation and another with multigas mitigation. In addition, we also investigate a lower stabilization level of 3 W/m^2 and look into the implications this has for abatement strategies. Our approach helps us to identify a portfolio of measures in the energy, industry and agricultural sectors for achieving a proposed climate target. We find that considering the full basket of GHGs improves the effectiveness of the mitigation portfolio resulting in significantly lower costs, especially in the short term. In the long run, the bulk of the emissions reductions are still seen to come from CO_2 and this effect becomes more pronounced under the more stringent climate target. This emphasizes the importance of a diverse mitigation portfolio that includes both CO_2 and non-CO_2 related abatement options in meeting long-term climate targets.

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1 Introduction

The United Nations Framework Convention on Climate Change (UNFCCC) calls for the stabilization of greenhouse gas (GHG) concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. The Kyoto Protocol to the Convention commits its parties to binding targets based on as a ‘basket’ of six GHGs, including carbon-dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). Most studies dealing with climate change, however, have almost exclusively focused on CO_2, which remains the main anthropogenic contributor to climate change. Even though non-CO_2 GHGs have so far only contributed around 40 percent to overall global warming (see IPCC 2001a), the interest in them is increasing. One reason for this is that the inclusion of non-CO_2 gases and their various mitigation options are expected to improve the cost-effectiveness in realizing climate targets (see Reilly et al. 2003).

In this paper we study the role that non-CO_2 gases might play in a long-term scenario which integrates a portfolio of mitigation measures for CO_2 and non-CO_2 gases alike. While CO_2 is mostly emitted from the energy sector, CH_4 and N_2O emissions are largely associated with activities in the industrial, agriculture and waste sectors. In the future, emissions from these sources are expected to grow, with the largest increases expected in developing countries. While population and economic growth are the main drivers for these emissions, changes in industrial processes, agricultural practices and waste management also play an important role. A number of effective and cheap mitigation options for different sources have been identified but their actual costs still remain uncertain. Some of them adversely affect food production and may involve substantive changes in traditional agricultural practices, thus making them difficult to implement, especially in developing countries.

In the context of these uncertainties, it becomes important to consolidate existing information on the non-CO_2 gases and include it in developing long-term responses to climate change. We employ a modeling approach that allows us to identify specific mitigation options for all the Kyoto gases as well as endogenize energy feedbacks in the agriculture and industry sectors. We develop so called ‘central’ mitigation scenarios aimed at achieving long-term stabilization of global radiative forcing at 4.5 W/m^2 by 2100 as compared to pre-industrial times. This roughly corresponds to a global temperature change of 2.5 degrees measured at median climate sensitivity. We compare and contrast a scenario, which accounts for mitigation of CO_2-only versus one that includes the full basket of GHGs. We also examine scenarios based on an alternative radiative forcing target of about 3 W/m2 and the implications of such a lower stabilization level for multigas mitigation strategies.

The remainder of the paper is structured as follows. Section 2 discusses the scenarios that we develop for this analysis. Section 3 is a detailed description of the main emission drivers and mitigation technologies. The scenario quantification and results are presented in Sections 4 and 5 respectively. Section 4 focuses on the central mitigation scenario aiming at the stabilization of radiative forcing relative to pre-industrial times at 4.5 W/m^2, and Section 5 gives a sensitivity analysis for a low stabilization target (3 W/m^2), broadly consistent with a long-term temperature change of 2°C. Section 6, summarizes our main conclusions.

2 Scenario Description

The baseline used in this analysis is the B2 scenario derived from IPCC's Special Report on Emissions (SRES 2000; Nakicenovic (ed.) 2000). The B2 storyline has been well documented (Riahi and Roerhl 2000). It describes a world in which the main emphasis is on local solutions to economic, social and environmental sustainability. We develop three mitigation scenarios based on this baseline. Our central cases comprise a CO_2-only scenario and a multigas scenario (including carbon sinks) aiming at the stabilization of radiative forcing at an intermediate level of about 4.5 W/m^2. In addition, a sensitivity case explores multigas strategies for attaining a low stabilization target of about 3 W/m^2.

In the CO_2-only central mitigation scenario, the system is constrained to meet a radiative forcing of 4.5 W/m^2 (in 2100 as compared to pre-industrial times) by reducing only fossil-fuel related CO_2 emissions. We calculate the '*total carbon equivalent*' of all GHGs from the CO_2-only scenario (using 100-year GWPs[1]) and apply this to the multigas scenario to obtain the same radiative forcing, but using all six GHGs. In addition, in the multigas scenario, mitigation from forest sinks is also included.

We use MESSAGE (Messner and Strubegger 1995) as the basis for incorporating emission sources and mitigation options. MESSAGE is a bottom-up systems engineering model based on a least cost optimization framework. The model maps the entire energy system with all its interdependencies from resource extraction, imports and exports, conversion, transport and distribution to end-use services. It is a long-term global model with a time horizon of a century (1990-2100). The main outputs of the model are primary energy and emissions of GHGs as well as local pollutants like SO_X and NO_X. For this analysis, MESSAGE was extended to cover all six Kyoto GHGs, their drivers and mitigation technologies. In addition, MESSAGE includes a simplified carbon cycle model for the estimation of atmospheric CO_2 concentrations.

In order to develop a CO_2-only scenario consistent with the proposed forcing target, we use MAGICC (Model for Greenhouse gas Induced Climate Change) version 4.0 (Wigley et al., 2002). MAGICC calculates the annual-mean global surface air temperature and global-mean sea level implications of emissions scenarios for greenhouse gases and sulfur dioxide (Raper et al., 1996). A MESSAGE-MAGICC iterative linkage is established whereby all GHG emissions, local pollutants and initial concentrations (to achieve stabilization) from MESSAGE are fed to MAGICC. Next, MAGICC calculates the imputed forcing due to the input emissions, on the basis of which a new CO_2 concentration limit is calculated and returned back to MESSAGE. This process is repeated until consistency between the GHG emissions from MESSAGE and the forcing target is achieved.

The MESSAGE-MAGICC iteration is performed just for the CO_2-only scenario. In order to obtain a consistent multigas scenario 100-year global warming potentials (GWPs)[3] are used- i.e.,

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[1] The global warming potential (GWP) is defined as the cumulative radiative forcing-both indirect and direct effects-integrated over a period of time from the emission of a unit mass of gas relative to some reference gas (CO_2) (IPCC 1996a). We use IPCC Second Assessment Report (IPCC 1996a) radiative forcing equivalents for all gases except the HFCs for which we use revised IPCC Third Assessment Report (IPCC 2001a) values.

we calculate the '*total carbon equivalent (TCE)*' of all GHGs from the CO_2-only scenario and apply this as a constraint to the multigas case.[2]

3 Emission Sources and Mitigation

In the context of multigas analysis, first developing plausible long-term emission profiles and then defining a reasonable mitigation portfolio assumes importance. In this section, we examine the drivers for the baseline emissions and the main mitigation assumptions. We then proceed to discuss each GHG in detail.

As mentioned earlier, there are various factors that influence future emission profiles for different gases. In this analysis, we adopt an approach that tries to take into account as many of these issues as possible. MESSAGE directly calculates CO_2 emissions due to fossil fuels, cement production and gas flaring. For the non-CO_2 gases, we use Delhotal et al., (2005) Schaefer et al., (2005) and DeAngelo et al., (2005) for emission estimates from the various sources until 2030. Thereafter, we use a range of economic drivers to model long-term emission profiles (for details see Appendix I to this paper available on the web at http://www.iiasa.ac.at/~riahi/Multigas_Mitigation/). Examples include population; gross domestic product (GDP); and agricultural & industrial gross value added (GVA). It is important to recognize that the emissions are not always linear with the drivers. In many sectors, emissions are already decreasing or expected to do so, due to ongoing environmental initiatives. An example is the SF_6 Emissions Reduction Partnership for Electric Power Systems'- a voluntary partnership between industry and the United States Environmental Protection Agency ((http://www.epa.gov/highgwp1/sf6/). Also for many of the non-CO_2 sources, there exists a close relation between productivity and emissions. For instance, ruminant animals with low levels of production efficiency have relatively high methane emissions per unit of product (FAO 2000). Increasing wealth and modern practices will lead to improved animal and agricultural productivity and indirectly to decreasing emission intensities from such sources. Based on such trends, we consider declining emission factors for many of the sources in the baseline itself.

For the mitigation scenarios, we mostly employ a bottom-up modeling approach based on representation of the costs and efficiencies of the different mitigation technologies. This information is obtained from various sector specific reports, as well as the technology-specific data sets provided by Delhotal et al., (2005) and Schaefer et al., (2005). This bottom-up approach allows us to examine the optimum mix of technologies across all the different sectors; endogenize energy feedbacks from mitigation[3] as well as capture any resulting ancillary benefits[4]. We also take into account differences in technology performance and costs between

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[2] Recent studies (e.g. O'Neill 2000, Bradford and Keller, 2003) highlight the debate over the inaccuracies of using GWPs. Some issues include the dependence on the time horizon used in calculations and the differences in lifetimes of the gases. These inaccuracies lead in our scenarios to slight differences of temperature and forcing profiles between the two mitigation scenarios (see Figure 7).

[3] For example, decreased coal use will indirectly lead to reduced CH_4.

[4] Imposing a CO_2-only constraint will lead to some reductions in energy-related CH_4, N_2O and SF_6

industrialized and developing countries. Another important part of the mitigation analysis is the assumptions on technological change in the system. Technological change is important to achieve the cost reductions and performance improvements necessary for a technology to become competitive in the long run (Grübler and Messner 1998). In this analysis, we model technological change exogenously, thus accounting for improvements in performance and declines in costs over time.

For mitigation from the livestock and agricultural sector (enteric fermentation, rice cultivation and soil management), we adopt a more top-down approach and directly implement marginal abatement cost curves (MACs) based on DeAngelo et al. (2005). Based on the large uncertainties that exist in the feasibility and costs of many of the mitigation options in this sector, we do not assume any major changes of the mitigation potential in the long run with the MACs[5], thus limiting the long-term mitigation potential in this sector. Future assessment of agricultural sources will require improved accounting for heterogeneity of emissions and yields, adoption feasibility and commodity market effects into mitigation decisions (DeAngelo et al., 2005)

The following sections describe the different GHG emissions; the related sources; drivers; and mitigation options.

3.1 ***CO_2***

CO_2 is the largest contributor to anthropogenic changes in global warming with a share of 60 percent. Current emissions are about 7 GTC, of which 6 GTC comes from fossil fuel combustion, while the remaining is due to land use changes (mainly deforestation).

The electricity sector is responsible for more than 35 percent of total energy-related CO_2 emissions worldwide. Other contributing sectors include transportation (25 percent) and direct use of fossil fuel in industry, residential and commercial sectors.

There are a number of options for reducing energy-related CO_2 emissions in the long term. These include switching from fossil fuels to renewable or nuclear power; efficiency improvements; fuel shifting (from coal to gas); and carbon capture. The entire portfolio of CO_2-reduction options-advanced nuclear, wind, biomass, solar, and hydrogen-based fuel cells is available to the model. Technological change in the form of cost declines and efficiency improvements are an important part of the assumptions, thus leading to a significantly high penetration of renewable technologies in the baseline scenario itself. In addition, we include various pre-combustion and post-combustion capture technologies for fossil fuel plants (see Riahi et al. 2004). We recognize that issues of storage potentials and leakage rates (see e.g. Parson and Keith, 1998) may limit the long-term adoption of such technologies. However, given the huge uncertainties that exist in the

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[5] MACs are given upto the year 2020. Thereafter, we assume that the same share of baseline emissions can be mitigated at the same prices as given in 2020

reported estimates, we have not imposed an upper bound for storage capacity in the model[6] and also do not consider leakage rates[7]. We also include in this analysis, biomass energy with carbon sequestration (BECS) - a combination of biomass gasification technology for power/hydrogen generation with carbon capture and storage permitting the production of energy with negative emissions. (see Obersteiner et al. 2002, Makihira et al. 2003).

While we already include CO_2 emissions from land-use change exogenously in our baseline scenario, carbon sinks are introduced as an additional mitigation option in the multigas scenario. We use an iterative approach between MESSAGE and the model developed by Sohnegen & Sedjo (2005) [8] to estimate the potential for forest sinks in the given scenario.

3.2 ***CH4***

CH_4 is the second largest contributor to global warming with a share of around 20 percent. Sources include both, energy related ones like the production and transport of coal, natural gas, and oil, as well as non-energy related ones like livestock, municipal solid waste, manure management, rice cultivation, wastewater, and crop residue burning. The energy sector presently contributes more than a quarter of overall CH_4 emissions, while enteric fermentation is the largest contributor in the non-energy sector making up more than 30 percent of total emissions.

We endogenize energy-related CH_4 sources by linking appropriate emission coefficients to various activity variables in the model. These include coal, oil and gas extraction and transportation; and energy-related (includes transportation) fossil fuel and biomass combustion. We assume gradual technological improvements for these energy-related sources in the baseline. For example, we assume reduced future pipeline leakage in the gas sector in the form of decreased emission coefficients.

For livestock and agriculture related CH_4 emissions, we mostly use sector specific economic drivers to develop the baseline emissions (see Appendix I at http://www.iiasa.ac.at/~riahi/Multigas_Mitigation/). As mentioned earlier, we assume declining emission factors for these sources based on projected productivity improvements in livestock management and agricultural production. In the baseline itself, we do not explicitly account for other factors like shifts in rice cultivation practices and agricultural land availability. However,

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[6] However in an earlier analysis by Riahi et al., (2005), the cumulative amounts of stored carbon from a MESSAGE mitigation scenario (A2CCT) was compared with estimates available from IEA, 2001 and found to be well below the upper estimate for deep saline reservoirs.

[7] Another important issue is the technological learning of carbon capture technologies (see Riahi et al. 2005 for a detailed discussion this).

[8] This approach consisted of first harmonizing assumptions on baseline land use change emissions between both models. We then used the shadow prices ($/TCE) from MESSAGE as an input to the forest model, which then estimates the corresponding mitigation from carbon sinks. The shadow prices and estimates for sinks are iterated between both models until convergence is achieved.

these factors are implicitly accounted for in our mitigation scenarios based on the MACs from DeAngelo et al. (2005).

For CH_4 emissions from solid waste, we use IPCC country-specific mass-balance methodology (IPCC 2000) to obtain estimates of current emissions. We then examine long-term trends in waste generation rates, recycling, gas recovery etc. to develop long-term emissions. For example, based on land availability constraints and current trends in most developed countries, the rates of recycling and incineration are assumed to increase around the world, thus leading to less waste being dumped in the landfills. We also assume better management of landfills in the future i.e. a transition from open dumping to covered landfills.

CH_4 mitigation from the energy sector is introduced in the form of higher cost extraction options with improved emission coefficients. For the non-energy sources, we consider diverse mitigation options (see Appendix II at http://www.iiasa.ac.at/~riahi/Multigas_Mitigation/). The technical complexity of these source reduction options can vary significantly, although this does not greatly influence their effectiveness (IPCC 1996). For example in the solid waste sector, labor-intensive composting is more common in developing countries as compared to high-skill machinery in developed countries. Some options are also climate specific like warm and cool climate farm-scale digesters in manure management. For methane emissions from enteric fermentation and rice cultivation, we use MACs from DeAngelo et al. (2005).

Recovery of CH_4 is an important factor in both energy and non-energy sectors. We assume that the shift from surface to deep coal mining is balanced by increased recovery of CH_4 (through degasification systems) which is fed back into the energy system. In the solid waste sector, the recovered CH_4 from landfills is directly used as gas by nearby industries or converted to electricity for end-use. [9]

3.3 ***N_2O***

N_2O contributes about 6 percent of the global warming (IPCC 2001a). Important sources include agricultural soil, animal manure, sewage, industry, automobiles and biomass burning.

Agricultural soil is the largest source of N_2O, contributing over 70 percent of overall emissions. Although N_2O is produced naturally in soils through microbial processes, many soil management activities affect the soil nitrogen (N) content and hence related N_2O emissions. Primary among those is N-fertilizer application. Nitrogen fertilizer production provides more than half of all anthropogenic fixed nitrogen (Socolow 1999). Based on the relation between fertilizer production and productivity, we use agricultural Gross Value Added (GVA) as the driver for N_2O emissions. However we recognize that future N-fertilizer use may become more efficient[10] and may indirectly lead to lower N_2O emissions. In order to account for efficiency

[9] We assume that in developed countries this recovery rate grows to about 30% in 2100 while it comes close to current developed country levels (around 15%) in developing countries.

[10] Due to practices like crop rotation, improved timing, soil testing etc.

improvements, based on Frink et al. (1999), we assume a 1 percent emission factor improvement per year in the baseline. For all other sources of N_2O, we develop baseline emissions based on various drivers listed in Appendix I of this paper publicly available at http://www.iiasa.ac.at/~riahi/Multigas_Mitigation/.

Defining mitigation options for agricultural soil is difficult due to large differences in soil management techniques worldwide. We use the MAC (DeAngelo et al., 2005) for N_2O mitigation from soil. Based on this, only a limited mitigation potential (less than 10 percent of the baseline) is available. For industrial sources of N_2O, we include specific mitigation technologies like high and low temperature catalytic converters. Appendix II (http://www.iiasa.ac.at/~riahi/Multigas_Mitigation/) lists all the different mitigation options.

3.4 *SF6 and Perfluorocarbons (PFCs)*

SF_6 and the PFCs (CF_4 & C_2F_6) are extremely high GWP gases. SF_6 is mainly used as an insulating gas in high voltage switchgear and also as a cover gas in magnesium casting. CF_4 is emitted during the anode effect in the production of aluminum. It is also used in the semiconductor industry for cleaning and etching processes.

The electric transmission and distribution activity levels in MESSAGE are assumed to drive SF_6 emissions from switchgear. The recent boom in primary production of magnesium and high demand growth for magnesium die casting in the automobile industry are likely to drive SF_6 emissions from magnesium production (see http://www.climatevision.gov/sectors/magnesium). Based on this, we use light-vehicle transportation demand from MESSAGE[11] as the driver for these emissions. In industrialized countries many SF_6 reduction initiatives are already underway. To account for these trends, we assume an annual emission factor decline of 1 percent in the baseline. Mitigation options are based on Schaefer et al. (2005) and include recycling of SF_6 and replacement of SF_6 as a cover gas with SO_2 (for details see Appendix II at http://www.iiasa.ac.at/~riahi/Multigas_Mitigation/).

Many countries have undertaken initiatives (industry/government) to reduce PFC emissions from aluminum smelting. In order to account for this global decrease in PFC emissions, we assume an emission factor decline of 1 percent per year in the baseline. The main mitigation option we consider is retrofitting (see Appendix II at http://www.iiasa.ac.at/~riahi/Multigas_Mitigation/).

3.5 *Hydrofluorocarbons (HFC)*

The sources for these emissions are diverse and include refrigeration and air-conditioning; insulation foams; fire extinguishers; medical and non-medical aerosols; HFC-22 production; and

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[11] Includes light-oil and hydrogen based transportation technologies

solvents. Traditionally, ozone-depleting substances (ODS) like chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) have been used in many of these applications. However since the Montreal Protocol (UNEP, 2000) mandates phase-out of these gases in the next few decades, HFCs are replacing them in most applications. Based on Schaefer et al., (2005), we assume that emissions of ODS substitutes will continue their rapid increase until 2030 in developed countries and 2040 in developing countries and then slow down. Already, HFC emissions management is occurring through voluntary measures and industry-government partnerships.

For HFC emissions from residential and commercial air-conditioners, mobile air-conditioners and insulation foams, we apply initial emission coefficients to various activity levels[12] calculated by MESSAGE. In order to account for the expected phase out of these emissions, we assume a 1 percent annual decline in emission factors after 2030. The other HFC emissions are projected using various economic drivers. Mitigation options include refrigerant recovery and leak repairs (for details on economic drivers and abatement technology see Appendix II at http://www.iiasa.ac.at/~riahi/Multigas_Mitigation/).

4 Scenario Results

In this section, we first present the quantification of our baseline scenario. We then discuss the results for the central mitigation scenarios, aimed at achieving long-term stabilization of global radiative forcing at 4.5 W/m^2 by 2100 as compared to pre-industrial times. .

In spite of assumptions on decreasing emission factors in many sectors, there is an overall increase in GHG emissions. Figure 1 shows the growth in emissions indexed to 2000 levels. By 2100 CO_2 emissions increase about two times from 2000 levels although the intensity of emissions actually declines from 17 kgC/GJ to 10 kgC/GJ in 2100 due to technological improvements and structural changes in the energy system. CH_4 emissions show a similar increase driven by increasing fossil fuel use and a growing urban population. In contrast, N_2O emissions peak in 2070 and then start to decline due to improved efficiency in fertilizer use. The F-gases are the highest growing emissions, increasing to five times their current values. The main source is HFC emissions from use of refrigerators and air-conditioning fuelled by increasing affluence, especially in developing countries.

[insert Fig. 1]

As Table 1 indicates, the baseline emissions profile looks different for today's industrialized and developing countries. For example, agriculture related emissions form almost a quarter of current GHG emissions in developing countries. But this share decreases by almost half by the end of the century due to the decreasing share of agriculture in the economy.

[insert Table 1]

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[12] Residential and commercial electricity and thermal end-use, transportation

We now turn towards the two central mitigation scenarios. Figure 2 shows the cumulative emissions reductions in the CO_2-only and multigas 4.5 W/m^2 forcing scenarios as compared to the baseline. In a CO_2-only case, there are a number of side benefits leading to lower CH_4, N_2O and SF_6 emissions as a by-product of carbon emissions reductions. These are due to structural changes in the energy system including shifts towards lower use of coal and higher use of gas as well as a move towards decentralized renewable electricity generation that in turn causes an overall reduction in the electricity transmitted and distributed in the energy system. In the multigas case, while CO_2 reductions are about 10 percent higher than the CO_2-only case (see Fig.2), there are considerable reductions in the other GHGs. The mitigation options available for the other gases give the system more flexibility in meeting the same climate constraint. For example SF_6 emissions in the multigas scenario are reduced by around 60 percent as compared to the baseline (see Fig. 2) mainly due to high technical efficiency of the mitigation options in this sector (see Appendix II at http://www.iiasa.ac.at/~riahi/Multigas_Mitigation/ for mitigation technology description).

[insert Fig. 2]

It is important to take into account the sources of reductions of the different GHGs. Figure 3 shows the wedge between baseline emissions and the multigas scenario and the contributions of the different sectors to this mitigation. The energy sector makes up the bulk of the reductions. The majority of this is reductions in fossil fuel related CO_2 emissions but energy-related CH_4, N_2O and SF_6 also decrease in total by almost 30 percent as compared to the baseline. For industrial N_2O and solid waste related CH_4, overall mitigation is large due to the high efficiencies of associated mitigation options (Delhotal et al. 2005). Although agriculture is a larger source of CH_4 and N_2O emissions, the mitigation in this sector is limited (DeAngelo et al. 2005)[13]. Less than 10 percent of overall emissions from this sector (includes manure management, enteric fermentation, rice cultivation and soil management) are mitigated. This reduced potential is mainly due to the linkages with agricultural productivity that cause uncertainties in defining exact potentials and costs for the mitigation technologies in this sector.

[insert Fig. 3]

The sector-wise contribution to mitigation efforts varies between currently industrialized and developing countries, depending on the relative shares in the baseline (see Table 2). A larger share of the reductions comes from the industrialized countries in the early part of the century especially in the energy and industrial sectors. But towards the latter half, due to the over proportional rise in baseline emissions in developing countries, they become the main contributors to overall mitigation (see Table 1). In addition, mitigation in the agriculture sector plays a more prominent role in these countries (see Table 2).

[insert Table 2]

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[13] We do not assume any technological change in the MACs. See footnote 5.

An important part of this analysis is the added flexibility offered by the inclusion of non-CO_2 mitigation technologies. Figure 4 shows the ranking of the most important technologies that contribute to overall mitigation in both the CO_2-only as well as the multigas scenarios.

[insert Fig. 4]

Carbon capture is the dominant technology for CO_2 reductions in both the CO_2-only and multigas central mitigation scenarios. Shifts in the energy system towards increased biomass (includes biomass-based carbon capture and storage systems) and nuclear use as well as fossil-fuel shifts from coal to gas are the remaining contributors. In the multigas case, mitigation from sinks assumes significance and is the second largest contributor. In the CO_2-only scenario, CH_4 mitigation from the energy sector occurs as an ancillary benefit. In the multigas case, the solid waste sector dominates CH_4 mitigation efforts. The main reason for this is that the CH_4 captured from landfills can be fed back into the energy system directly as gas or after conversion to electricity, thus making this an economical option. Rice cultivation and enteric fermentation also offer some potential for CH_4 mitigation. The industrial sectors (nitric & adipic acid) dominate N_2O reductions. A small share of overall N_2O mitigation (around 8 percent) comes from soil management techniques. Low-cost residential refrigeration and air-conditioning related mitigation technologies contribute close to all of the HFC reductions.

Also important in this analysis is the timing of mitigation options. Figure 5 shows the time scale for deployment of some of the important mitigation technologies i.e. the period in which they start making significant contributions. We define this as the point when the contribution of the technologies is more than 10 percent of the overall mitigation from the related GHG. Many non-CO_2 technologies start to contribute early in the century. Some of these include CH_4 technologies in the landfill sector (due to CH_4 capture for heat production); CH_4 related energy technologies[14]; and the high efficiency catalytic reduction technologies in the nitric acid sector. The higher-cost CO_2 reduction technologies like carbon capture begin to make significant contributions in overall reductions in the latter half of the century but go on to dominate the overall mitigation profile.

[insert Fig. 5]

We now turn towards the climate implications of the above scenarios in terms of radiative forcing, temperature and concentrations. As mentioned earlier, both central mitigation scenarios are constrained to stabilize radiative forcing at 4.5 W/m^2 compared to pre-industrial times. This corresponds to roughly a stabilization of global mean temperature change at about 2.5 degrees at median climate sensitivity[15] (see Figure 6a).

The forcing leads to significant reductions in temperature change as compared to the baseline (see Figure 6a); thus reducing the risks associated with large scale and irreversible impacts of

[14] Although there is a shift from surface to deep mining with higher CH_4 coefficients, this is balanced by increased recovery of CH_4 from these mines.

[15] As median climate sensitivity we assume 2.5 degrees. It is important to note that the climate results from MAGICC are 'best guess' estimates.

climate change considerably (see IPCC 2001b; Mastrandrea and Schneider 2004). The large uncertainties associated with the climate sensitivity (and also climate impacts), however, make an assessment of whether this level of mitigation is sufficient for avoiding "dangerous interference of climate change" as proposed by Article 2 of the UNFCC difficult. As illustrated in Figure 6a, the temperature change in the mitigation runs may - at higher climate sensitivities - even exceed the "best guess" estimate projected by the baseline.

[insert Fig. 6a and Fig. 6b]

One important feature of our model is the assumed full spatial and temporal flexibility of emissions reductions. The model is flexible as to when and where and from which GHG source emissions should be reduced to achieve the forcing constraint at optimal costs. The internal decision mechanism is driven by price equalization across mitigation options based on the GWP of the alternative greenhouse gases. This leads to alternative paths for the GHG emissions in the multigas and CO_2-only cases and also to alternative developments for their concentrations over time. We shall next discuss the implications for the concentrations of each of the main GHGs (CO_2, CH_4, and N_2O).

[insert Fig. 7]

Atmospheric CO_2 concentrations in the baseline increase rapidly from about 378 ppmv in 2000 to about 600 ppmv at the end of this century (see Figure 7). The concentration path is headed upwards at the end of the time horizon, indicating that this trend would continue in the absence of any GHG emissions mitigation. Comparing the concentration trajectories of the CO_2-only and the multigas scenario shows that the stabilization of radiative forcing at 4.5 W/m2 can be achieved at widely different CO_2 concentration pathways. It shows also that the CO_2 concentration level largely depends on the development assumed for the other non-CO_2 gases. If non-CO_2 gases continue rising without abatement, over proportional cutbacks in CO_2 become necessary, which in turn also lead to lower CO_2 concentration levels. A salient feature of both mitigation scenarios is that the CO_2 concentrations follow a long term stabilization path. CO_2 in the multigas scenario is stabilized at relatively higher levels (475 ppmv in 2150) as compared to the CO_2-only case (435 ppmv in 2150).

Another interesting observation is illustrated by the CO_2 concentration trajectory of the CO_2-only scenario, which is characterized by an overshoot of atmospheric CO_2 in the medium term. As shown in Figure 7, CO_2 concentrations increase initially, peak at 450 ppmv around the mid of this century, and decline later to achieve their eventual stabilization level of 435 ppmv (in 2150). This finding highlights the earlier mentioned importance of the full "when and where" flexibility of emissions reductions assumed in the model.

Due to increasing emissions, particularly in the non-energy sectors, atmospheric CH_4 concentrations in the baseline increase steadily from 1768 ppbv in 2000 to 3800 ppbv in 2100. As illustrated in Figure 7, a mitigation strategy focusing on CO_2 only, does not lead to any significant concentration changes in the short term. Only in the latter half of the century some associated benefits of carbon emissions reductions lead to CH_4 concentrations that depart from the baseline, stabilizing at 3300 ppbv in the long term. Clearly, the most pronounced changes in CH_4 concentrations are achieved in the multigas scenario due to direct mitigation aimed at the reduction of mainly non-energy CH_4 emissions. The combined effect of various low-cost mitigation options and the relatively short atmospheric lifetime of CH_4 (about 12 years) results in sizable reductions of concentrations already in the first few decades. In the long run, the CH_4 emissions reductions lead in the multigas scenario to cutbacks of concentrations of about 40 percent, corresponding to the stabilization of atmospheric concentrations at below 2400 ppbv (see Figure 7).

As to N_2O concentrations, the difference between the baseline and the mitigation cases is less pronounced (see Figure 7). None of the mitigation strategies leads to stabilization. In particular, there are almost no associated benefits from CO_2 emissions reductions and hardly any change in N_2O concentrations in the CO_2-only case (compared to the baseline). Also the N_2O concentrations in the multigas case are just reduced by 5 percent in the long run (by 2100), which is partly due to the long residence times, but also due to earlier mentioned conservative assumptions concerning the potential of N_2O mitigation for those sources where large uncertainties exist (such as agricultural soil).

Figure 8 shows the development of the global shadow prices of emissions reductions on a carbon-equivalent basis. Considering non-CO_2 mitigation options increases the flexibility of the system in meeting reduction requirements and leads to lower overall costs of mitigation. Consequently, the multigas scenario is seen to be significantly cheaper than the CO_2-only one.

[insert Fig. 8]

The relative price difference between the CO_2-only and the multigas scenario is more pronounced in the short and medium term. In the very long term, the bulk of the emissions reductions in the multigas scenario also stem from CO_2 and the disparity in prices between the scenarios become less significant. We find three main reasons for this trend. First, the high inertia of the energy system due its long-lived infrastructure (lifetimes > 30 years) make deep reductions in CO_2 (for example, premature phase-out of power plants) comparatively costly in the short term. Secondly as mentioned earlier there are a large number of cheap (below 10$/TCE)[16] non-$CO_2$ mitigation options available in the short-term, making them more attractive than relatively costly CO_2 reductions. The third effect comprises the comparatively limited long term mitigation potential of the non-CO_2 sources as compared to CO_2. Only one third of the baseline's total emissions in 2100 come from non-CO_2 sources. Consequently, as the emissions constraint becomes more stringent over time, deeper cutbacks of CO_2 become necessary in the multigas scenario, driving the overall price of mitigation closer to the one in the CO_2-only case.

Another decisive factor for the GHG price in the long term is the aggregated effect of technological change in the energy system, and the dynamics and pace at which advanced and clean technologies are diffusing into the market. For example, in the latter half of the century an important part of the mitigation portfolio in both scenarios consists of BECS (Biomass Energy with Carbon Capture and Sequestration), i.e., biomass-based negative emissions technologies. Assuming that these technologies would not be available to the system would significantly impact the GHG prices. As shown in Figure 8, the long-term GHG price without BECS increases

[16] All costs are given in 2000 US$ unless otherwise mentioned.

in 2100 by a factor of 6 in the CO_2-only and a factor of 2 in the multigas scenario. This result not only illustrates the vital role that biomass-based negative emissions might play in the long term, but perhaps more importantly highlights the importance of technological change (Grübler, 1998), its path dependency (Roehrl and Riahi, 2000), and the necessity of research and development in new emissions control technologies.

5 Sensitivity Analysis for Low Stabilization Targets

A number of scientific studies (Azar and Rhode, 1997; Hansen, 2005) as well as government bodies (European Council, 2005) argue that achieving extremely low stabilization targets would be necessary to avoid the risk of dangerous interference with the climate system. This section explores the mitigation related implications of achieving stabilization of radiative forcing at a level of about 3 W/m^2.. This target is approximately consistent with a temperature change of below 2°C compared to pre-industrial times.[17] We examine the associated multigas abatement strategy under such an alternate stabilization level.[18]

The baseline and mitigation scenarios presented here adopt the same assumptions for main emissions drivers as the central multigas case explained in detail in Section 4. They differ however with respect to two main aspects. First, we account for macroeconomic feedbacks of climate mitigation by estimating price-induced changes of GDP and energy demand using an optimal growth model of the economy (Manne and Richels, 1992; Messner and Schrattenholzer, 2000). Secondly, given the important role of bioenergy and negative emissions technologies in the mitigation portfolio, we use for this sensitivity analysis a spatially explicit global model of forest sink management and bioenergy supply (Obersteiner et al., 2005; Rokityanskiy et al., 2006) to provide a more detailed account of local conditions that may limit the potential use of these options.[19] Due to these changes the emissions profile of the baseline scenario has changed slightly, depicting higher growth in the first half of this century (compared to the baseline scenario presented in Section 4).

The four panels of Figure 9 summarize the main results of the 3 W/m^2 scenarios. Panel (a) illustrates the contribution of the principal mitigation measures. Panel (b) shows the evolution of the primary energy carriers and the deployment of carbon capture and storage for fossil fuels as well as biomass energy carriers. The resulting change in global mean surface temperature and the imputed GHG price ($/tC eq.) are given in Panels (c) and (d) respectively. For illustrative purposes panels (c) and (d) give also the results from a stabilization scenario for 4.5 W/m^2 sharing the same modified assumptions (compared to the scenarios presented in Section 4). A

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[17] Assuming an intermediate climate sensitivity of 2.5 °C for a doubling of CO_2 concentrations.

[18] We do not run a CO_2-only scenario for this target

[19] Rokityanskiy et al. (2006) have developed spatially detailed dynamic scenarios for the potential development of sinks given a range of carbon prices. Accounting for market imperfections and infrastructure barriers, we have limited the potential for sink enhancement to 50% of the potential of Rokityanskiy et al..

comprehensive data appendix (Appendix III) including regional results for all GHGs and main emissions derivers may be found at http://www.iiasa.ac.at/~riahi/Multigas_Mitigation/.

Achieving a stabilization target as low as 3 W/m^2 requires early mitigation as well as the rapid adoption of a wide portfolio of mitigation measures. As illustrated by Figure 9a, total GHG emissions peak already by 2020 and are headed downwards over the course of the century. Eventually, by 2100, emissions become negative due to the widespread deployment of biomass-based carbon capture and storage (BECS) technologies and global efforts for sink enhancement. These options together account for about 275 GtC eq. or 30 percent of the total cumulative mitigation burden (by 2100). It is important to note that although the bulk of the emissions reductions stem from options other than BECS or forest sinks (including non-CO_2 technologies), a 3 W/m^2 stabilization target is found to be unattainable in our modeling analysis without at least one of these options.

Another important difference here as compared to earlier results from the multigas central case is that the majority of the emissions reductions are now achieved through cut-backs in CO_2 in the energy sector. Thus, the relative importance of non-CO_2 gases is seen to be smaller at more stringent stabilization levels, primarily due to saturation effects of CH_4 and N_2O mitigation options in the agricultural sector. Principal CO_2-related mitigation measures are enhanced energy conservation and structural changes of the energy system, predominantly shifts away from carbon-intensive coal to natural gas, nuclear, and renewables (Figure 9a). These options in total account for about 55 % of total cumulative reductions by 2100.

Carbon capture and storage from fossil fuels (CCS) and biomass (BECS) account for more than 38 percent of total mitigation over the course of the century.[20] As illustrated by Figure 9b, CCS is predominantly fossil-based during the first half of the century, while the contribution of BECS is increasing rapidly in the latter of half of the century driven by the need for negative emissions contributions for attaining the low target. Cumulative storage of CO_2 in the low stabilization scenario is about 340 GtC, well below the "best guess" estimate for global geologic storage potential of about 500 GtC (IPCC, 2005).

Carbon (eq.) prices for achieving this low stabilization level increase over the course of the century to about 2,800 US$/tC (Figure 9b). This is roughly the same carbon price as computed for the 4.5 W/m^2 CO_2-only mitigation scenario assuming that negative emissions technologies (BECS) will not become available (see Figure 8). A more comprehensive measure for the mitigation costs is given by the loss in GDP or welfare (compared to the baseline).[21] The loss in

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[20] Costs of fossil CCS systems are based on same assumptions as reported by Riahi et al., 2005. For BECS we assume limited initial up-scaling potential for energy conversion plants in the next three decades, after which plant sizes of 100 to 200 MWe become attainable. The costs of BECS are thus assumed to be about 30 to 70 percent higher than equivalent coal-based CCS systems. In addition, we assume that CO_2 from BECS has to be transported over larger distances than CO_2 from fossil power plants, thus accounting for the fact that a large share of biomass power plants will be located in relative closer proximity of the biomass supply rather than prospective storage sites. Thus, costs of CO_2 transportation are seen to be higher than those from coal by more than a factor of two.

[21] In addition to MESSAGE we use for this study MACRO, a top-down macroeconomic equilibrium model (Manne and Richels, 1992). The capital stock, available labor, and energy inputs determine the total output of an economy

GDP is seen to be relatively modest, increasing to about 3.9% by 2100 for achieving the low stabilization target of 3 W/m^2 (compared to 1.9 % for achieving 4.5 W/m^2).

[insert Fig. 9]

6 Conclusion

In summary, we find that non-CO_2 mitigation plays a particularly important role in the short and medium term, bridging a cost-effective transition to a less GHG intensive long-term economy. In a multigas scenario, the bulk of reductions in the long term still come from CO_2, due to the comparatively limited mitigation potential for the non-CO_2 gases. The relative contributions of CO_2 and non-CO_2 gases in the mitigation profile are found to also depend on the stringency of the climate target under consideration.

We particularly emphasize the diversity of the mitigation portfolio in a multigas scenario. The bottom-up modeling methodology that we use enables us to evaluate optimum and point source technology strategies for reductions. Some promising technologies in the short term include recovery of CH_4 from landfills and reduction of N_2O from nitric acid production while carbon capture and sequestration, nuclear energy and BECS contribute significantly in the longer term.

The multigas scenario is seen to be significantly cheaper than the CO_2-only one. The relative price difference between the CO_2-only and the multigas scenario is more pronounced in the short and medium term. The evolution of long term prices in our analysis is largely driven by the assumptions on technological change and the adoption of advanced technologies in the system. While the exact path of this change is somewhat uncertain, we find that the deployment of advanced technologies including both CO_2 and non-CO_2 options is essential in enabling cost-effective climate change mitigation in the long term. Advanced technologies like biomass energy in combination with carbon capture and storage (BECS) are seen to increase in importance with stringent climate targets, due to their large potential in reducing the overall costs of mitigation. Thus a diverse mitigation portfolio including a range of CO_2 and non-CO_2 technologies is found to be central in achieving very low stabilization levels consistent with a temperature change of below 2°C.

We recognize that there are many uncertainties in current emission inventories for non-CO_2 GHGs, as well as the actual costs and potentials of the associated mitigation options (particularly in the livestock and agricultural sector). A better understanding of these uncertainties is essential in formulating multi-sector cost-effective policies that would gain acceptance by policy-makers and the public alike.

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according to a nested constant elasticity of substitution (CES) production function. MESSAGE and MACRO are linked iteratively to include the impact of policies on energy costs, GDP and on energy demand. The result is a fully consistent evolution of energy demand quantities, prices, and macroeconomic indicators (such as GDP, investments and savings). A detailed description of the link between the two models can be found in Messner and Schrattenholzer (2000).

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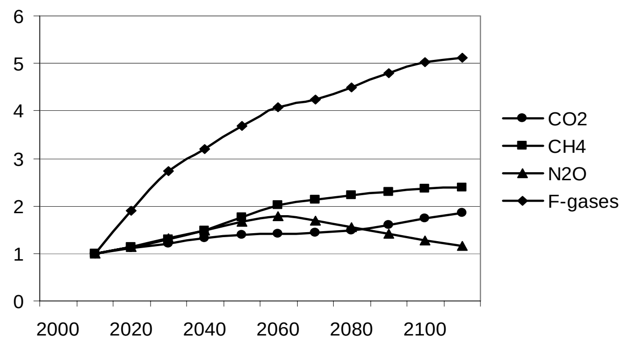

Figure 1: Increase in global GHG emissions in the baseline from 2000-2100. All emissions are indexed to 2000 values.

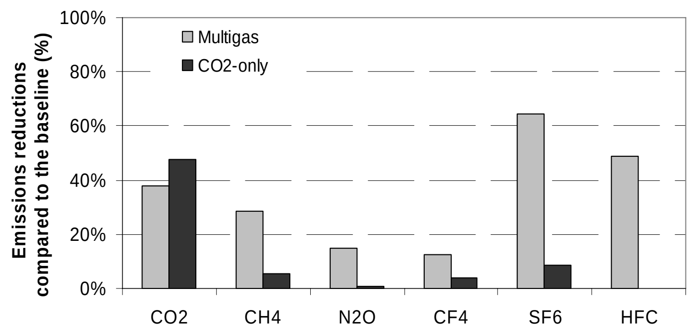

Figure 2: Cumulative emissions reductions in the mitigation scenarios. The bars indicate the cumulative percentage reductions from the baseline by GHG from 2000 to 2100. Also the CO_2-only mitigation case leads as a by-product to some reductions in non-CO2 GHGs. CO_2 reductions in the multigas case are about 10 percent lower than in CO_2-only, due to large contributions from other gases.

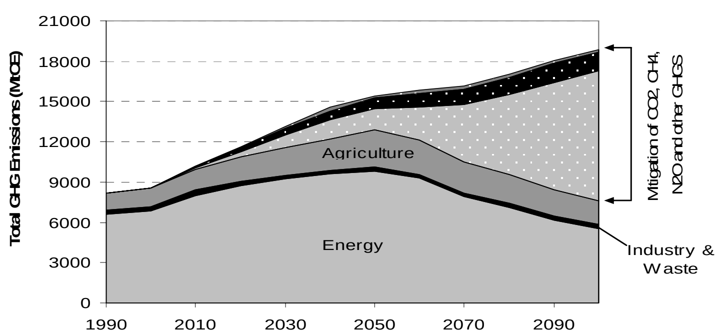

Figure 3: Sector-wise sources of multigas mitigation. The shaded areas show the composition of the different sectors in the total emissions of the multigas scenario while the corresponding dotted areas show the mitigation from these sectors as compared to the baseline.

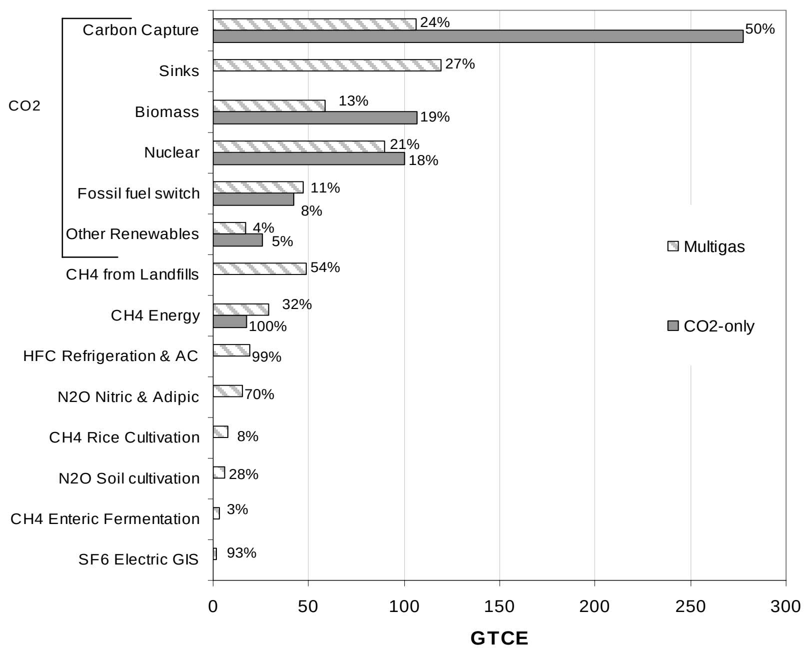

Figure 4: Ranking of main groups of mitigation technologies. The technologies are ranked according to the cumulative TCE reductions between 2000-2100. The percentages indicate the cumulative share of the technologies in total cumulative emissions reductions of the respective gas.

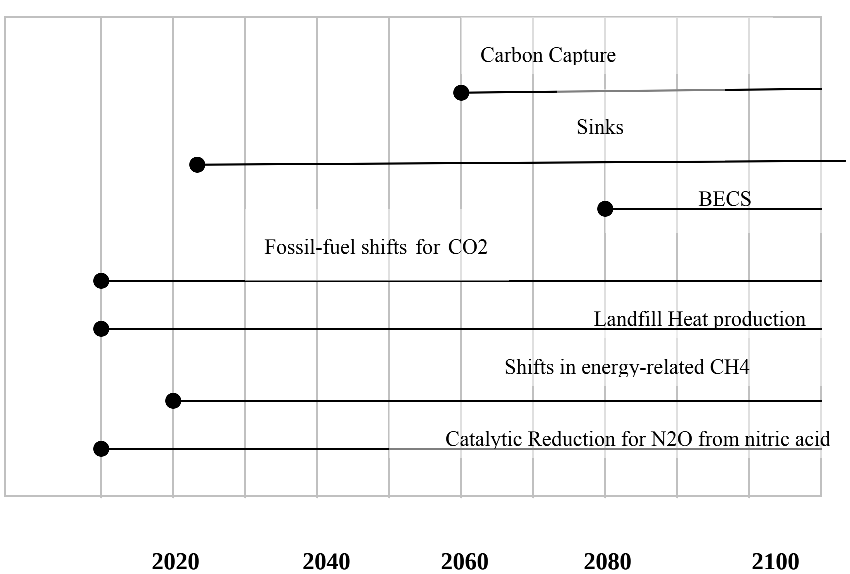

Figure 5: Timing of selected mitigation technologies in the multigas scenario.

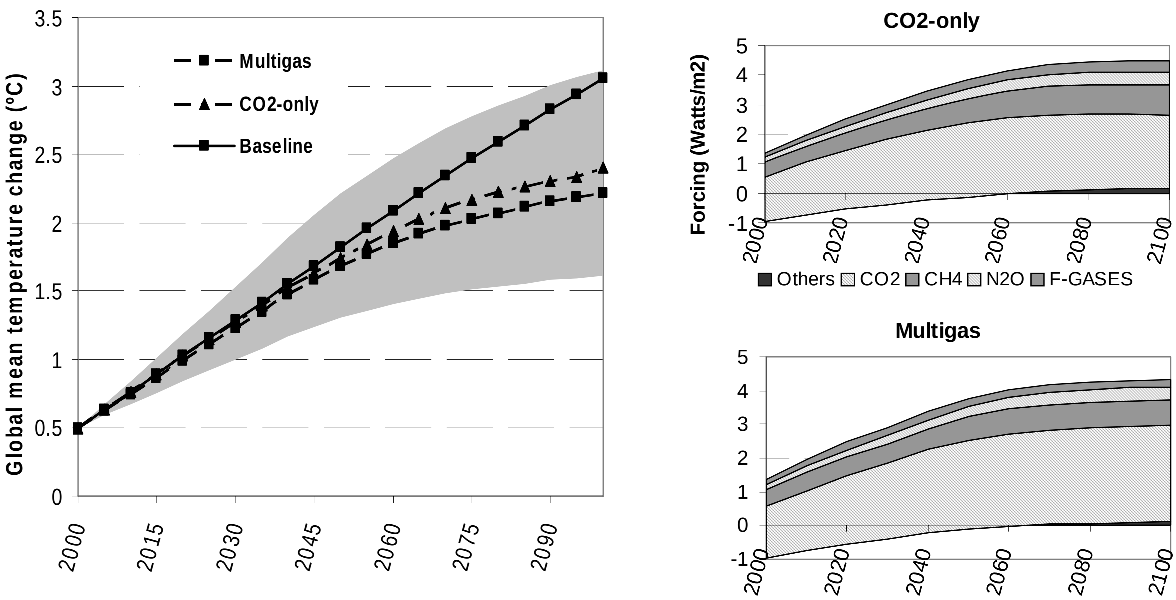

Figure 6: a) Development of global temperature change in the scenarios as compared to pre-industrial times (left-hand side). The shaded area illustrates the uncertainty range for the temperature change in the multigas scenario due to the variation of climate sensitivity between 1.5 and 4.5 degrees C. b) Contribution of different GHGs to overall radiative forcing in the CO_2-only and multigas scenarios.

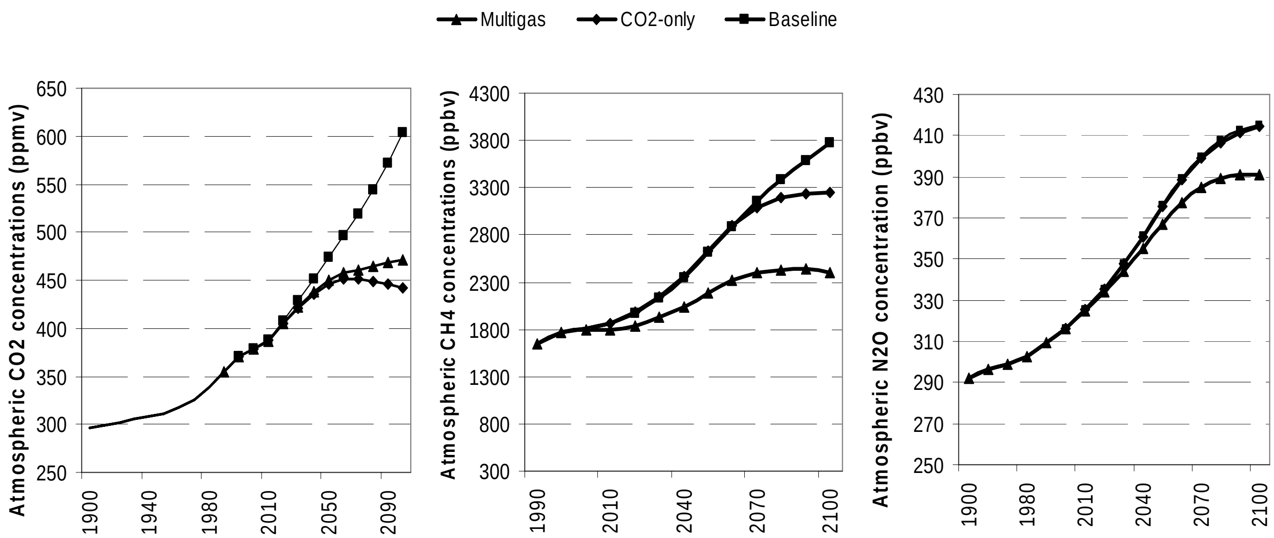

Figure 7: Development of atmospheric concentrations of CO_2, CH_4, and N_2O.

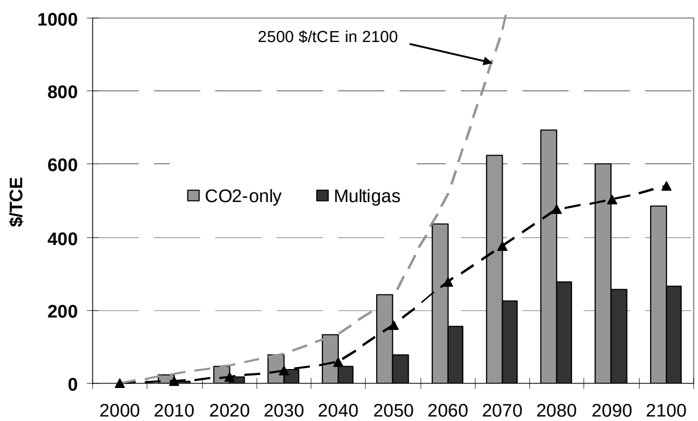

Figure 8: Development of GHG shadow prices. Bars indicate the shadow prices in the CO_2-only and multigas mitigation scenarios. Dashed lines show the development of the prices for the same scenarios without BECS.

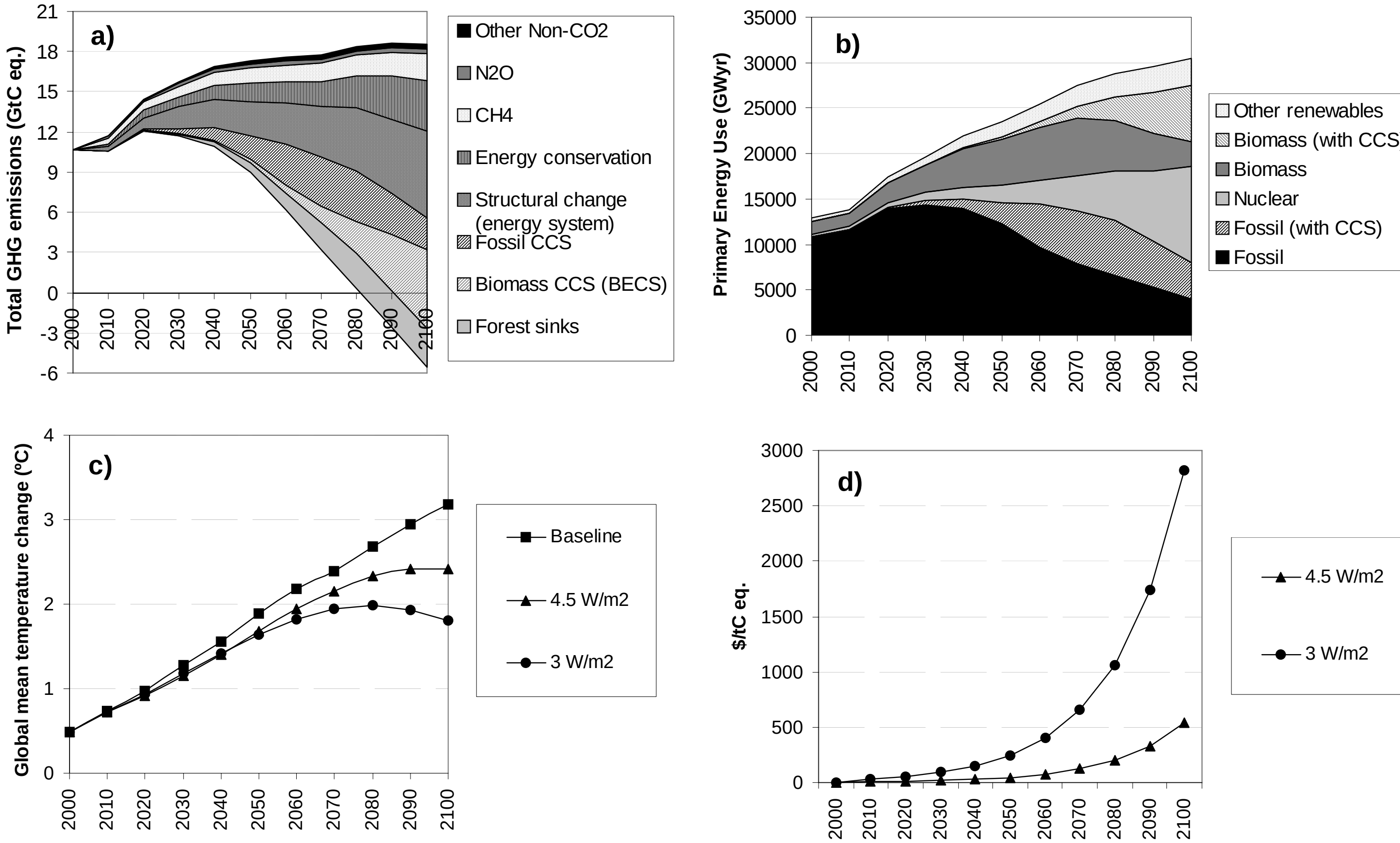

Figure 9: Sensitivity analysis for a low stabilization target. Panel a: Contribution of main mitigation measures for achieving a stabilization target of 3 W/m^2. Panel b: Development of primary energy carriers including the contribution of CCS (stabilization target of 3 W/m^2). Panel c: Development of mean temperature change. Panel d: Development of GHG shadow prices.

Table 1: Baseline GHG emissions in currently industrialized and developing countries. Emissions are shown both by sector and gas. Absolute values are given in MTCE, while the numbers in parentheses show the contributions of the different sectors (gases) in the overall mix.

	Industrialized			*Developing*		
By Sector	**2000**	**2050**	**2100**	**2000**	**2050**	**2100**
Agriculture	398 (8)	406 (7)	205.8 (4)	1005 (25)	23449 (23)	1739 (12)
Energy	4262 (86)	4798 (85)	4878 (89)	2665 (65)	6601 (65)	10331 (72)
Industry & Others	293 (6)	428 (8)	366 (7)	403 (10)	1202 (12)	1897 (14)
By Gas						
CO_2	4013 (81)	4505 (80)	4512 (83)	2425 (60)	6191 (60)	9545 (68)
CH_4	555 (11)	634 (11)	594 (11)	1000 (24)	2487 (24)	3133 (22)
N_2O	316 (6)	318 (6)	174 (3)	624 (15)	1354 (12)	916 (7)
F-gases	48 (2)	165 (3)	161 (3)	25 (1)	251 (2)	373 (3)

* Industrialized includes North America, Japan, Australia, New Zealand, Western & Eastern Europe & Former Soviet Union

Table 2: Mitigation in currently industrialized and developing countries. The emission reductions are shown in MTCE. The figures in parentheses show the shares of the different sectors in the overall mitigation.

	Industrialized			***Developing***			*Reduction ratio (industrialized to developing)*		
By Sector	**2020**	**2050**	**2100**	**2020**	**2050**	**2100**	**2020**	**2050**	**2100**
Agriculture	22 (1)	58 (4)	43 (1)	57 (7)	255 (12)	202 (6)	0.39	0.23	0.22
Energy	278 (75)	1258 (84)	3203 (94)	220(76)	1794 (58)	5712 (57)	1.3	0.70	0.56
Industry & Others	96 (24)	181 (12)	168 (5)	150 (18)	622 (30)	1225 (37)	0.64	0.29	0.14