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The Role of Non-CO_2 Gases in Flexible Climate Policy: An Analysis with the Energy-Systems GMM Model

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Abstract: This paper examines the effects of incorporating two main non-CO_2 greenhouse gases, namely methane (CH_4) and nitrous oxide (N_2O) into the "bottom-up", partial equilibrium, energy-systems Global Multi-regional MARKAL model (GMM). Abatement possibilities for these two greenhouse gases have been included using marginal abatement curves from the U.S. EPA study (2003). Our results illustrate the effect of these greenhouse gases on the composition of emissions mitigation strategies and associated costs, highlighting the importance of the "what" flexibility in climate-change policies. In addition, we emphasize the influence of assumptions regarding rate of deployment and technological change in non-CO_2 abatement potentials on the model's outcome.

Keywords: *Multi-gas abatement, flexible mechanisms, mitigation cost, technological change, MARKAL.*

1. Introduction

The consideration of non-CO_2 greenhouse gases (GHG) is an important aspect when examining cost-effective strategies for mitigation of global climate change (e.g. Manne and

Richels, 2000, 2004; Reilly et al., 1999, 2003). Although CO_2 is the most significant contributor to the human-induced climate change, other GHGs also play an important role, in particular because they are associated with a much more potent greenhouse effect in the atmosphere than CO_2. Including non-CO_2 GHGs may have noticeable effects on the costs and composition of mitigation strategies. These gases, therefore, represent an important component when it comes to enhance the degree of flexibility of climate-change mitigation strategies.

Flexibility is an important attribute of climate-change mitigation policies, particularly if the induced costs and the difficulties of reaching co-operative international agreements are taken into consideration. Different aspects of flexibility in climate-change policies have been highlighted in the literature in relation to the timing ("when" flexibility), geographical distribution ("where" flexibility) and portfolio of GHGs ("what" flexibility) associated with an emissions mitigation strategy (e.g. IPCC, 2001a; Reilly et al., 2003). An additional aspect of flexibility is related to technological pathways that could increase the ability of the global energy system to reach significant emission reductions in the long run (Hoffert *et al.*, 2002; Nakićenović, 2003).

The Kyoto protocol identifies six substances that can contribute to reaching the overall GHG mitigation goal. In addition to CO_2, the Kyoto-gases include methane (CH_4), nitrous oxide (N_2O), and the group of three fluorinated gases (F-gases) comprising hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6) (UNFCCC, 1999). The non-CO_2 GHGs, if weighted by their global warming potentials (GWP), represent about 30% of the current global budget of anthropogenic carbon-equivalent (C-eq) emissions (IEA, 2004). The majority of non-CO_2 GHGs originates from the agriculture and energy sectors, followed by industrial processes and waste treatment. Although the CO_2 emissions associated with the

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fossil-fuel combustion represent the far largest contribution to the total GHG emission levels (63%), ignoring other Kyoto-gases would lead to the abandonment of a range of cost-efficient abatement options and potential gains because of substitution among gases.

Several studies have analysed the implications of multi-gas abatement strategies for the Kyoto protocol, for example, Reilly et al. (1999), Burniax (2000) or Lucas et al. (2002), suggesting the reduction in total cost of implementing the Kyoto protocol to be within a range of 26% to 60% relative to policies that assume cuts only in CO_2 emissions. In this context, this paper analyses impacts of "what" flexibility in reaching the long-term post-Kyoto GHG-emission stabilisation targets applied for the global energy system. For this purpose, we use the global, multi-regional, "bottom-up" energy-systems MARKAL model (GMM), developed and applied at the Paul Scherrer Institute (PSI) in Switzerland (Barreto, 2001; Barreto and Kypreos, 2004; Rafaj et al., 2005). This kind of models provides a detailed representation of energy supply and demand technologies and is typically used to examine the role of energy-technology strategies in CO_2 mitigation.

Several possibilities for considering the effects of non-CO_2 GHG abatement in a "bottom-up" modelling framework can be identified. One possibility is the explicit inclusion of abatement technologies, which is an approach that has been followed by Rao and Riahi (2005) and Delhotal et al., (2004), among others. The second approach is the use of aggregate marginal abatement cost (MAC) curves that are built on the basis of assessment of abatement technologies. Here, following the work of Manne and Richels (2000, 2004) and Turton and Barreto (2004), we incorporate MAC curves for the two main non-CO_2 greenhouse gases in the GMM model, namely methane (CH_4) and nitrous oxide (N_2O), considering both energy-related and non-energy-related sources. By implementing MAC curves for these non-CO_2 GHGs, the scope for the examination of energy-technology strategies in the GMM model is substantially expanded.

Our results illustrate the effects of including these non-CO_2 GHGs on the composition of mitigation strategies and associated costs, while highlighting the importance of the "what" flexibility in climate-change policies. We also draw attention to the potential synergies between CO_2 and non-CO_2 GHG abatement efforts in the energy system, using the case of methane emissions from fossil fuel production as an example. In addition, we emphasize the influence of assumptions regarding technological change in non-CO_2 abatement potentials on the quantification of GHG mitigation strategies.

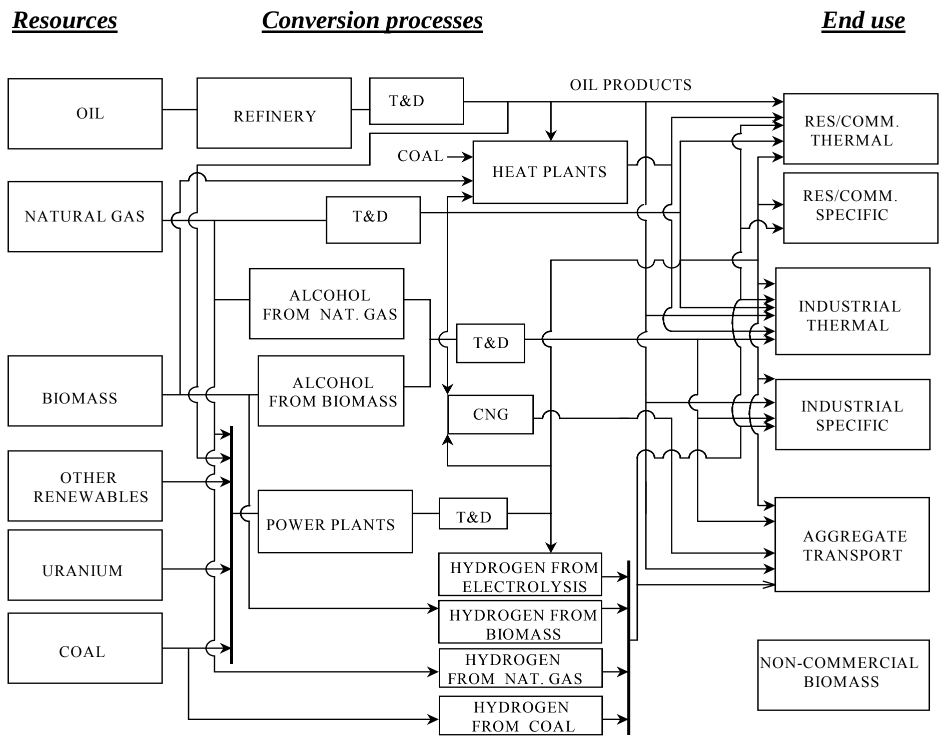
The remainder of this paper is organized as follows. Section 2 briefly describes the energy-systems GMM model. Section 3 presents our approach for incorporating the marginal abatement curves into the model. Section 4 portrays the main characteristics of the baseline scenario and illustrative policy scenarios for GHG abatement used in this analysis. Section 5 discusses some selected results and illustrates the influence of the inclusion of the non-CO_2 gases in the composition and costs of mitigation strategies. Finally, Section 6 outlines some conclusions from this analysis.

2. The energy-systems GMM model

The Global, Multi-regional MARKAL model (GMM) is a "bottom-up", partial equilibrium energy-systems model that provides a relatively detailed representation of energy supply technologies and a stylized representation of end-use technologies (Barreto and Kypreos, 2004; Rafaj *et al.*, 2004). GMM is part of the MARKAL family of models (Fishbone and Abilock, 1981; Loulou *et al.*, 2004), a group of perfect-foresight, optimization energy-system models that represent current and potential future technology alternatives through the so-called Reference Energy System (RES) and are typically used to obtain the least-cost energy system configuration for a given time horizon under a set of assumptions about end-use demands, technologies and resource potentials. Figure 1 presents the reference energy system (RES) used in all the regions in the GMM model.

GMM addresses technology dynamics in the energy system by endogenizing technology learning for selected electricity generation technologies. This approach reflects the fact that some technologies can experience declining unit costs because of the process of 'learning-by-doing' (LBD) and enables analysis of the way in which respective technology enters the energy market through learning-induced unit-cost reductions. The energy end-use demands that drive GMM are elastic to the own prices, which are endogenously computed by the model in the Baseline case. These demands are self-adjusted to the changes (increases) in marginal cost of services that results from the imposition of a given policy constraint.

The GMM model comprises five regions. Two regions portray the industrialized world, North America (NAM) and the rest of the OECD countries in the year 1990 (OOECD). One region comprises the economies-in-transition in Eastern Europe and the Former Soviet Union (EEFSU). Two additional regions represent the developing world. The first of them brings together developing countries in Asia (ASIA) and the second region groups Latin America, Africa and the Middle East (LAFM). The model has been calibrated to year-2000 energy statistics (IEA, 2001) and the time horizon is 2000 to 2050 with ten-year time periods. Unless specified otherwise, a discount rate of 5%/year is used in all calculations.



<<**Figure 1:** Reference energy system (RES) used in the energy-systems GMM model. T&D stands for transport and distribution chains; CNG is compressed natural gas.>>

Assumptions about energy resources and demands for energy services have been taken from the B2 scenario quantified with the MESSAGE model (Riahi and Roehrl, 2000) for the IPCC (2000). The B2 scenario constitutes a “middle-of-the road” development where economic growth, population and other driving forces evolve gradually and in a consistent way with historical trends. Since, among other factors, technology dynamics, time horizon, regional disaggregation, etc, in the GMM model differs from that in the MESSAGE model, we do not claim the Baseline scenario reported herein to be a consistent characterization of the B2 storyline of IPCC (2000). Still, it could be regarded as one plausible picture of future developments.

3. Description of the MAC approach

As is mentioned in Section 1, there are basically two approaches for including non-CO_2 GHGs applicable to MARKAL-type models. First, a bottom-up approach that requires the incorporation of abatement systems and mitigation options per emission source for all non-CO_2 Kyoto-gases directly into models in the same way as those for CO_2 reductions. Bottom-up representation of mitigation technologies defines cost and performance characteristics for a number of existing and future abatement systems and processes (e.g., capturing of methane in coal mines and from landfills, limiting the CH_4 leakages from natural gas pipelines, etc.)

In the second approach, here referred to as a MAC approach, the marginal abatement cost curve defines the supply of GHG abatement opportunities as a function of cost, and the resulting function is nothing else but a summary representation of the detailed engineering analysis of a range of abatement technology options. In this section, a brief description of the approach for incorporating marginal abatement curves in the GMM model is presented. The MAC approach used here is based on the work of Manne and Richels (2004) for the MERGE model, and Turton and Barreto (2004) for the ERIS model. This approach uses the regional marginal abatement cost curves for non-CO_2 GHGs estimated by U.S EPA (2003).

3.1. Definition of baseline emissions

Following US EPA (2003), the categories considered in this analysis are as follows: CH_4 emissions from coal, oil and gas production, solid waste management and manure management, N_2O emissions from adipic and nitric acid production. Baseline emissions must be defined for these different sources of emissions. Baseline emissions can be endogenous if they are linked to a model variable or exogenous if they are specified from sources external to the model. In this formulation, energy-related methane emissions from coal, oil and gas production are endogenous to the model. Emissions from other sources are exogenous to the model.

Other sources of CH_4 (enteric fermentation and rice paddies) and N_2O (soils) emissions can also be considered exogenously. However, since no MAC curves are specified for them in the US EPA study (2003), they are treated here as non-abatable emissions. It must be noticed that these sources of emissions currently represent a large fraction of the total emissions of these non-CO_2 gases worldwide (Reilly et al., 2003) but uncertainties still abound regarding the potential, costs, and feasibility of implementation of mitigation measures.

3.2. Definition of marginal abatement cost curves

A MAC curve typically represents the additional cost of reducing or abating the last unit of a given emittant. Any emission reduction for a gas and for a region can be represented as a point on the associated MAC curve. If several gases are allowed to contribute simultaneously to emission reductions in a given region, and if the marginal costs associated with those reductions are different, the aggregate cost of meeting the reduction target will be lower to the extent that a gas with higher marginal costs of abatement can be substituted for a gas that is less costly to abate. The difference in the marginal costs associated with each substitutable gas can create a potential gain (reduction) in total cost for the same volume of GHG reduction because of the increased supply of new or cheaper abatement opportunities. Considering the local circumstances and the different regional abatement potentials for selected GHGs, the potential trade-off between gases is affected by the location of the emission reduction.

The MAC curves are introduced to the GMM model as stepwise curves relating abatement costs and abatement potentials. These abatement potentials are given either as absolute potentials (e.g., in tons of the respective GHG or carbon-equivalent), or in relative terms (e.g.

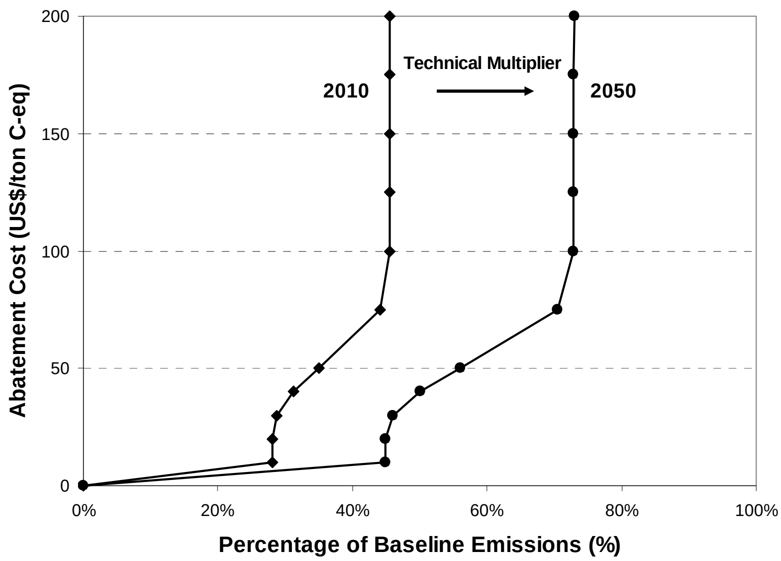
percentage) of a given baseline. In what follows, it is assumed that the abatement potentials are given as a fraction of the baseline and that emissions from non-CO_2 GHG are expressed in terms of carbon-equivalent (C-eq) emissions using the 100-years global warming potentials (GWP) reported by IPCC (2001b), namely 23 for CH_4 and 296 for N_2O.[1] Correspondingly, abatement costs are given in US$/ton C-eq.

The abatement potentials have been derived on the basis of considerations of availability, reduction efficiency and technical and economic applicability of the different abatement options (Delhotal et al., 2003). Abatement potentials per price step, region, and GHG are specified for a reference time period, here chosen as 2010. We did not consider no-regrets options in this specification. That is, all MAC curves were shifted upwards such that abatement costs are always positive. Abatement potentials for other periods are computed using the so-called technical-progress multipliers (tm). These multipliers represent the fact that abatement technologies may improve over time, thus increasing the abatement potential achievable at a given cost. The multipliers allow extrapolating the MAC curves beyond 2010, the reference year, as depicted in Figure 2.

It has to be recognized that these multipliers provide only a rudimentary way to represent technical change in non-CO_2 abatement options and that this takes place only exogenously (i.e. it does not depend on the amount of cumulative abatement). Moreover, at this point their choice is somewhat arbitrary and dependent on the modeler's judgement. Delhotal *et al.* (2003) have proposed a methodology for shifting the MAC curves into the future on the basis of technology assessment for individual technologies, but figures are not yet available for multiple regions and/or sectors.

[1] The use of global warming potentials (GWP) has been criticized in the literature because they do not constitute an adequate "exchange rate" between GHGs (O'Neill, 2000; Manne and Richels, 2000; Fuglestvedt et al., 2003). Specifically, they fail to capture a number of physical and chemical interactions between GHGs and differences in their persistence in the atmosphere, among others. Also, they lack an economic rationale. However, the use of alternative, economic indices proposed in the literature, which rely mostly on the monetization of damages due

This approach also allows for trade of C-eq emission permits across regions, since it is likely that under the multi-gas mitigation strategy it would be extended to other GHGs as well. The basic equations of the MAC curve formulation in the GMM model are summarised in Appendix. The complete description of the source code used for implementation of MACs in the GMM model together with underlying assumptions on MAC curves and baseline-emissions are presented in detail in Barreto et al. (2004).



<<**Figure 2:** Illustration of the effect of technical multipliers to shift marginal abatement curves out into future periods.>>

3.3. Limitations

As discussed earlier, the MAC-curve approach can be extended to the anthropogenic GHG emission sources generated from other economic sectors, i.e., industry, agriculture or forestry. In this case, the abatement options and related costs have to be associated to the activity of the respective sector to reflect the impact on supply and demand resulting from an abatement

to climate change, has not been possible so far given the huge uncertainties that currently surround the assessment of climate damages (Reilly et al., 2003).

activity. This approach is applicable to models that allow for the full economy feedback from all sectors, such as computable general equilibrium (CGE) models (Hyman et al., 2003). Since GMM is a partial-equilibrium model describing the energy sector, we focus our analysis on the energy-related GHG emissions. However, the MAC curves for CH_4 and N_2O emissions from solid waste management, manure management, adipic and nitric acid production are included for illustrative purposes.

Inclusion of CH_4 emissions from fossil fuels production, handling and transmission, as implemented in this study, accounts for approximately 80% of the total non-CO_2 GHG emissions from the energy sector (Olivier and Berdowski, 2001). Because of the paucity of the data, some of the energy-related non-CO_2 GHGs are, however, not considered, e.g., CH_4, N_2O and Fluorinated gases from direct fossil fuel combustion and biomass combustion. Main reasons for exclusion of these emission sources are: a) the limited abatement potentials, b) a relatively high level of aggregation of some of the demand sectors in the model, e.g., transport, and c) no MAC curves are provided for them by U.S. EPA (2003).

4. Scenarios

A set of four illustrative policy scenarios, as summarised in Table 1, is adopted herein over the Baseline development to provide insights into the role of non-CO_2 gases in the global GHG mitigation strategy.

The first scenario refers to the Soft landing scenario described in detail in Rafaj et al. (2004). This scenario envisages a global implementation of Kyoto-type flexibility mechanisms to achieve a stabilisation of CO_2 emissions below 10 GtC/yr by the year 2050. The regions OOECD and EEFSU start to apply the prescribed reduction targets from 2010, while the NAME region adopts mitigation target from 2020 onwards. Developing regions (ASIA and

LAFM) join the mitigation and trading regime in 2020, and it is assumed that by ~2030 the increase in emissions from developing regions must be at most equal to the reduction of the Annex-B countries. Inter-regional trading of carbon permits allows for “where” flexibility in CO_2 abatement.

Regional reduction targets that take into consideration emissions of non-CO_2 gases apply in the Multigas scenario. Sources of CH_4 and N_2O emissions comprise fossil fuels production, solid waste management, manure management, adipic and nitric acid production. The regional distribution of GHG emission reduction entitlements, based on GWP-weighted carbon-equivalents (C-eq), follows the same approach as in the Soft landing scenario. Although the relative reduction in C-eq emissions in the Multigas scenario over the Baseline is equal to the relative decrease in CO_2 emissions in the Soft-landing scenario, in absolute terms the amount of emissions that has to be avoided is higher proportionally to the higher level of the Baseline emissions of all GHGs (see Figure 3). The reduction targets can be achieved by curbing emissions of both CO_2 and non-CO_2 gases and at the same time the regions are allowed to trade C-eq permits. This scenario refers to a ‘cap-and-trade’ policy assuming a “where + what” flexibility in GHG abatement.

To illustrate the contribution of non-CO_2 gases in the Multigas scenario, the Multigas/CO_2-only scenario is designed so that the same emission reduction targets have to be fulfilled while only CO_2 emissions can be reduced.

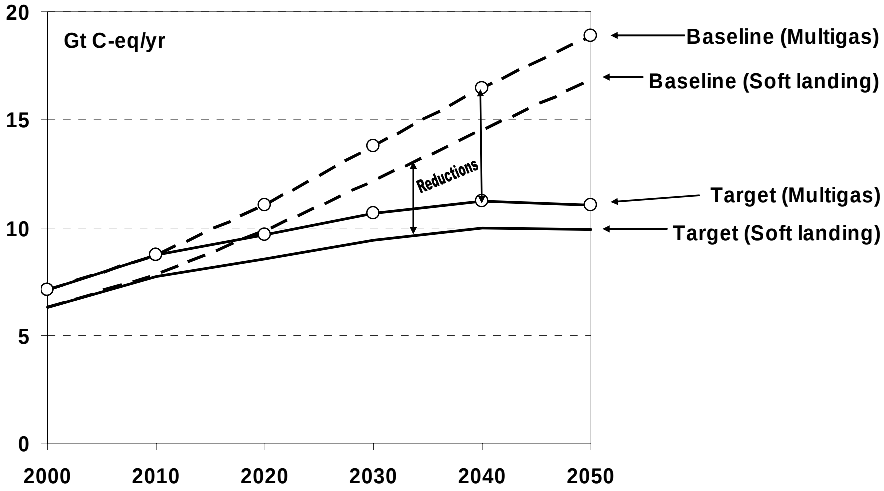
Finally, the fourth scenario is defined by a cumulative global C-eq constraint equal to the integral of regional C-eq emission targets up to 2050 as prescribed by the Multigas scenario. This illustrative cumulative constraint of the Multigas/Cumulative scenario helps to identify an optimal timing in C-eq abatement and simultaneously allows for mitigation of all GHGs and trading of C-eq permits. This scenario provides a full “where + what + when” flexibility in achieving the C-eq mitigation goals.

Scenario	Description	GHG abatement	Flexibility
Baseline	No reduction target	No	No
Soft landing	Regionalised reduction target, Trade of carbon permits	CO_2	"where"
Multigas	Regionalised reduction target, Trade of C-eq permits	CO_2, CH_4, N_2O	"where + what"
Multigas/CO_2-only	Regionalised reduction target, Trade of carbon permits	CO_2	"where"
Multigas/Cumulative	Global cumulative reduction target, Trade of C-eq permits	CO_2, CH_4, N_2O	"where + what + when"

<<**Table 1:** Scenarios naming and definition.>>

One of the consequences of the inclusion of non-CO_2 gases in the mitigation strategy is that the level of "hot air"[2] in the Multigas scenario increases by 20 % as compared to the Soft landing scenario due to a drop in energy-related CH_4 emissions in the EEFSU region in 2010 relative to the levels in 1990. Burniax (2000) projects the contribution of non-CO_2 gases to the total amount of "hot air" to be around 90 Mt C-eq. In our analysis, only 50% of the total available "hot air" is allowed for trading between OOECD and EEFSU regions in 2010.

In the results of the Multigas scenario provided in Section 5, a maximum annual growth rate for non-CO_2 gases abatement of 10%/yr and the seed value for initial abatement of 5 MtC-eq for all CH_4 and N_2O sources is assumed (see Appendix, Equation 7). For simplicity, a common technical-progress multiplier has been applied across all non-CO_2 GHG-emission categories projecting a 5% total increase in abatement potential by 2050 over the MAC reference year 2010 (see Appendix, Equation 1). This rather conservative assumption is made in order to avoid unrealistic levels of GHGs reduction by 2050 since the abatement potentials assumed by U.S. EPA (2003) for the year 2010 are already significant, and due to uncertainties related to technical change in abatement options. To illustrate the influence of aforementioned parameters on the cost and composition of multi-gas mitigation strategy, a parametric analysis has been performed and is reported in Section 5.4.



<<**Figure 3:** Global GHG emissions (CO_2, CH_4, N_2O) in the Baseline scenarios and the reduction targets in the Soft landing and Multigas scenarios. CO_2 here refers only to energy-related emissions.>>

5. Results

5.1. GHG emissions

Baseline emissions of the three GHGs considered herein (CO_2+CH_4+N_2O) increase with an annual growth rate of 1.96% until 2050, and reach a level of 18.9 GtC-eq/yr. The annual growth is lowered to 0.9% in the Multigas scenario. By 2030, the total GHG emisons are stabilised to around 11 GtC-eq/yr. The cumulative C-eq reduction between 2010-2050 is quantified at 177 GtC-eq.

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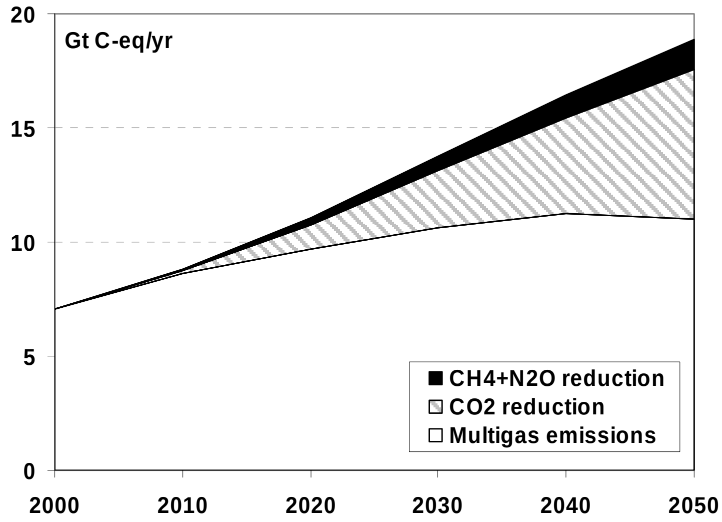
[2] In the context of the Kyoto protocol "hot air" represents a gap between projected emission levels and prescribed emission reduction targets for Annex-B countries of EEFSU during the 2008/2012 commitment period.

Figure 4 shows the contribution of non-CO_2 abatement options to the overall C-eq reduction over the Baseline for the Multigas scenario. The fraction of CH_4 and N_2O reduction decreases from 23% in 2020 to 15% in 2050, suggesting that the non-CO_2 GHGs abatement can play a transition role in the GHG mitigation strategy. Energy-related CH_4 emissions contribute 74% of the total non-CO_2 GHG emission reduction in 2050. The contribution of non-energy related CH_4 and N_2O emission abatement in 2050 is 21% and 5%, respectively.

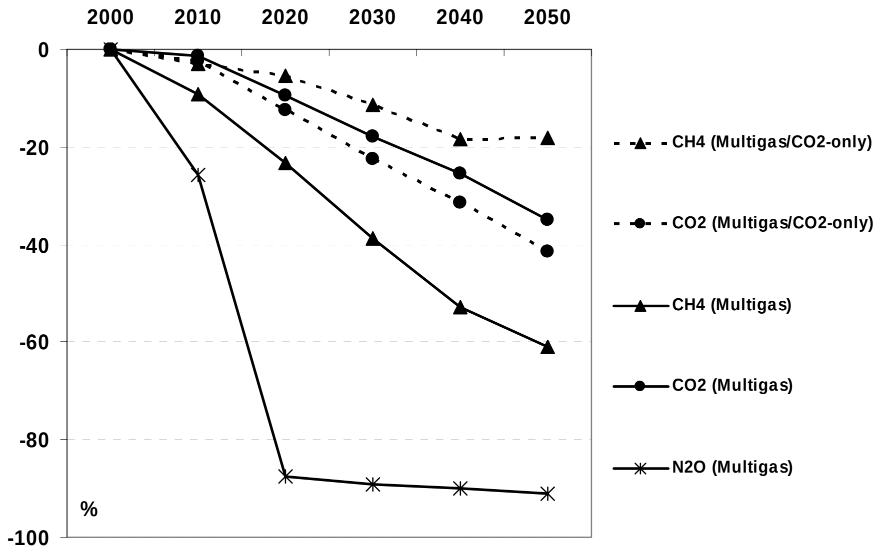


<<**Figure 4:** Multigas emissions reduction under an illustrative Multigas scenario. The contribution of non-CO_2 GHGs to the mitigation is distinguished.>>

Change in the global GHG emissions relative to the Baseline in the Multigas and Multigas/CO_2-only mitigation scenarios is summarised in Figure 5. While the energy-related CO_2 emissions are reduced by 35% in 2050 in the Multigas scenario, the methane emissions reach levels that are 60% below the Baseline development. Substantial reductions in N_2O emissions are achieved already by 2020 and further mitigation of N_2O emissions is bounded by the abatement potentials defined by MACs.

Under the Multigas/CO_2-only scenario, the CO_2 emissions are reduced by 42% relative to the Baseline. Although the reduction target is achieved entirely by mitigation of the CO_2

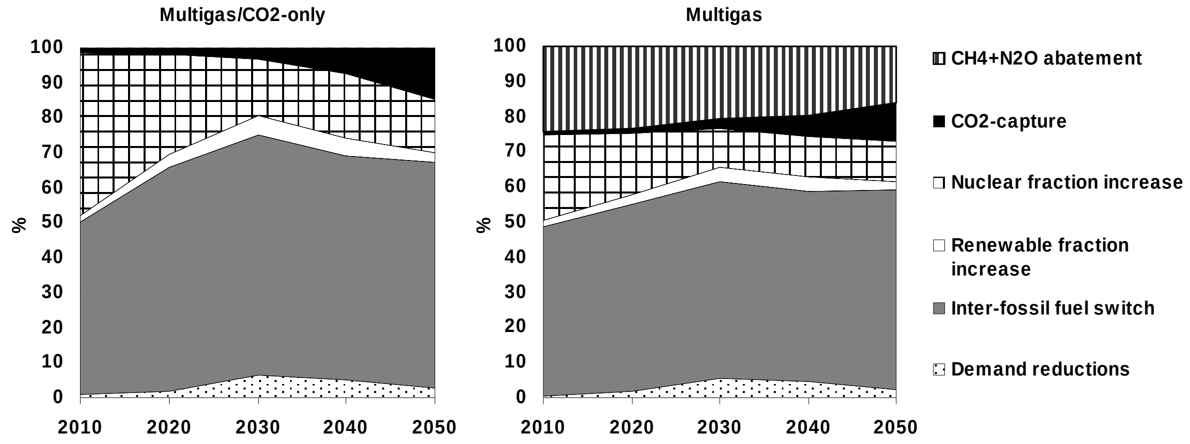
emissions, some reduction of methane emissions (by 18% in 2050 over the Baseline) already takes place due to significant decrease in the use of fossil fuels. This finding suggests that synergies can be expected between "Kyoto-gases" under C-eq mitigation constraints and at the same time indicates that the C-eq price reported for the CO_2-only scenarios can be overestimated.



<<**Figure 5:** Change in the global CO_2, CH_4 and N_2O emissions relative to the Baseline in the Multigas and Multigas/CO_2-only mitigation scenarios.>>

The importance of non-CO_2 GHGs abatement in the mitigation strategy is contrasted in the Figure 6, where a break-down of different C-eq reduction components is provided. An inter-fossil fuel switching, e.g., substitution from coal to natural gas, plays dominant role in the global mitigation process in both Multigas and Multigas/CO_2-only scenarios. However, important differences are observed for the role of nuclear energy and CO_2-capture. The inclusion of options to abate non-CO_2 GHGs reduces the contribution of nuclear energy by 50% to 25% between 2010 and 2050. Similarly, the CO_2-capture contributes by 26% less to the C-eq reduction in 2050 as compared to the case where only CO_2 emissions can be abated.

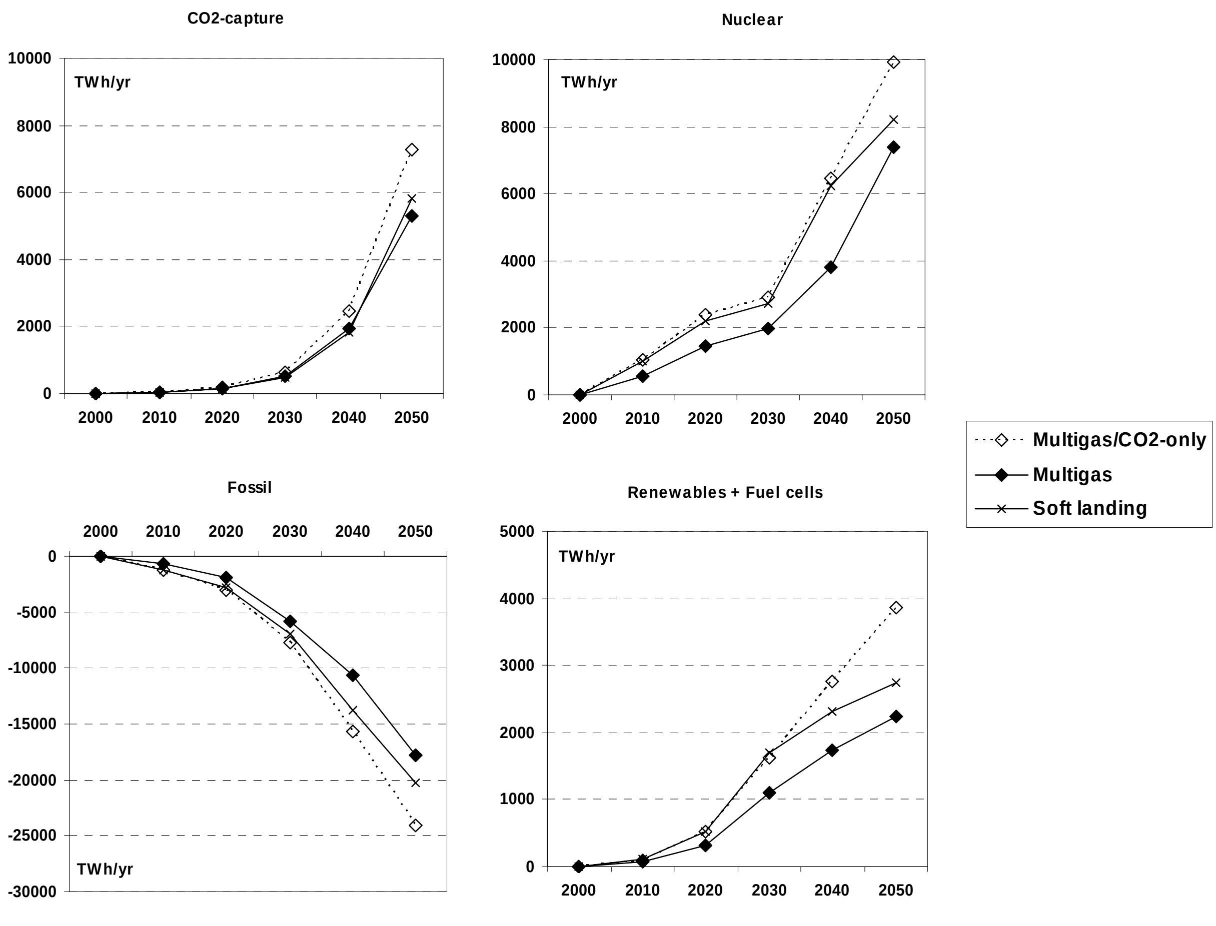
Implication of this result is that the reduction of non-CO_2 GHGs can shift the need to invest in capital-intensive technologies, e.g., nuclear or CO_2-capture, towards later decades.



<<**Figure 6:** Break-down of GHG reduction components for the Multigas and Multigas/CO_2-only scenarios.>>

5.2. Electricity generation

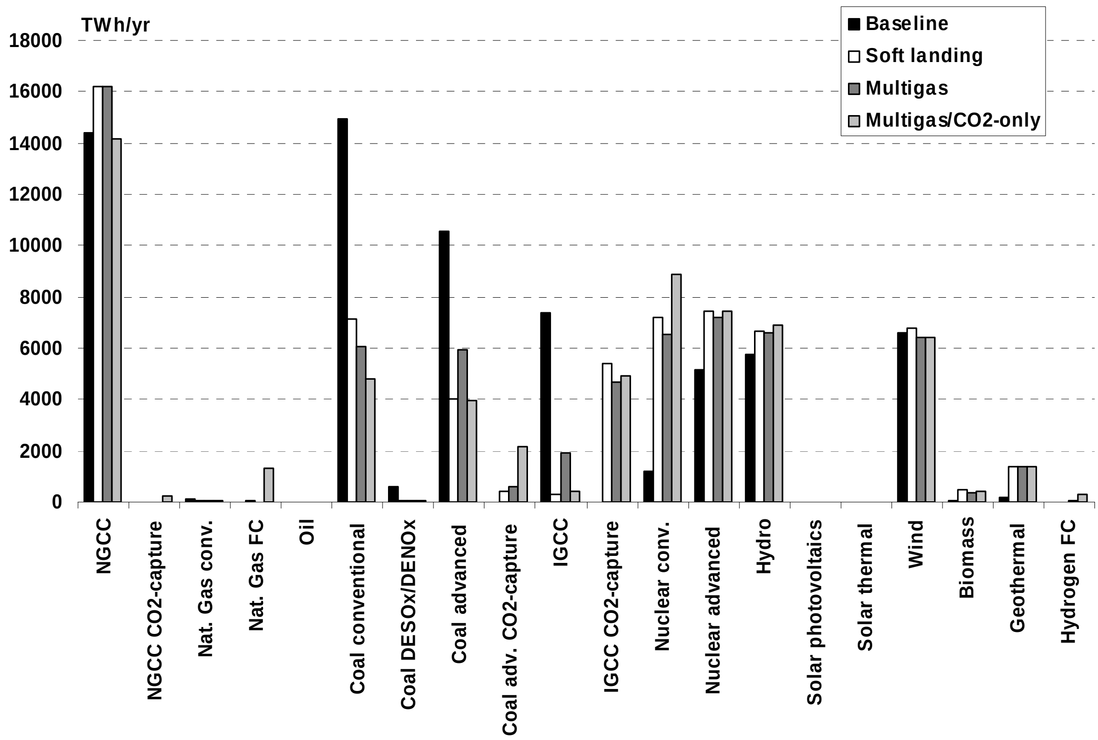
Although the analysis of the impacts of non-CO_2 GHGs takes place in the context of the global energy system as a whole, the development in the global electricity sector is portrayed in detail herein given that, among others, the reduced number of actors and the relatively wide range of technology options as compared to other sectors make it likely to be one the main targets of GHG-mitigation policies. As shown in Figure 7, imposition of C-eq constraint induces considerable changes to the electricity generation market regardless of the type of flexibility mechanism used to reach the emission reduction targets. A common trend is observed across the Soft landing, Multigas and Muligas/CO_2-only scenarios as compared to the Baseline development: the amount of power generation based on fossil fuels combustion undergoes substantial reduction over the time horizon and is balanced by an increased contribution from advanced fossil and carbon-free sources. The substitution effect is most pronounced in the Multigas/CO_2-only scenario as this scenario implies a more severe reduction target as compared to the Soft landing scenario and at the same time excludes CH_4 and N_2O from the portfolio of abatable gases. While both the Soft landing and Multigas/CO_2-only scenarios allocate similar increases in nuclear and renewable power production between 2010 and 2030, implementation of abatement options for non-CO_2 GHGs in the Multigas scenario reduces significantly the contribution of nuclear energy and renewables over the whole time horizon as the penetration of these technologies is replaced by cheaper options associated with CH_4 and N_2O mitigation. Similarly, the rise in the power production from systems with CO_2-capture is lower in the Multigas scenario relative to the cases where the mitigation efforts involve only the CO_2 emissions reduction.



<<**Figure 7:** Change in the global electricity generation over the Baseline scenario for C-eq abatement scenarios. *Nuclear* refers to conventional and advanced nuclear plants; *Renewables + Fuell cells* graph refers to the aggregated contribution from hydro power, wind, biomass,

geothermal, solar electricity and all types of fuel cells; *CO_2-capture* aggregates coal and natural gas technologies equipped with carbon capture systems; *Fossil* comprises all generation sources based on combustion of coal, natural gas and oil without CO_2-capture.>>

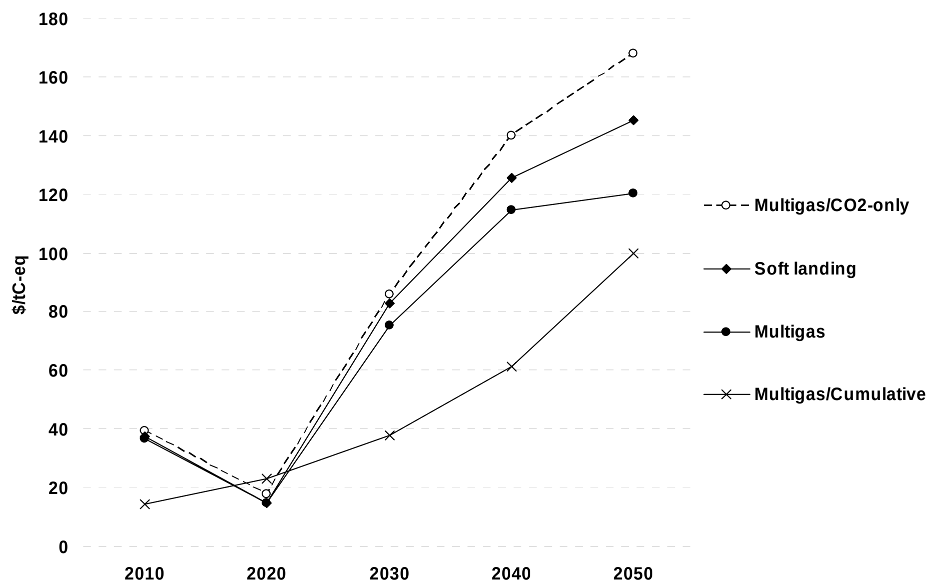
Figure 8 illustrates the power generation mix in the year 2050 for the Baseline and for the set of GHG mitigation scenarios. While the power generation in the end of horizon for the Baseline scenario is dominated by conventional and advanced coal systems, natural gas combined cycle (NGCC) becomes the main source of electricity for GHG-constrained scenarios. The only coal-based systems that undergo substantial increase over the Baseline are the advanced coal plants and integrated coal gasification combined cycle (IGCC) with CO_2-capture. Penetration of these technologies is the highest in the Multigas/CO_2-only scenario, and the lowest in the Multigas scenario. The same observation is reported for the generation from nuclear power plants. Differences in the power production from the renewable sources appear at a smaller extend. Generation from the hydropower and both hydrogen and natural gas fuel cells (FC) in the Multigas/CO_2-only scenario, however, increases remarkably over the Baseline development.



<<**Figure 8:** Contribution of technologies to the global electricity generation mix in 2050.>>

5.3. Cost impacts

In all scenarios that consider the "where" flexibility in GHG abatement, the price of C-eq permits globally traded across regions increases over the time horizon, with the exception of the period around 2020. The reduction in marginal cost in this period is associated with the increased supply of C-eq permits originated from Non-Annex-B countries joining the GHG-mitigation regime from 2020 onward. In 2050, the C-eq permit price reaches 145 $/tC-eq for the Soft landing scenario. This price is increased by 16% when the more severe Multigas mitigation target is applied without possibility to abate non-CO_2 GHGs. As shown in Figure 9, inclusion of CH_4 and N_2O in the emission mitigation strategy reduces the marginal price of C-eq relative to the CO_2-only scenario over the time horizon between 7% in 2010 to 28% in 2050. These results are consistent with the observations made above for the technology dynamics in the electricity sector suggesting that the "what" flexibility can result in important cost reductions by postponing the investments in expensive technologies, e.g., CO_2-capture or nuclear power plants, necessary to reach GHG abatement targets. Benefits in terms of C-eq price reduction invoked by adopting different flexibility concepts are further pronounced for the Multigas/Cumulative scenario allowing for a full "where + what + when" flexibility in GHG abatement. The reduction in C-eq permit price over the Multigas/CO_2-only scenario accounts for 40% and is attributed to the cost-optimality in a) timing of GHG mitigation, b) allocation of abatement possibilities across the world regions, and c) mix of gases available for abatement.

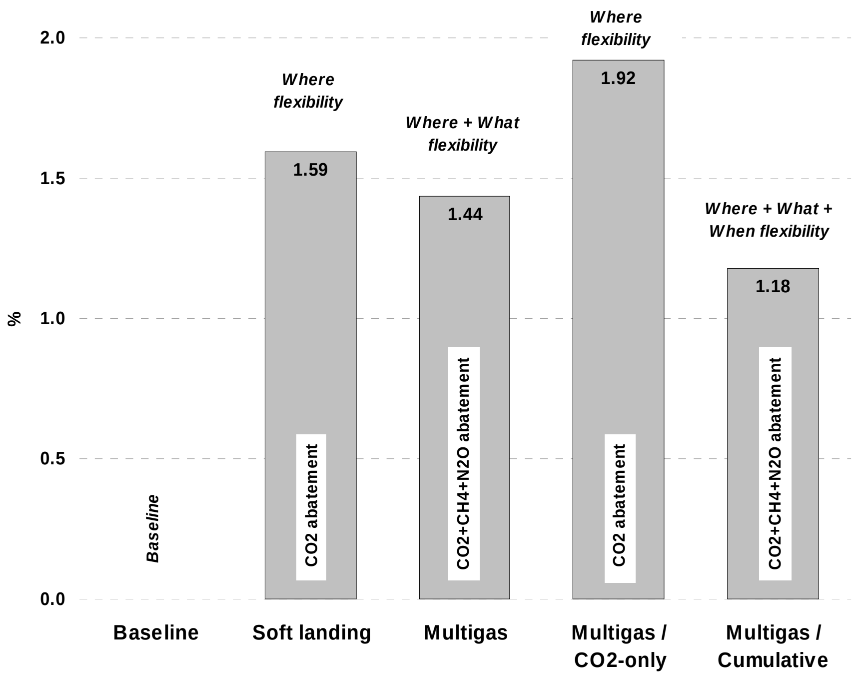


<<**Figure 9:** Marginal cost of C-eq emission permits for scenarios adopting different type of flexibility in the GHG mitigation.>>

Cost impacts of different flexibility modalities associated with global GHG mitigation efforts are demonstrated further in Figure 10 by calculation of the difference between the total discounted system costs and the welfare loss due to demand reductions for the Baseline and C-eq constrained scenarios. The total discounted energy-system cost increases by 1.6% over the Baseline in the Soft landing scenario that aims at stabilizing the global energy-related CO_2

emissions at a level of 10 GtC-eq by 2050. Applying the “what” mitigation flexibility in the Multigas scenario reduces the total cost by nearly 10% relative to the Soft landing case, although the total amount of C-eq avoided is higher proportionally to the differences in the reference C-eq emissions. Exclusion of the “what” flexibility option in the Multigas scenario results in a total cost increase of 33%. Allowing for the full abatement flexibility in the Multigas/Cumulative scenario suggests additional gains in moderating the cost penalty due to the GHG policy constraint by 18%.

To put the presented results in the right perspective, it has to be emphasised that a number of factors limit the capability of the approach used for this analysis to seize fully the potential benefits of adopting the climate policies based on the “what” flexibility. First, some sources of the energy related GHGs, e.g., direct fuel combustion, were omitted from the total emission balance due to the lack of data and limited abatement potential for those sources. Furthermore, being GMM a partial equilibrium model (energy sector only), inclusion of non-energy related GHGs would require to construct a set of sub-modules able to depict economic impacts of abatement activities in sectors, where the non-energy GHGs originate, i.e., agriculture or industry. Nevertheless, the findings reported herein are in accordance with the studies on multi-gas strategies performed with other “bottom-up” models (Criqui, 2002; Rao and Riahi, 2004).



<<**Figure 10:** Change in the cumulative discounted energy system cost and the welfare loss due to demand reductions relative to the Baseline for scenarios adopting different type of flexibility in the GHG mitigation.>>

5.4. Parametric analysis

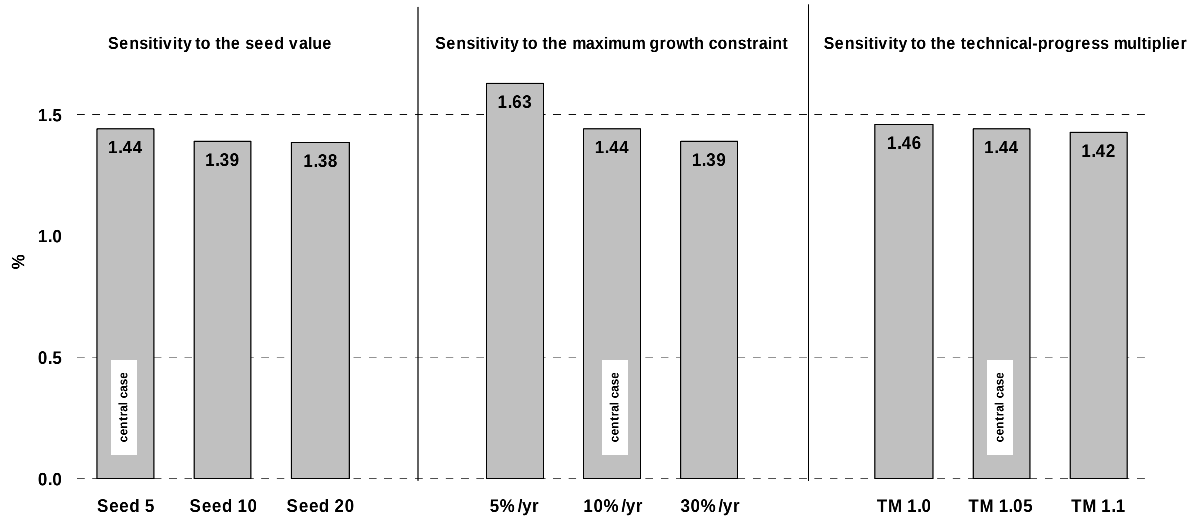
The dependence of the mitigation cost and time evolution of energy related methane emissions to the changes in some key parameters for the Multigas scenario is analysed in this section. The parameters under investigation are a) the seed value of initial non-CO_2 GHGs abatement, b) maximum growth rate for deployment of CH_4 and N_2O abatement options, and c) the technical-progress multipliers. The first two parameters refer to the maximum growth constraint for non-CO_2 abatement defined in Appendix, Equation 7. The third parameter is defined in Section 3.2.

Results presented in the previous sections refer to the central case of the Multigas scenario assuming a maximum growth rate of abatement of 10%/year, a seed value of 5 MtC-eq and an abatement potential that increases by 5% in 2050 relative to 2010. Figure 11 shows the impact of key parameters on the change of total systems cost over the Baseline for the Multigas scenario.

Selection of the seed value influences the penetration of the abatement option in the initial period when the option becomes competitive or cost effective. It is particularly important for the multigas abatement strategy, since the role of the non-CO_2 abatement is largest in the first periods of adoption of GHG policy constraint. Figure 11 shows that the increase in the seed value to 20 MtC-eq produces a reduction in total system cost by 14%. For simplicity, a uniform seed value has been used across GHGs and regions. However, for a model with higher regional resolution the seed value would have to be adjusted to the baseline emission levels of respective region.

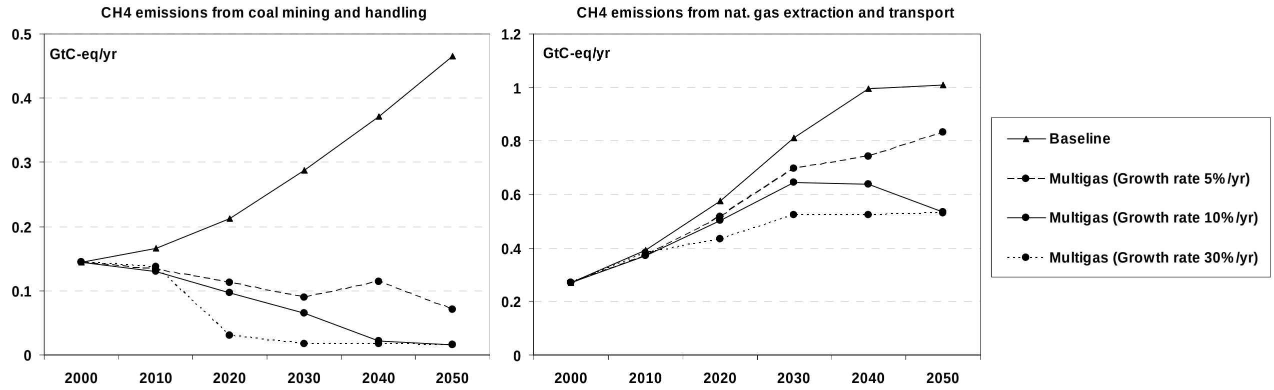
The variations in the change of total system cost over the Baseline for the Multigas scenario is most pronounced for the assumptions made for annual growth constraint on CH_4 and N_2O abatement. The increase in the total system cost is by 43% higher relative to the central case when the annual growth rate is halved. This cost increase is associated primarily with investments due to larger penetration of expensive technologies, e.g. nuclear or CO_2-capture, as compared to the cases allowing for faster exploitation of non-CO_2 abatement potential.

Finally, the total system cost changes are compared in Figure 11 as resulting from the modification of technical multipliers. In the case where no improvement of abatement technologies over time is foreseen (TM 1.0), the total cost increases by 5% relative to the central case (TM 1.05), and by 10% relative to the case assuming 10% abatement improvement until 2050 (TM 1.1). That is, changes in the total system cost are proportional to the change in the technical progress assumption, which suggests that the abatement potential is fully utilised for all three sensitivity cases.



<<**Figure 11:** Comparison of increases in total system costs over the Baseline for selected variants of the Multigas scenario differing on assumptions about the seed value for initial abatement, maximum growth rate of abatement and the technical multipliers.>>

The time evolution of the global CH_4 emissions from coal and natural gas production in the Baseline and Multigas scenarios with different assumptions on the maximum growth constraint for the penetration of abatement technologies is illustrated in Figure 12. If a growth rate of 30%/yr is assumed, the total emission reduction reaches the abatement potential for the coal production in 2020, and for the natural gas production in 2030. A smoother reduction for both sources is reported in the case allowing for 10% annual growth, and the abatement potentials are reached in 2040 and in 2050, respectively. Reduction of the growth rates to 5%/yr results in a remarkably lower total CH_4 abatement in both sectors, as other systems (CO_2-capture, nuclear power) increase their penetration in order to fulfil the C-eq reduction targets. It has to be mentioned that the uptake of low-carbon power generation technologies is accelerated by 'learning-by-doing' cost reduction effects simulated in the GMM model.



<<**Figure 12:** Influence of the maximum growth constraint of abatement on resulting global methane emissions from coal and natural gas production sectors.>>

6. Conclusions

This paper has presented an analysis of the effect of non-CO_2 greenhouse gases on the composition and costs of flexible climate policies. Being the global energy system the focus of our analysis, flexibility here refers generally to its ability to change and adapt to new conditions and circumstances invoked by imposition of the GHG mitigation constraint.

The non-CO_2 emission abatement is incorporated in the “bottom-up” partial equilibrium global MARKAL model (GMM) by using marginal abatement cost curves (MAC) for selected sources of energy and non-energy related CH_4 and N_2O emissions. In our approach, the energy related methane emissions from fossil fuels production are modelled endogenously, while methane emissions from solid waste and manure management, and N_2O emissions from adipic and nitric acid production are exogenous to the model.

The role of non-CO_2 gases in strategies aiming at curbing the GHG emissions is demonstrated within a set of policy scenarios adopting different flexibility mechanisms. The Soft landing scenario represents a “where” flexibility mechanism allowing for international trading of C-eq permits. The Multigas scenario combines the permit-trade with the “what” flexibility approach allowing for abatement a cost-effective mix of gases. The role of optimal timing in C-eq emission abatement is highlighted in the Multigas/Cumulative scenario that represent a full "where + what + when" flexibility type of mitigation strategy.

In agreement with similar studies, the results presented in this analysis suggest a significant cost-reducing effect associated with the inclusion of non-CO_2 gases in the long-term GHG stabilisation strategies. The total discounted system cost in the Multigas scenario, including the invoked welfare loss, is by 33% higher as compared to the scenario where the "what" flexibility is excluded. On the other hand, allowing for a cost-optimal timing path in the Multigas scenario produces additional total cost reduction of 18%. In 2050, the marginal cost of the Soft landing constraint is quantified at 145 $/tC-eq. This cost is reduced to 120 $/tC-eq in the Multigas scenario, although the amount of GHG emissions abated is higher than in the Soft landing case.

Abatement of non-CO_2 GHGs contributes by 23 % to the total GWP-weighted GHG emission reduction in 2020 and this fraction decreases to 15% in 2050 suggesting that CO_2 emissions will remain the main focus of climate protection efforts. Nevertheless, the abatement of other gases can moderate the cost of stringent C-eq reduction targets by postponing investments in capital-intensive technologies, e.g., nuclear power, renewables or CO_2-capture, towards the later decades.

From the methodological perspective, the application of marginal abatement curves in the "bottom-up" modelling context exhibits a number of limitations the modeller must be aware of and should therefore be used carefully. Still, we found that the use of MAC curves provide a compact and aggregate mechanism for representing the effect of non-CO_2 GHGs in our "bottom-up" model and the magnitude of cost impacts reported in this paper indicates the potential benefits that can be expected from inclusion of non-CO_2 GHGs in the climate response policies.

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APPENDIX: Computation of abatement and remaining emissions

In what follows, we describe the basic equations of the MAC formulation in the GMM model. The following notation is used here for sets, parameters and variables:

Sets

GHG:	GHG emissions category
ERGHG:	Energy-related GHG emissions (a subset of GHG)
NERGHG:	Non-energy-related GHG emissions (a subset of GHG)
MSTEP:	Step of the MAC
REG:	Region
TP:	Time period

Parameters

$abtpref_{GHG,REG,TP}$: Abatement potential for the reference period (percentage)

$abatepot_{GHG,REG,TP}$: Abatement potential for other periods (percentage)

$bline_{NERHG,REG,TP}$: Exogenous baseline emissions for non-energy-related GHGs

$tm_{GHG,REG,TP}$: Technical multipliers

$gr_{GHG,REG,TP}$: Growth rate

$seed_{GHG,REG}$: Seed value for initial GHG abatement

Δt: Period length

GWP_{GHG}: Global Warming Potential of a given GHG

Variables

$EMGHG_{GHG,REG,TP}$: GHG emissions per GHG category, region and time period

$EREM_{ERGHG,REG,TP}$: Baseline energy-related GHG emissions per ERGHG category, region and time period

$ABATE_{GHG,REG,TP}$: Abatement per GHG category, region and time period

$CEQEM_{REG,TP}$: Carbon-equivalent emissions (CO_2+CH_4+N_2O)

The abatement potentials for time periods beyond the reference period (in our case 2010) are defined as the abatement potential for the reference period multiplied by the corresponding technical-progress multipliers:

$$abatepot_{GHG,REG,TP} = tm_{GHG,REG,TP} * abtpref_{GHG,REG,TP} \qquad (1)$$

The baseline energy-related emissions ($EREM_{ERGHG,REG,TP}$) are computed as a function of the related activity variables in the model (in this case CH_4 emissions from coal, oil and gas production). Notice that the corresponding emission coefficients may be reduced over time if, for instance, a reduction of leakage in pipelines is assumed.

The amount of abatement per period, region and sector is constrained to (for energy-related and non-energy-related emissions respectively):

$$ABATE_{ERGHG,MSTEP,REG,TP} \leq abatepot_{ERGHG,MSTEP,REG,TP} * EREM_{ERGHG,REG,TP} \quad (2)$$

$$ABATE_{NERGHG,MSTEP,REG,TP} \leq abatepot_{NERGHG,MSTEP,REG,TP} * bline_{NERGHG,REG,TP} \quad (3)$$

The resulting energy-related emissions are computed as the endogenous baseline emissions minus the corresponding abatement as follows:

$$EMGHG_{ERGHG,REG,TP} = EREM_{ERGHG,REG,TP} - \sum_{MSTEP} ABATE_{ERGHG,MSTEP,REG,TP} \quad (4)$$

Similarly, the resulting non-energy-related emissions are computed as the exogenous baseline emissions minus the corresponding abatement:

$$EMGHG_{NERGHG,REG,TP} = bline_{NERGHG,REG,TP} - \sum_{MSTEP} ABATE_{NERGHG,MSTEP,REG,TP} \quad (5)$$

The carbon-equivalent (C-eq) emissions are computed as:

$$CEQEM_{REG,TP} = \sum_{GHG} GWP_{GHG} * EMGHG_{GHG,REG,TP} \quad (6)$$

In order to avoid abrupt changes in non-CO_2 emissions as a result of cost-effective abatement, we have introduced a maximum growth constraint for the abatement of non-CO_2 GHGs. This constraint also reflects the fact that, in reality, abatement technologies will experience a diffusion process that takes time and, thus, their abatement potential cannot be tapped fully at once. As illustrated in Section 5.4, this constraint plays an important role in the level of non-CO_2 abatement in our MAC implementation.

$$\sum_{MSTEP} ABATE_{GHG,REG,TP} \leq \left[\sum_{MSTEP} ABATE_{GHG,REG,TP-1} \right] * (1+gr)^{\Delta t} + seed_{GHG,REG} \qquad (7)$$