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Network Activities on non-CO_2 Greenhouse Gases

Rapport
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I Summary of objectives

The general objective of the action supported by the grant was twofold:

- To pursue and enhance the activities originated in the GECS project regarding the economic modelling of CO2 and non-CO2 abatement activities. Special attention was to be devoted to the question of how the incorporation of non-CO2 GHG and sink credits affects the cost of given climate change policies.
- To take part to the 21st round of the *Energy Modeling Forum* (Stanford University), focusing on the development of multi-gas abatement modelling, and with the comparison of the costs of CO_2-only vs multigas policies.

II Description of work

II.1 Pursuit of the GECS modelling activities

The GECS modelling activities were developed and lead to the production of two scientific papers (cf. annex I).

The paper by Criqui, Russ and Deybe aims at identifying global emission profiles and international emission permit endowment schemes that are consistent with recent developments in the on-going scientific assessment of climate change and international climate negotiation. It does so based on the modelling results of a version of POLES extended to integrate non-energy GHG abatement potentials. These abatement potentials are drawn from the GECS project and the EMF 21st round, translated to marginal abatement cost curves and introduced in POLES, either directly, or after being processed by AGRIPOL, a new modelling framework for the simulation of the impacts of the introduction of a carbon value in agricultural activities at the world regional level. Testing international emission permit endowment schemes with this enhanced modelling structure allows to reach a set of conclusions: (1) changing from a CO2 to a multi-gas strategy either allows to increase total abatement of 25 % for the same Marginal Abatement Cost or to decrease the MAC of approximately 30 % for the same total abatement ; (2) the impact of the GHG constraint on the energy systems is significantly reduced in the multi-gas approach, which allows to limit the required reduction from this sector. This may even be considered as a drawback from this scenario as it is less stimulating for new technology development than pure CO2-only cases. (3) all scenarios imply a significant restructuring, both in the world primary energy supply and in the global demand for energy.

Along the same lines, the objective of the paper by Böhringer, Löschel and Rutherford is to lay out an integrated framework for evaluating efficient multi-gas emission control strategies. It presents a multi-sector, multi-region computable general equilibrium model (PACE) that features a reduced form representation of the key links between anthropogenic emissions of different greenhouse gases and climate change (radiative forcing and temperature), based on the data accessed thanks to its participation to the EMF 21st round. Numerical simulation with this integrated assessment model allow to investigate the importance of “what”-flexibility—taking into account the full set of non-energy GHG—, on top of “where”- and “when”-flexibility, for alternative emission control schemes that prescribe long-term temperature targets and eventually impose additional constraints on the rate of temperature change. It concludes that “what”-flexibility substantially reduces the compliance costs under alternative emission control schemes. When comparing policies that simply involve long-term temperature targets against more stringent strategies that include additional constraints on the rate of temperature increase, it turns out that the latter involve huge additional costs. These costs may be interpreted as additional insurance payments if damages should not only depend on absolute temperature change, but also on its rate.

II.2 Participation to the EMF 21st round

The EMF 21st round developed along four international reunions, from December 2002 to May 2004. The four reunions developed following similar patterns (cf. programs in annex II), with presentations evenly split between "bottom-up" expertise of sectoral GHG emissions, and presentation of "top-down" modelling frameworks, with a strong accent on the methodologies of introduction of the sectoral data, readily made accessible through the EMF website.

Beneficiary of the grant took advantage of these meetings to give seven presentations about their ongoing work. Patrick Criqui thus took the floor in May 2002 and May 2003; Daniel Deybe in December 2002 and December 2003; Christoph Böhringer in May 2003; Andreas Löschel and Alban Kitous in December 2003. These presentations were an excellent opportunity to benefit from modelling experiences among the most prominent in the global community (cf. annex III for a list of attendees to the EMF round).

III Concluding remarks

Beyond the research material exposed in the two papers attached to this report, the beneficiaries of the grant agreement want to stress the benefit they retrieved from being able to participate to such a prominent scientific forum as the EMF. Together with their own presentations, the general discussions of other teams' research during the sessions, as well as more informal contacts between those sessions or during social events, lead to the development of a networking that has proven very productive scientifically, and can expect to be so in years to come. Based on this experience, the beneficiaries express their gratitude to the Commission, and a strong motivation to request renewal of the funding for the EMF round to come.

Annex I

Scientific papers based on research activities supported by the grant

Impacts of multi-gas strategies for greenhouse gas emission abatement: insights from a partial equilibrium modeling approach

Patrick Criqui[1], Peter Russ[2], Daniel Deybe[3]

1 INTRODUCTION

The limitation of climate change and of its adverse effects will require significant reductions in greenhouse gas emissions along the next century. Beyond carbon dioxide, which accounts for more than 70% of all greenhouse gas emissions, other gas contribute to global warming: in the Kyoto protocol a set of six GHG, the “Kyoto basket” is addressed. In order to design robust and cost-effective strategies, multi-gas abatement strategies have to be fully examined and assessed in economic terms. In this perspective, the development of a convenient analytical framework based on the POLES model, has required to:

i Identify global emission profiles and international emission permit endowment schemes that have to be consistent with the development in the on-going scientific assessment of climate change and international climate negotiation.

ii Develop reference projections for non energy-related GHGs, bottom-up assessments of the different technological options to reduce these gas, and finally Marginal Abatement Cost curves for the different world regions and time horizons.

iii Build a new modelling framework for the simulation of the impacts of the introduction of a carbon value (CO_2 equivalent) in agricultural activities at the world regional level (the AGRIPOL model).

iv Include all abatement options and MAC curves describing the potential abatement for the 6 Kyoto GHGs into the POLES model and then simulate the above-mentioned global emission profiles.

This paper presents the substantial POLES model improvements and the results that have been achieved in a collaborative multi-model research project on multi-gas abatement strategies. In section 2. the POLES 5 (i.e. multi-gas) version of the model is briefly described, along with the additional modules added in order to allow the analysis of multi-gas strategies are described, in particular the AGRIPOL model, developed for agriculture. The corresponding reference projection scenario, as well as the marginal abatement cost curves for other GHG are presented and analysed. The second part of the paper provides insights on the economic assessment of multi-gas strategies with the new modelling system. Finally, the key conclusions of the study are given.

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2 THE POLES MODEL AND THE OTHER GREENHOUSE GAS MODULES

2.1 A brief introduction to the POLES modeling system

POLES (**P**rospective **O**utlook for the **L**ong-term **E**nergy **S**ystem, European Commission, 1996) is a global sectoral simulation model for the development of long-term energy supply and demand scenarios. While on-going developments aims at studying the 2050 horizon, the version used for this exercise only covers the 2000-2030 time-frame. For global energy scenarios (European Commission, 2003), the model provides endogenous international energy prices and detailed information on energy balances for each of the model's country or region. A major part of recent applications has been dedicated to the study of greenhouse gas abatement policies, with particular emphasis on the impacts on the world energy system and on energy technology deployment (see eg. Gusbin et al., 1999, IPTS, 2000, Criqui et al., 2003).

The POLES model has been developed in the framework of a hierarchical structure of interconnected sub-models at the international, regional, national level. The dynamics of the model is based on a recursive (year by year) simulation process of energy demand and supply with lagged adjustments to prices and a feedback loop through international energy prices.

In the current geographic disaggregation of the model, the world is divided into thirty eight countries or regions, allowing to identify the key parties in the climate negotiation process as well as the world regions identified in most world energy studies: North America; South America; Western Europe; Central Europe; Former Soviet Union; North Africa and Middle-East; Africa South of Sahara; South Asia; South East Asia; Continental Asia; Pacific OECD.

For each region, the POLES model articulates four main modules dealing with:

- Final energy demand by main sector,
- New and renewable energy technologies diffusion,
- The conventional energy and electricity transformation system,
- Fossil fuel supply.

While the simulation of the different energy balances allows for the calculation of import demand or export capacities by region, the "horizontal integration" is ensured in the energy markets module. Only one world market is considered for the oil market (the "one great pool" concept), while three regional markets (America, Europe, Asia) are identified for coal, in order to take into account for different cost, market and technical structures. Natural gas production and trade flows are modelled on a bilateral trade basis, thus allowing for the taking into account of geographical conditions and of the existing or potential export routes.

2.2 The modelling framework for the Other Greenhouse Gas

The Other GreenHouse Gases (OGHG) module simulates and projects emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), perfluorocarbons (PFC), hydrofluorocarbons (HFC), and sulphur hexafluoride (SF_6) gas, i.e. the 5 GHGs identified in the Kyoto protocol on top of energy-related CO_2. All GHGs are connected to an activity (production or consumption) and when possible the activity level is taken from an endogenous or exogenous variable of the POLES model. A generic relationship has been elaborated for all types of emissions. The standard equation in the model analyses the variation of a given category as the result of changes in three factors, namely the emission intensity of the activity, the activity indicator and an autonomous technical change factor.

For the scenarios developed in a multi-gas approach, the abatement options for the OGHGs, unlike for energy CO_2 emissions that are restricted mostly to fuel combustion and substitution (via energy prices and consequent behavioural changes or technologically substitutions), involve a series of particular emission abatement technologies. Thus, to capture the impacts of the introduction of a Carbon Value, the OGHGs emissions are calculated by the model for each tax level as a combination of:

i A price effect through energy demand and technology substitutions as far as energy related OGHGs are concerned (methane, N_2O, …).

ii An activity effect through production changes in the different sectors for non-energy GHGs.

iii A long-term price elasticity simulating the response to the implementation of the different emission reduction technologies.

In order to take into account the latter effect, Marginal Abatement Cost curves have thus been developed for all non-energy OGHGs emissions[4].

CO_2 and N_2O from fuel combustion

CO_2 emissions from energy combustion and N_2O emissions from some activities (transport, power generation) are directly derived from the POLES energy demand module. The reductions result directly from changes in the fuel-mix structure and energy consumption from the energy model functions at each carbon tax level.

Non CO_2 gas from energy and industry GHGs

For the other non-CO_2 gas in energy and for industrial GHGs, endogenous interactions of POLES activity variables with emission intensity (EI) or emission intensity index (EII) equations have been elaborated. They are linked to the activity variables that are directly simulated by POLES and this allows to include behavioural patterns that are consistent with the exogenous MAC curves.

OGHGs from agriculture

For the agriculture sector, the optimisation model AGRIPOL (see next Section) allows for an endogenisation of the relationships between the activity indicator AI and emission intensity EI. This is obtained through the production of a set of MAC curves for agriculture that are introduced into POLES through reduced-form independent functions. From this, both activity and emissions are simulated for the different GHG tax levels.

2.3 Multi-gas Abatement Cost Curves for agriculture: the Agripol approach

Research on GHG abatement or sequestration options in agriculture stems from the need to evaluate and compare the abatement options in all emitting sectors. In current research, this issue is tackled with two different approaches:

- Globally, in integrated assessment models (IAM) combining GHG emissions scenarios with models of climate change impacts, and ensuring consistency on resources use and availability. Generally, two schools of IAM can be distinguished (Rotmans and Dowlatabadi, 1998, IPCC 1996b): i. macroeconomic models, which describe the whole economy and where agriculture, represented as a individual sector, is included with its emissions coefficients (Kemfert, 2001); biosphere-climate process-oriented models, such as Image[5] (Alcamo et al., 1998), which consider the impacts on production and on climate of expected trends of population evolution, economic growth, as well as changes in production and consumption patterns, the demand for agricultural products and the feedback of agriculture on climate.
- at the plot level in bottom-up crop growth models, such as Cropsyst, Epic or Stics[6], where agricultural practices are represented with the corresponding emissions, for diverse and locally specified soil and climate conditions, without the corresponding detailed costs information.

A hybrid type of models in which agriculture is considered specifically, draws on both approaches. It addresses the issue of the leeway for GHG emissions mitigation provided by agricultural practices,

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[4] A detailed description can be found in the reports on the GECS project (Criqui, 2002).

[5] www.rivm.nl/image

[6] Cropsyst (www.bsyse.wsu.edu/cropsyst), Stics (www.inra.fr), Epic (www.brc.tamus.edu/epic).

through a representation of production and technical choices, as influenced by carbon penalties. Such models provide a consistency framework for building Marginal Abatement Costs curves. Their development requires: the processing of data collected or simulated at the plot level, the development of related emission and abatement indicators, a detailed representation of the production systems (objectives, constraints and context) and the decision making process at farm level. The price of carbon is included among the costs that may induce changes in land uses and technological choices (see Alig et al., 2001; Chang et al., 2002; among works of Dr Bruce McCarl from Texas A&M University[7],.Saunders and Wreford, 2003).

However, the detailed information on agronomic and farming systems required by this type of models is not currently available worldwide. Besides, hybrid models are highly site- or country-specific, which makes the comparison and the aggregation of results difficult. A complementary type of model is therefore proposed with Agripol, it maintains a behavioural approach while using a single framework worldwide, exploiting and extrapolating available data, and incorporating risk associated with changes in agricultural practices, in order to allow for the simulation of possible responses to carbon prices.

Agripol, a simulation model to describe the responses of agriculture to carbon pricing

The purpose of Agripol (Deybe and Fallot, 2003) is to process available information on agricultural practices and constraints affecting production, in order to determine the sectoral response to a carbon price. Such incentive stands as a proxy variable for the introduction of policies aiming at reducing emission constraints in agriculture . The approach proposed aims at consistency across world regions and across activities, in order to allow for comparisons of abatement potentials with other sectors.

Agripol is a static economic optimisation model that runs for each of 40 world sub-regions. On the basis of projections from the IMAGE model Business-As-Usual (BAU) scenario, the model considers the double constraint of production levels and agricultural resources at the regional level.

In its present version, Agripol accounts for 8 major non-CO_2 GHG emitting activities[8], and only considers agricultural and forestry land uses. Analysing possibilities for policy-induced abatement in the agricultural sector implies to describe the processes allowing for lower emissions through different practices in cropping systems, animal feeding, irrigation, or fertilizer dosing.

For each commodity the representative[9] agent whose choice of practices is modelled, portrays the “regional commodity producers” which maximise their net revenues from the agricultural activities and minimise the risk associated with this choice, according to the attitude prevalent amongst commodity producers. Only land availability is currently binding the model, because of the lack of precise information on most of other resources. Forestry and grassland can be transformed into agricultural land. The equations on the other resources are used for "metering", accounting for the quantity of resources required, to eventually check consistency with other models' results.

Data on average GHG emissions by activity was obtained from IPCC Guidelines for National Inventories, the reference manual for Agriculture. The impact of technological choices on emissions levels was then investigated among experts under the European Climate Change Programme (ECCP) Agriculture working group[10], the non-CO_2 GHG network[11], and to a lesser extent, the OECD group on soil carbon indicators and FAO initiatives (experts’ consultation, forum) on carbon sequestration[12]. For each activity, energy consumption is also considered, as an indirect CO_2 source, so as to properly

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[7] http://agecon.tamu.edu/faculty/mccarl.

[8] Dairy livestock producing milk and emitting CH_4 and N_2O, non-dairy livestock producing beef and emitting CH_4 and N_2O, rice production as a source of CH_4, three N_2O emitting crop productions, pastures or grassland management, world wide livestock productions, rice plantations and other fertilised crops, for respectively 26%, 7% and 6% of land-use emissions (IPCC, 2001a).

[9] For each commodity and region, the risk aversion coefficient allows to reproduce a variability in farmers' choices of practices that was assumed to be a proxy for diversity in farmers' population and attitudes.

[10] http://www.europa.eu.int/comm/environment/climat/eccp.htm
http://europa.eu.int/comm/environment/enveco/climate_change/agriculture.pdf

[11] Documents are available on the Energy Modelling Forum website: http://www.stanford.edu/group/EMF.

[12] Respectively, http://www.oecd.org/agr/env/indicators.htm and
http://www.fao.org/landandwater/agll/lada/emailconf.stm.

deal with energy-intensive processes. Extrapolation was worked out from data available in published and discussed reports or recomputed from own local sources. Economic data are composed of operational costs and structural costs, prices that multiply yields (with corresponding yields and income variances) and additional revenues and subsidies accounting for agricultural policies.

The simulation lies on responses to the carbon price. This price directly affects the variable costs, thus modifying net economic margins. It also affects indirectly fixed costs, when less emitting practices require capital investments. When the carbon price changes, substitutions take place between practices and such substitutions modify land requirements for the different activities and for grassland. The model allows the incorporation of forest and grassland into arable land, explicitly considering substitutions in land uses. Reforestation is not yet considered.

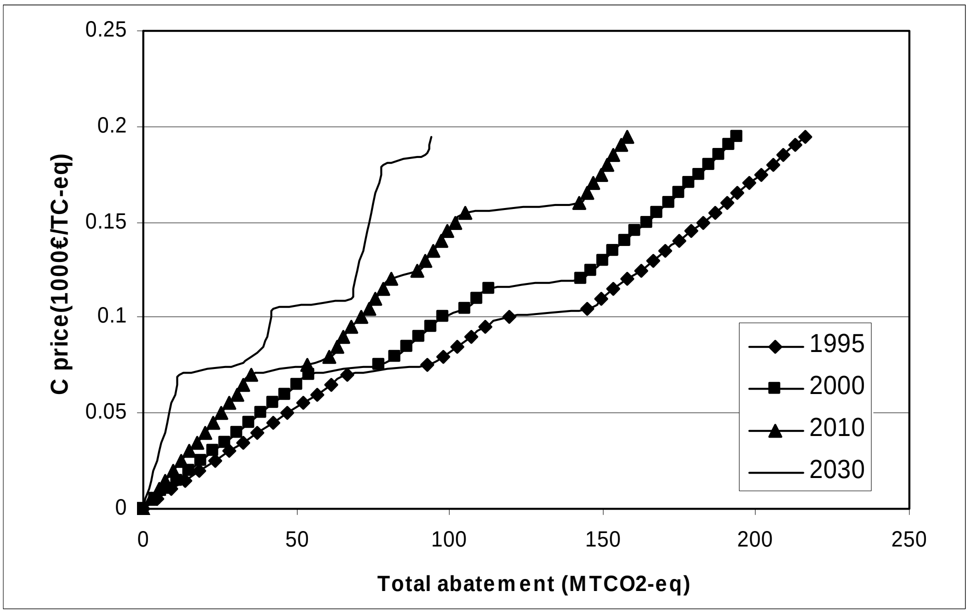
Simulation results: abatement potentials in agriculture

For years 1995, 2000, 2010 and 2030, simulations have been run for the BAU scenario and two carbon prices: 20 and 50 US$/tCO$_2$e.

For the BAU scenario in 1995, the level of emissions estimated by the model for the 8 agricultural activities considered correspond to 1.1 GtCO$_2$. Five regions account for around 50 % of them: Europe, USA, India, China and Brazil. In Europe emissions decrease by 2030, thanks to a combination of technical improvements and lower food demand as a consequence of a decreasing population. USA slightly increases emissions throughout the period. In the case of India and China, the foreseeable increase in population and the changes in consumption patterns along with economic growth, will imply more land dedicated to higher emitting activities (namely more animals). Currently available technology improvements might not be sufficient to meet this increase in food demand, in particular for livestock products.

In the 20 $/tCO$_2$e simulation case the economic abatement potential corresponds to 5 MtCO$_2$e in 1995 and 1.5 MtCO$_2$e in 2030. Potentials are more deeply exploited when applying a price of 50 $/tCO$_2$e: 1.2% (12.8 MtCO$_2$e) in 1995, 0.2% (2.6 MtCO$_2$e) in 2030.

Figure 1: Global marginal abatement Cost Curves in agriculture



The Marginal Abatement Cost curves (Figure 1) imply a lower response to carbon price throughout time due to higher pressure on demand and production, lower potential technological progress and limitation of land availability.

While the Agripol model provides a consistent assessment framework, two pending issues still limit the relevance of these first sets of results. First, because of the difficulties in modelling the impacts of prices on food products demand and consumption patterns, it is still assumed that farmers and herders bear the whole carbon price, do not transfer it to consumer prices. Second, agricultural sinks are not considered, especially the soils where carbon could be stocked with adequate production practices. Hence, further research is needed, on the one hand to introduce possible impacts on the demand for agricultural products, and on the other hand for a thorough representation of the sink capabilities provided by agriculture.

3 THE POLES 5 REFERENCE AND THE ASSOCIATED MAC CURVES

3.1 The multi-gas 2030 Reference projection

The set of hypotheses and parameters such as GDP growth, economic structure, population growth and urbanisation have been developed under a reference case that serves as a basis for comparison.

The detailed analysis of GHG emissions, respectively by region and GHG category under the reference case assumptions basically reflect the economic growth and autonomous technological progress dynamics over time. Generally the developing countries show a rapid growth in emissions, whereas the other regions show a lower growth in emissions. However, within each economic group and each GHG emission category, broad generalisations should be avoided and the key outcomes of the Reference multi-gas projections can be stated as follows:

- Reference CO_2 emissions are projected to increase substantially at the rate of 2.1%/year to reach 46.2 $GtCO_2$ in 2030. Most of the increase comes from China (10 $GtCO_2$ in 2030, from 3.2 $GtCO_2$ in 1995) and from other Asian regions, due to rapid increases in energy consumption. The CO_2 emissions in the Economies In Transition are projected to recover their 1995 level by 2010 and to increase slowly afterwards.
- CH_4 emissions in Industrialised Countries are practically stable, while they are expected to increase significantly in the Developing Countries, mostly in relation with the expansion of agricultural activities (livestock and manure, waste management) and fossil fuel production. In the case of the Economies In Transition the increase in emissions is mostly due to fossil fuel production and transport. Total CH_4 emissions would reach 8.4 $GtCO_2$ in 2030 up from 6.3 $GtCO_2$ in 1995, if no policy action were taken during this period.
- The growth in nitrous oxide emissions is substantially lower than for the other GHGs. For developed countries, N_2O emissions are even projected to decline in Western Europe or to stabilise in North America. As in the case of methane emissions, developing countries represent the largest increase in N_2O emissions, related to agricultural activities such as fertiliser utilisation and animal waste, and to industrial activities such as nitric and adipic acid production. N_2O emissions from transport represent less than 2% of total N_2O emissions (2.4 $GtCO_2$ in 2030, compared with a total of 40 Mt CO_2 in 1995).
- Concerning the so called High Global Warming Potential gas (HFC, PFC, and SF_6), a remarkable economic growth in developing countries, due to the industrialisation process will lead to an exceptional increase of these gas during the period. The developing countries will become the largest source of those emissions by the year 2030. Altogether, these three HGWP gas will reach the level of 2 $GtCO_2$ in 2030 compared with 355 $MtCO_2$ in 1995.

Table 1: The POLES 5 world GHG Reference projection

	MtCO2					Annual % change				
	1995	2000	2010	2020	2030	1995/2000	2000/2010	2010/2020	2020/2030	2000/2030
co2ene	21 685	23 783	29 379	36 742	44 502	1.9%	2.1%	2.3%	1.9%	2.1%
ch4oil	212	203	222	240	243	-0.9%	0.9%	0.8%	0.1%	0.6%
ch4gap	418	439	556	810	986	1.0%	2.4%	3.8%	2.0%	2.7%
ch4gat	604	670	769	882	920	2.1%	1.4%	1.4%	0.4%	1.1%
ch4cos	76	81	90	106	125	1.1%	1.1%	1.6%	1.7%	1.5%
ch4cou	742	743	757	816	904	0.0%	0.2%	0.8%	1.0%	0.7%
n2otra	31	33	35	37	40	1.4%	0.8%	0.6%	0.5%	0.6%
sf6ele	87	92	113	142	169	1.0%	2.1%	2.3%	1.8%	2.1%
GHG Energy	23 854	26 043	31 922	39 775	47 889	1.8%	2.1%	2.2%	1.9%	2.1%
co2ind	698	855	1 215	1 502	1 690	4.2%	3.6%	2.1%	1.2%	2.3%
n2oind	222	179	157	165	170	-4.2%	-1.3%	0.5%	0.3%	-0.2%
hfcind	131	285	757	1 220	1 585	16.7%	10.3%	4.9%	2.7%	5.9%
pfcsem	17	23	34	51	69	6.7%	3.8%	4.1%	3.2%	3.7%
pfcalu	69	59	58	61	63	-3.0%	-0.1%	0.4%	0.4%	0.2%
sf6ind	52	55	69	82	91	1.0%	2.3%	1.7%	1.1%	1.7%
GHG Industry	1 189	1 456	2 290	3 080	3 668	4.1%	4.6%	3.0%	1.8%	3.1%
ch4agr	3 036	2 994	2 981	2 755	2 536	-0.3%	0.0%	-0.8%	-0.8%	-0.6%
n2oagr	1 020	1 019	1 073	1 610	2 176	0.0%	0.5%	4.1%	3.1%	2.6%
ch4wst	1 242	1 393	1 775	2 228	2 719	2.3%	2.5%	2.3%	2.0%	2.3%
GHG Agr+Waste	5 298	5 405	5 829	6 593	7 430	0.4%	0.8%	1.2%	1.2%	1.1%
GHG TOTAL	30 341	32 904	40 041	49 448	58 988	1.6%	2.0%	2.1%	1.8%	2.0%

However, these analyses by emission category may give a misleading interpretation of the relative impacts of the different gas on climate change. CO_2 emissions are, and will remain, by far the dominant source of GHG. In spite of the rapid growth in non-CO_2 emissions, the weight of CO_2 in total GHG reference case is even projected to increase, accounting for about 79% of total in 2030). This implies that fossil fuel combustion will remain the first source of GHG emissions in the next decades, while methane emissions will remain the second one, with a slightly decreasing share, to 14 % of total GHG emissions in 2030.

3.2 Marginal Abatement Costs and the fundamentals of multi-gas strategies

In order to assess the global impacts of multi-gas abatement policy, this sub-section considers the whole set of Marginal Abatement Cost curves developed for the POLES 5 model. The key outcome of this detailed analysis is probably that it reveals strong differences among the 17 activities and across regions. These can be described as follows:

- Some activities – such as CO_2 from cement industry or CH_4 and N_2O from agriculture – are highly inelastic in all regions, with reductions of about one or two percentage points even for high carbon values. While this weak sensitivity is straightforward for the case of cement, the interpretation for agricultural activities involves much more complex elements. They are mostly related to the definition of technologies in the agriculture and to the limitations imposed to the agriculture model (e.g. the fixed demand and regional production hypothesis described in previous section).
- Conversely, a set of activities show a very high sensitivity to the introduction of a carbon value, with reductions beyond 50 % when the carbon value is sufficiently high (50 €/tCO_2). This is the case for CH_4 from gas transport and coal mines (surface and underground), for N_2O from chemical industry and for PFC, both from aluminium and semi-conductor industry. An extreme case is the one of SF_6 from industry, where a 100 % reduction is obtained with a 20 €/tCO_2e carbon value.

- Most other activities show an intermediate sensitivity level, with reductions in the range of 15 to 30 % for a 50 €/tCO_2e carbon value. This is in particular the case for the largest activity in terms of emissions, i.e. CO_2 from the burning of fossil fuel. CH_4 from oil and from gas production, CH_4 from waste and landfills, SF_6 from electricity sector and finally HFC from industry show similar reduction profiles.

Figure 2 and Figure 3 show the world global 2010 MAC curves, respectively by key sector and by GHG category. These curves provide a rough description of the behaviour of the model and of the potential gains from multi-gas policies. From the results of a simplified case for 2010 with an intermediate carbon value of 25 €/tCO_2e and a hypothetical world full flexibility, world 2010 GHG emissions would be reduced by 7.8 GtCO_2e, from a total of 40 GtCO_2e in the Reference case. This represents a 20% reduction from the Reference, but there would still be in that case a 11 % increase from the 1990 GHG emission level. The results synthesized in Figure 2 allow to identify the key sectors for GHG abatement and illustrates the predominance of the energy sector, as fossil fuel combustion represents 72 % of the total abatement and as the other GHGs from the energy sector – mostly methane – represent an additional 17 %. Industry is the following sector with 7 % of the total abatement, while agriculture and waste/landfill – indeed mostly waste/landfill – correspond to 4% of the total.

Figure 2: Global 2010 MAC curves, by sector

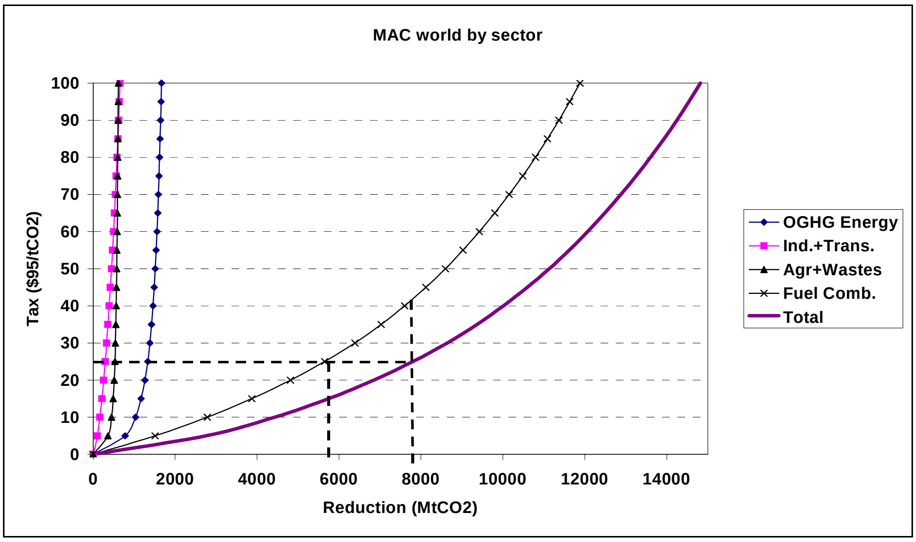


Figure 3: Global 2010 MAC curves, by gas categories, 2010

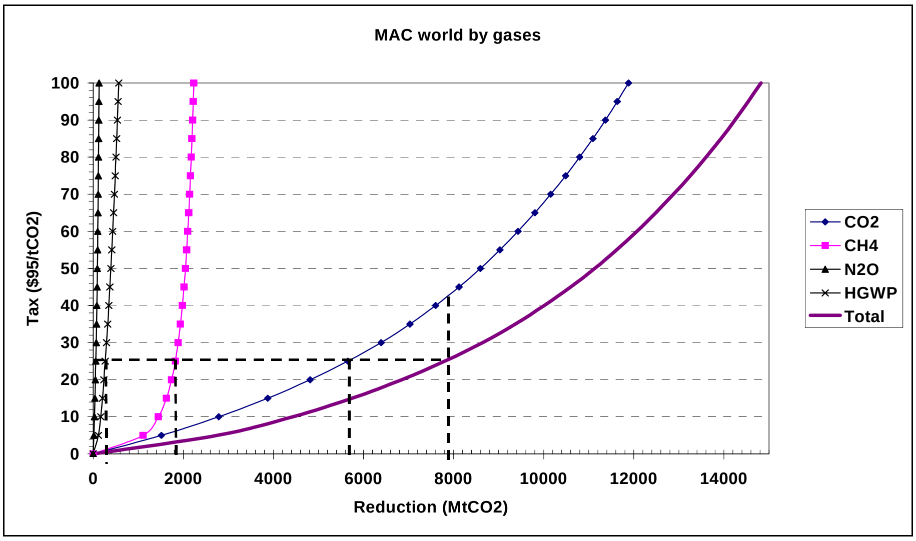
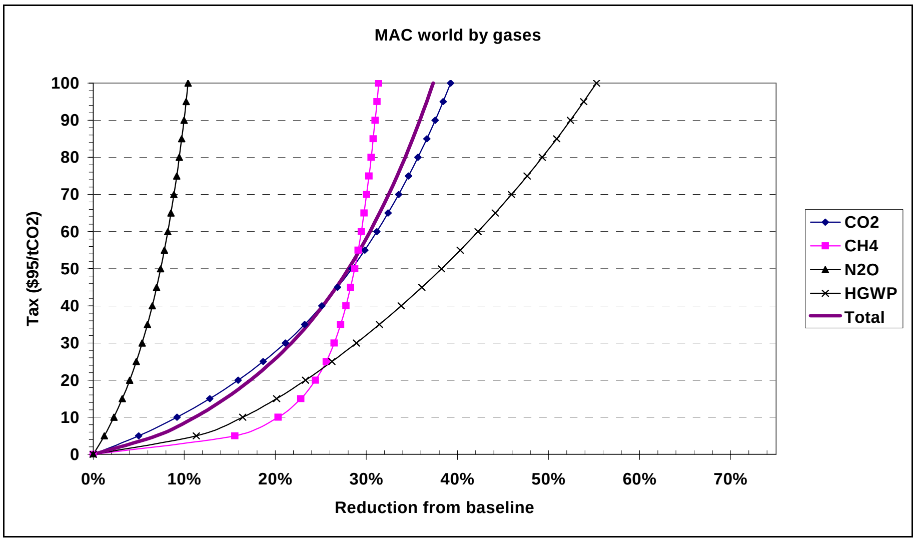


Figure 3 illustrates the contribution of each type of GHG and it appears that CO_2 is, not surprisingly the main contributor to total abatement, in quantities (5.6 $GtCO_2$) and proportion (72%). Its contribution is indeed almost equal to the one of the “fossil fuel burning” activity, as the contribution of the cement industry to total abatement is negligible. Methane is the second option in total abatement with a significant 23 %, followed by the more modest contributions of HGWP gas 4% and N_2O, only 1%. This predominance of the fossil CO_2 in potential abatement, doesn’t mean that multi-gas strategies do not have an important impact on abatement costs or environmental effectiveness. The key conclusion of this first-cut quantification of the multi-gas approach can be formulated in two different but complementary ways:

- for the 25 €/tCO_2e carbon value supposed here – corresponding to a relatively ambitious abatement program – the inclusion of other gas would allow to increase total reductions by 38 % (from 5650 tCO_2 to 7800 tCO_2e)
- in another perspective, reaching the same total reduction in a “CO_2 only strategy” would imply a carbon value slightly superior to 40 €/tCO_2 and thus cost approximately 60 % more – also in terms of total cost – than a multi-gas approach.

These gains in total abatement for a given carbon value or in marginal and total cost for a given abatement in volume do not translate into a significant change in the total MAC curve plotted against percentage reductions, whether it is expressed for CO_2-only or for the 6 GHGs. Surprisingly enough, the two MACs are very close to each other, as shown in Figure 4. This is because the lower abatement costs for CH_4 and HGWP gas are compensated by the steeper MAC curve for N_2O, originating in the weak response of agriculture. This means in particular that in the multi-gas analyses, the gains in total cost for the same volume abatement is allowed principally by the supply of new abatement opportunities and not by relatively cheaper options for the other gas, on average.

Figure 4: Global 2010 MAC curves in % from baseline reduction, by gas categories



While taking into account the fact that sinks and CO_2 from Land Use are not modelled and accounted for in this exercise, these first analyses are largely consistent with the corresponding results from the other studies on this issue. In any case, they fully confirm the relevance and importance of the multi-gas approach for economically sound emission control strategies.

4 THE GHG EMISSION REDUCTION SCENARIO

To assess multi-gas emission reduction strategies to 2030, i.e. in a post-Kyoto time frame, it has been necessary to select, from existing long-term scenarios, a target emission path for the period 2010-2030. The scenario should satisfy a clearly identified GHG concentration target and related global temperature evolution, and in that way represent a useful basis for the comparison of the different scenarios computed.

The IPCC 2001 scenarios, published in the Working Group I & III reports, follow an integrated approach between geophysics and economics and provide modelling results that link the emission paths to the GHG concentration and global temperature change. The IPCC special report on emissions scenarios (SRES) (IPCC, 2000) and the IPCC third assessment report (TAR) (IPCC, 2001a and 2001b) therefore provide a consistent set of references that allows to jointly analyse the emission scenarios and their consequences on GHG concentrations and global temperature on a century time scale. In order to identify the suitable emission paths for the assessment in the TAR and SRES reports, it has been considered that the emission path should be compatible with CO_2 concentration stabilisation around 550 ppm before 2150.

From the four main "storylines" in the IPCC scenarios, the B1 category has been selected as it best responds to the above criteria. The B1 storyline and scenario family describes a convergent world with a global population that peaks by mid-century and declines thereafter, and with rapid changes in economic structures toward a service and information economy, reductions in material intensity, and the introduction of clean and resource-efficient technologies. The B1 category of scenarios shows emission paths that allow a stabilisation around 550 ppm of CO_2. The corresponding emission path indeed imply early action to curb current emission trends. As the time horizon of the POLES 5 model is 2030, a comparison with the results from the B1 storyline appears then as an appropriate choice for studying the impacts of multi-gas abatement strategies.

4.1 Global constraint profiles, endowment schemes and scenarios

The global profile and three alternative endowment scenarios

The total amount of emissions that are considered as compatible with long-term climate objectives, have thus been taken from the B1 scenario. The international distribution rules have been selected from the analysis of the literature on international and intergenerational equity principles (see eg Banuri et al., 1996, Rose et al., 1998). Then the allocation rules have been applied in order to define the regional endowments in the POLES model's 38 regions.

The development of the international endowment schemes has thus been based on a three-stages process, resulting in a total of 2+2 scenarios:

i The selection of a global emission profile, the B1-IMAGE IPCC-SRES scenario (IMAGE team, 2001).

ii The identification of an international emission endowment schemes, aiming at a relatively progressive introduction of the emission constraint for non-Annex B countries, which is defined as "Soft Landing (SL)".

iii Finally the definition of two "CO_2-only" variants, the "CO_2-only only" (COO) and the "CO_2-only proportional" case (COP).

The Soft Landing scenario (SL)

In the SL-MG scenario, the 38 POLES countries/regions are split in two groups: Annex B and non-Annex B countries. Annex B countries (or "Category 1") have "Kyoto-like" targets up to 2030. It is supposed that: for all OECD countries (as of the 1990 OECD definition) the emissions in 2030 should be 15% lower than the corresponding level in 2010; for the Eastern Europe and Former Soviet Union that emissions in 2030 should be stabilised to the corresponding 2010 level.

The non-Annex B countries are due to stabilise their emissions at a certain date in the future, depending on their level of per capita GDP in 2010. This methodology is very close to the one used in Blanchard et al., 2002[13]:

- regions with a per capita GDP above 60% of the 2010 OECD90 per capita GDP have to stabilise their emissions in 2030 to the 2015 level: "Category 2"; South Korea is the only country entering into this category;

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[13] The "soft landing" approach has been used in other studies. See Criqui et al., 2003, Russ and Criqui, 2004.

- regions with a per capita GDP between 15% and 60% of the 2010 OECD90 have to stabilise their emissions to the 2030 level, in 2030. This creates the "Category 3", to which pertain non-Annex B parts of Eastern Europe and Former Soviet Union, Mexico, South America, Turkey, North Africa non-OPEC, Middle-East (including the Gulf countries) and China; the joint 2+3 Category is hereafter referred to as "Developing Countries" (DCs);
- regions with a per capita GDP lower than 15% the 2010 OECD90 stabilise their emissions in 2045. This is the "Category 4" that encompasses the Sub-Saharan Africa, India and the Rest of South Asia, the Rest of South-East Asia (South-East Asia without China and South Korea), Egypt and North Africa OPEC and the Rest of Central America; the Category 4 is hereafter referred to as "Least Developed Countries" (LDCs).

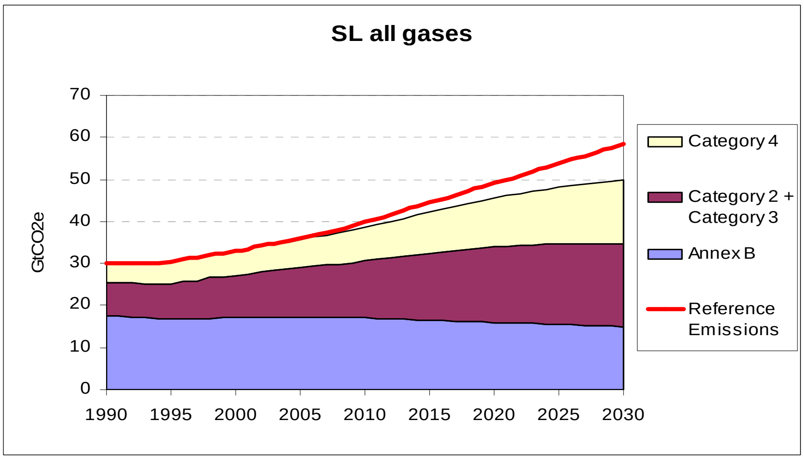
The analyses concerning the "CO_2-only" cases are carried out simply by reporting:

- the whole volume of reductions from the Soft Landing Multi-Gas (SL-MG) scenario to the energy related CO_2 emissions for the SL CO_2-only "only" scenario (COO);
- and by applying the same percentage reduction to CO_2 than to all gas in the SL CO_2-only "proportional" scenario (COP).

4.2 Resulting endowments by main regions

In all scenarios and up to 2010 all constrained Annex B countries - with the exception of the USA - follow their Kyoto targets (reached in 2010), while non-Annex B countries follow their baselines. The USA follows a path that is close to the so-called "Bush plan[14]". It is assumed that, from 2011 onwards, all countries participate to the global allocation schemes described below. This constitutes only a rough estimation of the possible emission trajectories as it corresponds to a "linearisation" of the more complex system of the 5-year Commitment Period in the Protocol. Those Annex B countries that are in effect not constrained because of their "hot air", i.e. the Eastern European Economies (EEE) and the Former Soviet Union (FSU), follow their baseline emissions: there is no use of "hot air" up to 2010. The SL endowment scheme is then applied for the 2010-2030 time-frame.

Figure 5. SL-MG scenario, total endowments



In the SL case, the Developing Countries' total endowment is the largest in volume (about 20 $GtCO_2e$), while Annex B and the Least Developed Countries benefit from comparable total endowments (15 $GtCO_2e$). In terms of energy-CO_2 emissions, the 2030 global endowment is of course lower in the COO case than in the COP case: 35 vs.. 37 $GtCO_2$, the Reference POLES energy-CO_2 emissions being of 44 $GtCO_2$ in 2030). In both cases, Developing Countries are allocated the largest share (14.5 $GtCO_2$ for COO and 14.8 $GtCO_2$ for COP). Least Developed Countries get the same

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[14] This plan calls for a -18% of reduction of the emissions intensity in the USA over the 2002-2012 period.

allocation in the two cases (10 $GtCO_2$) while Annex B gets slightly more in the COP case: 11.6 $GtCO_2$ vs.. 10 $GtCO_2$.

5 ASSESSMENT OF THE MULTI-GAS ABATEMENT STRATEGY

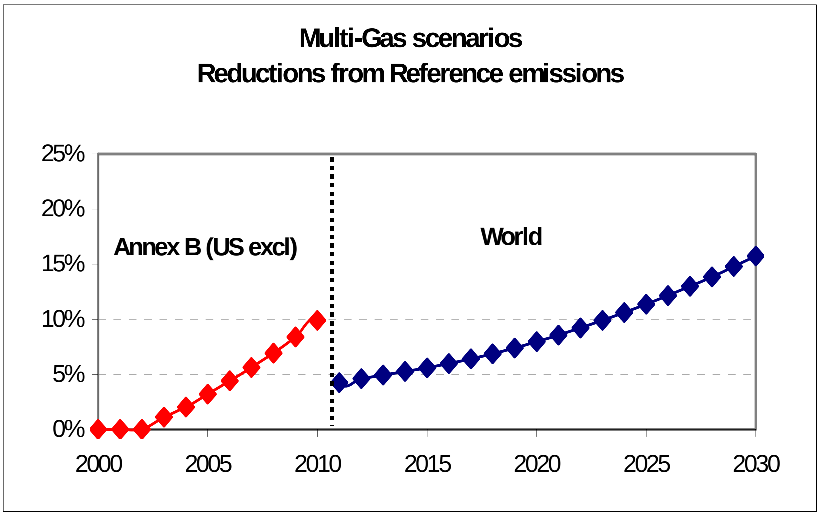
Once the international endowments corresponding to the four above-described scenarios have been calculated, the multi-gas assessment (MGA) studies have been performed with the POLES 5 model in a two stages approach:

i the calculation with the "endogenous permit price" version of the model of the time-path of the carbon value that would allow for the compliance to the global emission target;

ii the assessment, on a region by region basis of the domestic emission reductions, traded emissions and abatement costs (domestic costs plus costs or benefits from trade).

Until 2010 the "bubble" of the countries submitted to quantitative targets consists in the Annex B countries, excluding the USA. According to its current policy line this country follows a "dynamic target" of a reduction of 18% in the emission intensity of GDP over the 2002-2012 period. This is translated into a reduction of 15% of the same emission intensity over 2002-2010 in this study. After 2010, all the 38 POLES countries/regions are included in the bubble and thus receive quantitative emission targets, according to the different endowment schemes and under the global emission profile. Figure 6 illustrates the corresponding reductions from baseline or Reference case.

Figure 6: Emission reduction from Reference



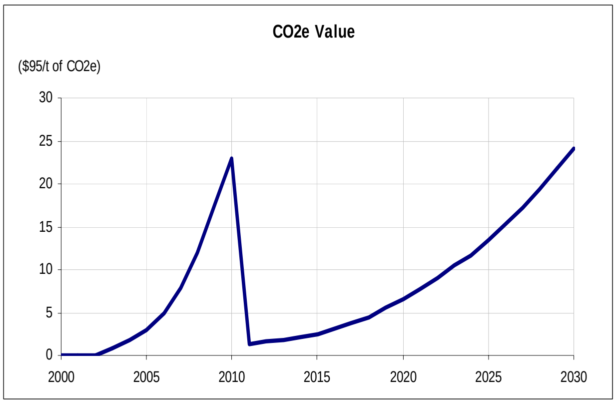
5.1 The time-path of the Carbon Value

The endogenous permit price module developed for the POLES 5 model allows to compute – through a year-by-year iterative process – the carbon-equivalent value (expressed in €$_{99}$/tCO_2e, equivalent to \$$_{95}$/$tCO_2e$) that allows for compliance to the quantitative emission targets in a fully dynamic approach of the carbon value.

The Multi-Gas Soft Landing case (SL-MG)

Both multi-gas scenarios differ by the way allocations are distributed in the various regions/countries but they have identical global emissions profiles. Therefore, in a full-trading hypothesis framework, the related endogenous carbon value is the same for both schemes. Figure 7 below displays the value of a ton of CO2e from 2000 to 2030 for the SL-MG case[15].

Figure 7: CO_2e value in the multi-gas scenario



In the Kyoto Protocol time-horizon, the carbon value increases from a zero value in 2002, when it is supposed that still no constraint applies, to 23 €/tCO_2e in 2010, when Annex B countries (except the US) reach their Kyoto objectives. After 2010, the entry of all non-Annex B countries in the bubble of constrained countries entails a sharp decrease in the CO_2e value that drops to 1.3$/t$CO_2$e. Of course, the explanation for this drop is to be found in Figure 6, which shows that the relative reduction burden imposed to the global bubble is suddenly much less severe immediately after 2010, as the constraints on non-Annex B regions is almost nil at the very beginning of the Post-Kyoto period. Basically the discontinuity in the carbon value is explained by the discontinuity in the space of the emission reduction potentials, while for the sake of simplicity, no hypothesis have been made for CDM reductions in the Kyoto time-frame. Later on, the carbon value then increases regularly with the growing effort of global reductions up to 24$/t$CO_2$e in 2030.

The CO2-only cases: CO2-only “only” (COO) and “proportional” (COP)

In these two scenarios it is hypothesised that after the Kyoto time-frame, the economic instruments of Climate Policies are limited to CO_2 reductions. Up to 2010 both CO_2-only “only” and CO_2-only “proportional” scenarios correspond to the Kyoto reduction target from base-year, supposing that the same percentage reduction is obtained for the other gas through Policies And Measures. This results of course in the same carbon value for both COO and COP. In 2010 the carbon value reaches 27 €/tCO_2. After 2010, with the inclusion of the non-Annex B countries in the bubble, it is supposed either that the Policy And Measures are applied to the other gas (COP), or that the multi-gas flexibility is abandoned and that the overall cap is now reached only through CO_2 reductions (COO). In both cases, the carbon value drops sharply almost to zero in the COP case. As expected, the COP carbon value is continuously lower than the COO value over the entire period. By the end of the simulation, the 2030 values are of 23 €/tCO_2 in the COP case and 34 €/tCO_2 in the COO case (Figure 8)

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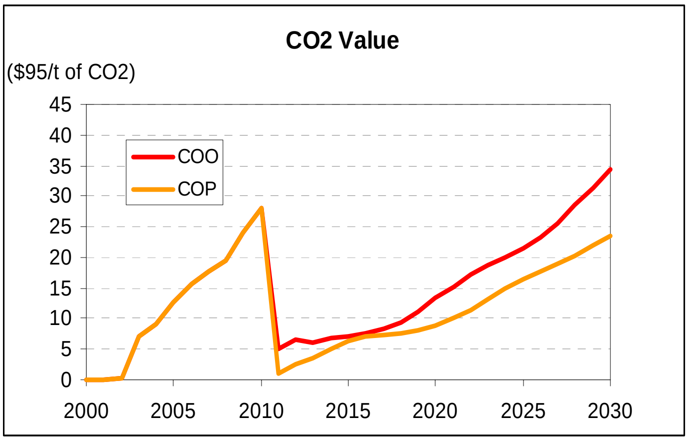
[15] No banking of emission permits was allowed. The emission targets had to be met in each year.

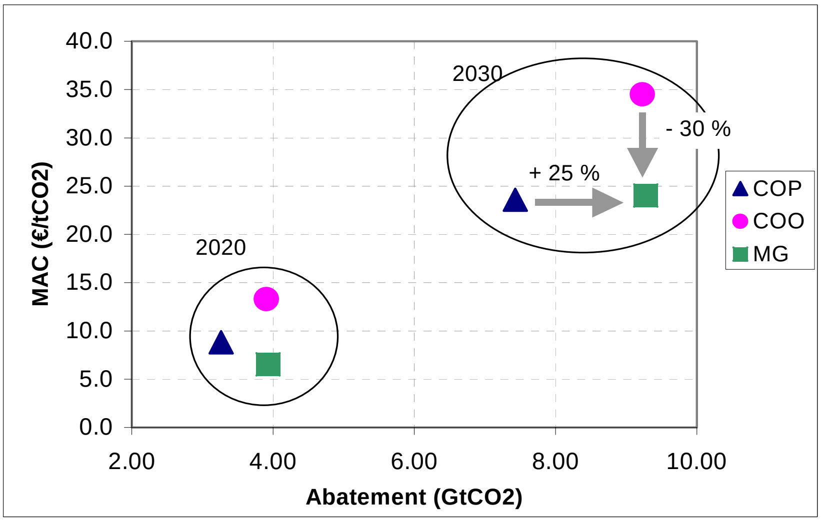
Figure 8: CO_2e value in the two CO_2 only cases



Finally, the key advantages of multi-gas strategies relatively to CO_2-only approaches are clearly illustrated in Figure 9 : Going from CO_2-only to multi-gas strategies either allows:

- to significantly increase the total abatement for the same marginal cost (+ 25 % in 2030)
- or to significantly reduce the marginal (and total) cost for the same quantity abated (- 30 % in 2030).

Figure 9: MAC vs. total abatement in 2020 and 2030, MG, COO and COP scenarios



5.2 Impacts on the World Energy Balances

The impacts of the different scenarios can also be analysed in terms of impacts on the world energy balance. In the following section, the balances of the different emission control scenarios are compared with the one of the POLES model Reference projection to 2030. Table 2 present the key results of the Reference scenario, while Table 3and Table 4 present the percentage changes from the Reference of respectively SL-MG, and COO.

The main conclusion is that the different scenarios lead to a decrease in primary energy use of 7-10 % according to the scenario. As expected, the energy sector is less affected in the multi-gas cases, as the other GHG emissions offer significant additional opportunities for least cost reductions. The reduction in primary energy consumption is mostly due to the sharp decrease in the use of solid fossil fuels (coal, lignite) in all scenarios. In 2030 and compared to the reference scenario, the solid fossil fuel consumption is 27 to 37 % lower in the abatement scenarios. The use of oil and gas are also affected, although in much smaller proportions for the gas: reductions (- 8 to 10 % for oil, - 2 to 3 % for natural gas). The impact on oil consumption also results in a lower world oil price, in a range of 6 to 9 % in 2030.

These lower levels of fossil fuel consumption are compensated by an increased use of non-fossil energies: large hydro and geothermal energies, other renewables and nuclear energy. Most of the increase in non-fossil fuels goes to the renewable energies (from 30 to 50 %) and to nuclear energy (from 20 to 30 %, with an increase mostly in the last decade due to the time constant for the deployment of this technology).

As should be expected, the stronger the constraint, and the greater the possibility for new technologies to substitute to fossil fuels. Therefore the development of the non fossil energy options is greater in the COO case, than in the multi-gas cases. This constitutes an unavoidable effect of any multi-gas strategy: while decreasing the pressure that is imposed on the energy sector, they create a global context with less incentives for the development and diffusion of new carbon-free energy technologies.

Table 2. The world energy balance in the POLES Reference scenario:-

POLES - REFERENCE WORLD	1990	2000	2010	2020	2030	y.a.g.r 2000-2030
Population (M)	5248	6102	6855	7558	8164	1.0%
Per capita GDP (95$/cap)	5867	6786	8513	10506	12590	2.1%
GDP (G$95PPP)	30793	41407	58350	79400	102788	3.1%
Energy Intensity of GDP (toe/M$95)	282	241	206	182	165	-1.3%
Primary energy (Mtoe)	8682*	9990	12012	14458	16971	1.8%
Carb intensity of energy (tCO2/toe)	2.41	2.38	2.43	2.52	2.59	0.3%
CO2 emissions (MtCO2)	20930	23775	29210	36426	43970	2.1%
All GHGs emissions (MtCO2e)	NA	32904	39856	49119	58430	1.9%
Primary Energy Supply (Mtoe)						
Solids	2168	2348	2858	3611	4599	2.3%
Oil	3104	3604	4254	5102	5881	1.6%
Gas	1747	2146	2876	3710	4331	2.4%
Others	1665	1892	2024	2035	2160	0.4%
of which						
Nuclear	509	663	800	795	890	1.0%
Large Hydro + Geoth	193	238	290	342	393	1.7%
Trad. Biomass	791	820	682	569	477	-1.8%
Other Renewables	171	170	252	329	400	2.9%
World Oil Price ($95/bl)	27.2	26.5	23.7	28.7	34.9	0.9%

* 1992 figure

Table 3. The multi-gas scenario compared to the Reference case

Multi-gas Scenarios / Reference	2000	2010	2020	2030
Energy Intensity of GDP (toe/M$95)	0.0%	-1.2%	-2.2%	-6.7%
Primary energy (Mtoe)	0.0%	-1.2%	-2.2%	-6.7%
Carb intensity of energy (tCO2/toe)	0.0%	-2.1%	-3.6%	-8.2%
CO2 emissions (MtCO2)	0.0%	-3.3%	-5.7%	-14.3%
All GHGs emissions (MtCO2e)	0.0%	-6.7%	-7.4%	-15.0%
Primary Energy Supply (Mtoe)				
Solids	0.0%	-5.0%	-10.1%	-27.0%
Oil	0.0%	-2.6%	-3.5%	-7.6%
Gas	0.0%	-1.4%	-1.4%	-1.9%
Others	0.0%	7.2%	13.9%	29.3%
of which				
Nuclear	0.0%	0.0%	1.3%	18.9%
Large Hydro + Geoth	0.0%	0.2%	0.5%	1.8%
New Renewables	0.0%	4.9%	8.5%	29.9%
World Oil Price ($95/bl)	0.0%	-2.9%	-3.5%	-6.5%

Table 4. The carbon-only "only" scenario compared to the Reference case

COO Scenario / Reference	2000	2010	2020	2030
Energy Intensity of GDP (toe/M$95)	0.0%	-2.2%	-4.8%	-9.6%
Primary energy (Mtoe)	0.0%	-2.2%	-4.8%	-9.6%
Carb intensity of energy (tCO2/toe)	0.0%	-2.4%	-5.4%	-11.3%
CO2 emissions (MtCO2)	0.0%	-4.6%	-9.9%	-19.8%
Primary Energy Supply (Mtoe)				
Solids	0.0%	-6.4%	-18.6%	-37.2%
Oil	0.0%	-3.7%	-5.7%	-10.2%
Gas	0.0%	-3.3%	-2.2%	-3.3%
Others	0.0%	8.2%	17.2%	38.1%
of which				
Nuclear	0.0%	-0.1%	3.5%	31.7%
Large Hydro + Geoth	0.0%	0.4%	1.0%	2.5%
New Renewables	0.0%	12.9%	22.6%	48.6%
World Oil Price ($95/bl)	0.0%	-4.3%	-5.3%	-8.8%

6 CONCLUSIONS

The POLES 5 model has been developed and applied in the perspective of the assessment of multi-gas emission reduction strategies. Abatement options for all non-CO_2 GHG have been introduced. For the agricultural sector Marginal Abatement Cost curves have been derived from the Agripol model, which introduces innovative treatments for simulating the impacts of a GHG penalty on emissions from agriculture, through changes in the basket of agricultural techniques.

The international emission permit endowment scenarios used, based on the Soft Landing scheme, respond to a clear principle, of “a differentiated slowdown in emission growth for developing countries”. The global cap chosen in the exercise along the B1-SRES scenario, although respecting climate targets of 550 ppmv provides a relatively soft constraint case and allows for relatively generous endowments to developing countries.

The multi-gas analyses first of all demonstrate the relevance of this approach for the design of global abatement policies. Changing from a CO_2 to a multi-gas strategy either allows to increase total abatement of 25 % for the same Marginal Abatement Cost or to decrease the MAC of approximately 30 % for the same total abatement.

The impact of the GHG constraint on the energy systems is significantly reduced in the multi-gas approach which allows to limit the required reduction from this sector. This may even be considered as a drawback from this scenario as it is less stimulating for new technology development than pure CO_2-only cases. This is however an unavoidable fact that any low cost abatement opportunity, which will be highly welcome in the design of climate policy, will also reduce the incentive for more costly options.

All scenarios imply a significant restructuring, both in the world primary energy supply and in the global demand for energy. In 2030, the latter is 7 to 10 % lower in the different abatement cases than in the reference. But the fuel mix in energy supply is of course also profoundly modified, with reductions in coal consumption of 27 to 37 % in 2030 and increases in nuclear and new renewable energy of respectively 19 to 32 % and 30 to 49 %, according to the case considered.

Not surprisingly indeed, the impacts on world demand and primary fuel mix are less pronounced in the multi-gas than in the CO_2-only cases. This phenomenon may be viewed as an adverse consequence of the multi-gas approach, but it is easily understandable as being the counterpart of introducing more margins of freedom in the abatement effort, with the corresponding gains in terms of total cost of the programme to be implemented.

7 ACKNOWLEDGEMENT

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Efficiency Gains from "What"-Flexibility in Climate Policy

An Integrated CGE Assessment

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Abstract

We investigate the importance of "what"-flexibility on top of "where"- and "when"-flexibility for alternative emission control schemes that prescribe long-term temperature targets and eventually impose additional constraints on the rate of temperature change. We find that "what"-flexibility substantially reduces the compliance costs under alternative emission control schemes. When comparing policies that simply involve long-term temperature targets against more stringent strategies that include additional constraints on the rate of temperature increase, it turns out that the latter involve huge additional costs. These costs may be interpreted as additional insurance payments if damages should not only dependent on absolute temperature change but also on the rate of temperature change.

JEL classification: D58; Q43

Keywords: Climate policy; Integrated Assessment; What-flexibility

1. Introduction

Flexibility is a central element in market-based economies in order to foster the efficient use of scarce resources. In the context of climate policy, efficiency translates into questions of how much and what anthropogenic greenhouse gas (GHG) emissions should be abated, when, and where, i.e. by whom. Given complete information, comprehensive cost-benefit analysis could deliver precise answers to these questions. However, neither costs nor benefits of GHG emission abatement are easy to quantify. In particular, there are large uncertainties in external cost estimates for climate change. The chain of causality – from GHG emissions to ambient concentrations of GHGs in the atmosphere, from temperature increase to physical effects such as climatic and sea level changes – is very complex. Moreover, economists do not even agree on the methodology to be used for valuing such potential climate change impacts as the extinction of a species. The large uncertainties in predicting global climate change, as well as quantifying and monetizing the associated biophysical impacts explain much of the controversy on the desirable long-term level of GHG concentrations in the atmosphere and the scope and timing of emission mitigation measures.

Presuming that uncertain future outcomes of climate change could be extreme and irreversible, risk aversion may justify the adoption of a precautionary cost-effectiveness approach rather than hinging on traditional cost-benefit analysis (Gollier et al. 2000). In this vein, the United Nations Framework Convention on Climate Change (UNFCCC) aims at establishing an ample margin of safety based on recommendations from natural science on “tolerable” emission levels. The UNFCCC’s stated goal is the “stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system” (UNFCCC 1992, Article 2). In its Third Assessment Report the Intergovernmental Panel on Climate Change (IPCC), which serves as the scientific advisory board to the UNFCCC, laid out several long-term stabilization scenarios for greenhouse gas emissions with an associated range of expected increases in the global mean temperature (IPCC 2001). Given some stabilization or likewise temperature targets, rational climate policy should minimize the net economic costs of limiting temperature change. Cost-effectiveness suggests that the marginal costs of emission control should be equalized across all sources in space and time.[1] This comes down to comprehensive “where“, “when”, and “what”-flexibility. With the first, reductions should take place *where* it is cheapest to do so,

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[1] Note that - in contrast to cost-benefit analysis – it is no longer assured that marginal costs are equal to the marginal benefits of emission reduction.

regardless of the geographical location. With the second, reductions should take place *when* the cost-benefit calculus yields a positive value. With the third, decisions can be taken on *what* greenhouse gas should be abated under cost-effectiveness considerations.

While the potentials for efficiency gains from "where"-flexibility have been investigated in broader detail (see e.g. Weyant 1999), the implications of "when"-flexibility have been analyzed less intensively, and there are only relatively few studies that have addressed aspects of "what"-flexibility. There are good reasons for the shortage of studies on "when"- and "what"-flexibility. First, the quality of data for sources and abatement options of GHGs other than CO_2 is poor. Second, an appropriate analysis of "when"- and "what"-flexibility demands for integrated assessment of economic and climatic relationships in a dynamic framework that poses considerable challenges to modeling. Third, the long-term nature of climate change implies substantial uncertainties in economic analysis as it requires tenuous assumptions on the business-as-usual development that will be a key driver for adjustment costs to some climate policy objective.

Against this background, the primary objective of this paper is to ascertain the relative importance of a multi-gas emission control strategy (in our case: CO_2 *and* CH_4) vis-à-vis a CO_2-only abatement strategy. In other words: We want to sort out how much can be gained if we put "what"-flexibility on top of "where"- and "when"-flexibility. The explanatory power of such a comparison depends crucially on the proper design of the overall analytical framework. Therefore, we place special emphasis on the description of the baseline calibration and the integration of climate relationships into PACE, a dynamic multi-sector, multi-region computable general equilibrium (CGE) model of global trade and energy use.

Based on numerical simulation with this integrated assessment model we find that "what"-flexibility substantially reduces the compliance costs under alternative emission control schemes. When comparing policies that simply involve long-term temperature targets against more stringent strategies that include additional constraints on the rate of temperature increase, it turns out that the latter involve huge additional costs. These costs may be interpreted as additional insurance payments if damages should not only dependent on absolute temperature change but also the rate of temperature change. Our calculations also confirm the shortcomings of the global warming potential (GWP) approach to represent the contribution of different greenhouse gases to global temperature change because the relative contribution may vary substantially over time.

The remainder of this paper is organized as follows. Section 2 lays out the generic general equilibrium framework that serves as a starting point for subsequent extension to accommodate integrated assessment of multi-gas abatement strategies. Section 3 describes the baseline calibration of our model to long-term projections on economic growth and energy use. Section 4 elaborates the inclusion of non-CO2 greenhouse gases (in our case: CH_4). Section 5 provides a summary of the reduced-form climate sub-module and its linkage to the energy-economy model. Section 6 outlines the policy scenarios and interprets the simulation results. Section 7 concludes.

2. Generic Model Structure

Computable general equilibrium (CGE) models have become the standard tool for the analysis of the economy-wide impacts of greenhouse gas abatement policies on resource allocation and the associated implications for incomes of economic agents (see e.g. Bergmann 1990, Grubb et al. 1993, Weyant 1999). The main reason for this is that the general equilibrium framework represents price-dependent market interactions as well as the origination and spending of income for various economic agents based on rigorous microeconomic theory.

In this section, we lay out the generic structure of a multi-sector, multi-region CGE framework of global trade and energy use. A multi-region framework is indispensable for the analysis of global GHG emission constraints. In a world that is increasingly integrated through trade, policy interference in open economies not only cause adjustment of domestic production and consumption patterns but also influence international prices via changes in exports and imports. The changes in international prices, i.e. the terms of trade, imply secondary effects, which can significantly alter the impacts of the primary domestic policy (Böhringer and Rutherford 2002). In addition to the consistent representation of trade links, a detailed tracking of energy flows is a pre-requisite for the assessment of climate policies. Combustion of fossil fuels is a driving force of global warming through the release of the man greenhouse gas CO_2 (CH_4 also originates to a significant share from fossil fuel production and consumption). Beyond the comprehensive spatial coverage, climate policy analysis requires an explicit dynamic framework since policy interference applies over longer time periods as climate change is an inherently dynamic problem and happens on larger time scales. On the consumption side, dynamics involve the representation of the savings behavior of households. On the production side, dynamics involve the description of investment decisions of firms. To build dynamic features into the modeling of the economic behavior of households and firms one has to make an assumption on the degree of foresight of the economic agents. Assuming that the agents in the model know as much concerning the future as the modeler, implies a model with "consistent expectations" or "perfect foresight" where all agents consistently anticipate all current and future prices ("clairvoyance"). Such a framework reveals plausible effects of policy changes on intertemporal consumption and investment (savings) decisions and allows for the measurement of transitional effects that can be significant relative to long-term impacts.

Below, we first provide a short non-technical summary on the static intra-period sub-module and then describe the dynamics of the overall model. Finally, we point out the advantage of implementing the model in a mixed complementarity format rather than adopting a nonlinear programming (optimization) approach.

2.1. The Static Sub-Module

Figure 1 lays out the diagrammatic structure of the single-period static sub-module that underlies our dynamic multi-sector multi-region CGE model of global trade and energy use PACE. Primary factors of a region *r* include labor, capital and resources of fossil fuels *ff* (crude oil, coal, and gas). The specific resource used in the production of crude oil, coal and gas results in upward sloping supply schedules. Production Y_{ir} of commodities *i* in region *r*, other than primary fossil fuels, is captured by aggregate production functions which characterize technology through substitution possibilities between various inputs. Nested constant elasticity of substitution (CES) cost functions with several levels are employed to specify the KLEM substitution possibilities in domestic production sectors between capital (K), labor (L), energy (E) and non-energy intermediate inputs, i.e. material (M).

Final demand C_{ir} of the representative agent RA_r in each region is given as a CES composite which combines consumption of an energy aggregate with a non-energy consumption bundle. The substitution patterns within the non-energy consumption bundle as well as the energy aggregate are described by nested CES functions. CO_2 emissions are associated with fossil fuel consumption in production, investment, and final demand.

All goods used on the domestic market in intermediate and final demand correspond to a CES composite A_{ir} of the domestically produced variety and a CES import aggregate M_{ir} of the same variety from the other regions, the so-called Armington good (Armington, 1969). Domestic production either enters the formation of the Armington good or is exported to satisfy the import demand of other regions.

Endowments of labor and the specific resources are fixed exogenously. Capital supplies are price-responsive (see section 2.2.). Within any time period, we assume competitive factor and commodity markets such that prices adjust to clear these markets.

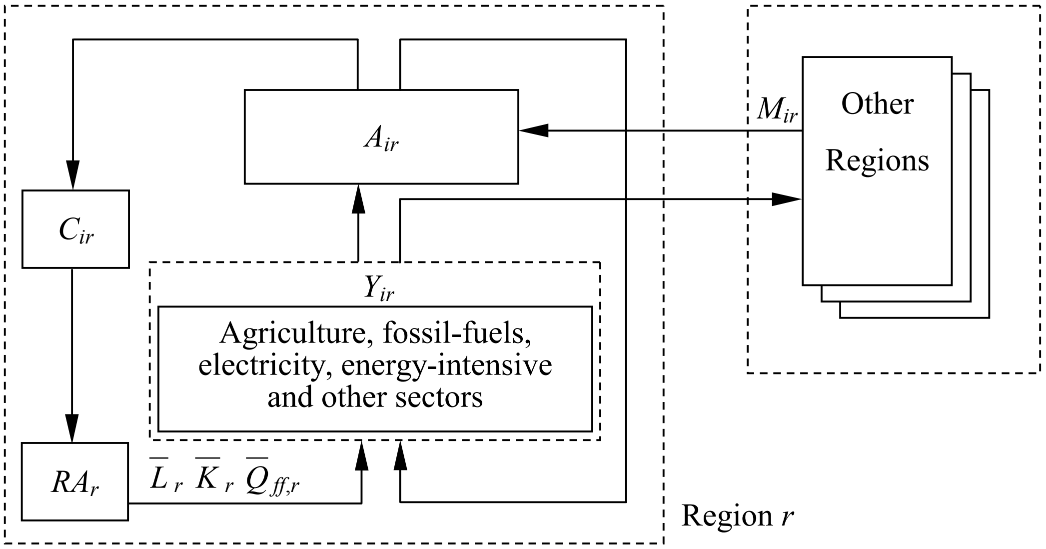

Figure 1: Structure of the intra-period sub-module

2.2. Dynamics

The notion of consistent expectations is coupled with the simplifying assumption of an infinitely-lived representative agent who makes explicit choices at the margin between current and function consumption. The representative agent maximizes welfare subject to an intertemporal budget constraint. In equilibrium the present value of consumption equals the present value of income over the infinite horizon. Within a given period, however, a region may run a current account surplus or deficit, depending on the difference between national income and expenditure.[2]

Figure 2 illustrates the basic dynamics of the model. The representative agent for each region maximizes his discounted utility over the model's time horizon. The primary factors, capital, labor, and energy are combined to produce output in period *t*. In addition, energy is delivered directly to final consumption. Output is divided between consumption and investment, and investment augments the (depreciated) capital stock in the next period. Capital, labor, and the energy resource earn incomes, which are either spent on consumption or retained for savings, i.e. investment.

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[2] Closure of financial flows within the model implies that the deficit is equal to the difference between the value of commodity imports and commodity exports.

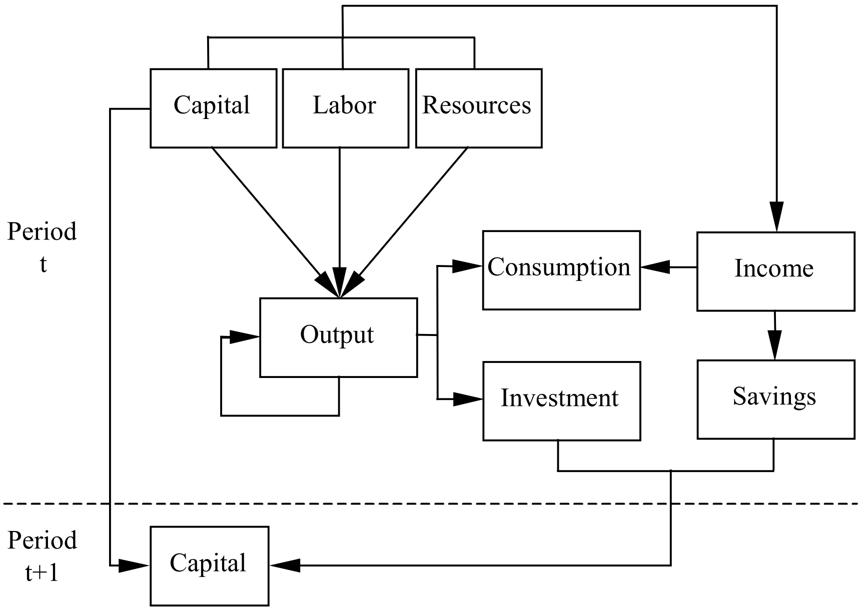

Figure 2: Dynamic model settings

Investment is driven by consistent expectations where the return on investment (with quadratic adjustment costs) is balanced against the cost of capital. In equilibrium, investments are placed in the region (sectors) where they will receive the highest return. International capital flows are thus endogenous, and the demand and supply of savings jointly determine the international interest rate. The baseline equilibrium growth path is calibrated to a common marginal product of capital in all regions. Capital stocks evolve through constant geometric depreciation and new investment. Following Uzawa (1969), we assume that capital installation costs depend on the rate of gross investment (relative to the existing capital stock). Given the level of investment, the cost of new capital decreases when the capital stock increases and vice versa. A quadratic installation cost function relates net to gross investment. For large adjustment costs, rapid changes in the regional capital stock are costly and the model exhibits a slower speed of adjustment of capital stocks to changes in the rate of return.[3]

Dynamic general equilibrium models exhibit a turnpike property, and one can exploit this when an infinite horizon equilibrium must be approximated with a finite model. To assure invariance of model results with respect to the time horizon, a set of appropriate terminal conditions must be specified. We adopt here the strategy proposed by Lau et al. (2002) where (i) terminal capital stocks are chosen to be consistent with smooth growth in investment in the final

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[3] Note that when there are no adjustment costs, the model reduces to the standard Ramsey model.

periods of the model and (ii) terminal assets are determined in consistency with budget balance and steady-state growth for the post-terminal horizon.

2.3. MCP Implementation

Algebraically, our model is implemented as a mixed complementarity problem (MCP). The MCP formulation provides a general format for economic equilibrium problems that may not be easily studied in an optimization context. Only if the complementarity problem is "integrable" (see Takayma and Judge 1971), the solution corresponds to the first-order conditions for a (primal or dual) programming problem. Given integrability, the nonlinear optimization problem can be interpreted as a market equilibrium problem where prices and quantities are defined using duality theory. In this case, a system of (weak) inequalities and complementary slackness conditions replace the minimization operator (see e.g. Rutherford 1995).[4] However, taxes, income effects, spillovers and other externalities, interfere with the skew symmetry property which characterizes first order conditions for nonlinear programs. In contrast to various models for long-term policy assessment that adopt an explicit optimization approach (see e.g. Manne and Richels 2001), our modeling framework is directly suited to investigate policy interference in (real-world) second-best settings. Compared to equilibrium conditions cast as system of equations the MCP framework allows for a straightforward representation of restrictions on prices or quantities that may become binding in equilibrium or not. Numerically, the model is implemented in MPSGE (Rutherford 1999) as a subsystem of GAMS (Brooke et al. 1986) using PATH (Dirkse and Ferris 1995) for solving the MCP problem.

3. Calibration

In quantitative policy analysis, the effects of policy interference are measured with respect to a reference situation - usually termed business-as-usual (BaU) - where no policy changes apply. When we want to simulate the potential effects of some policy measure, information on the future BaU development is required. Apparently, the BaU projections are a crucial determinant for the overall magnitude and distribution of adjustment costs For concreteness,

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[4] In this context, the term „mixed complementarity problem" (MCP) is straightforward: „mixed" indicates that the mathematical formulation is based on weak inequalities that may include a mixture of equalities and inequalities; „complementarity" refers to complementary slackness between system variables and system conditions.

exogenous policy constraints such as stabilization or temperature targets will bind future economies the more, the higher projected BaU growth in GHG emissions. Substantial differences in model-based analysis can often be traced back to different assumptions about the reference case. Yet, the central role of baseline assumptions in general receives little attention in the literature. Regarding long-term climate policy analysis, the issue of baseline projections becomes very critical in view of the tremendous uncertainties regarding BaU developments over several decades. Not only is there the question why one baseline should be preferable over another, but often projections based on partial equilibrium judgements/analysis stand out for large internal inconsistencies.

Against this background, a careful documentation of the baseline calibration is a conditio-sine-qua-non for the interpretation of results. In this section, we first describe the consistency conditions to calibrate a dynamic model along the global steady-state growth path. Second, we lay out a pragmatic approach how we can accommodate differential growth rates across various regions while avoiding potentially large deterioration in the terms of trade through the model horizon. Third, we sketch how exogenous projections on GHG emissions (i.e. in particular fossil fuel use) can be incorporated in a plausible manner along with projections of GDP growth rates. Fourth, we outline the inclusion of non-CO2 GHG abatement possibilities. Fifth, we describe the concrete parameterization of the intertemporal model that will be used for impact analysis of GHG alternative stabilization scenarios.

3.1. Steady-state calibration

The challenge in setting up a dynamic model is to reconcile the dynamic equilibrium conditions in terms of the benchmark data that incorporates base-year values for capital earnings, investment, and current account. Along the steady-state all quantities increase at the exogenous growth rate, while all prices expressed as present values decline at some interest rate (reflecting the pure rate of time preference). Steady-state growth implies mutual consistency of growth and interest rates together with capital earnings and investment values. However, in the benchmark data set, the steady-state conditions are typically not satisfied for arbitrary assumptions on dynamic parameters such as the growth, interest, and depreciation rates. If we assume plausible values for the latter parameters, the steady-state capital values share implied by steady-state growth, e.g., differ substantially from reported base-year values. To assure consistency and avoid re-calibration of the investment demand vector, one can calibrate capital and other factor shares to match the capital values share implied by the base year investment. For identical growth rates across all regions, this data adjustment assures consistency to steady-state growth.

3.2. Differential growth rates

In applied policy analysis, growth rate projections typically differ across regions. In this situation, the baseline equilibrium must be computed. When regions grow at different rates, there may be a substantial induced change in the terms of trade, and this makes it difficult to calculate a baseline growth path that matches economic targets such as investment and consumption. A pragmatic means of dampening changes in terms of trade for differentiated baseline growth rates is to adjust Armington share parameters over time in proportion to potential GDP. As a country grows faster, it is assumed that this produces an autonomous (non-price induced) change in the demand for the country's goods both in the home country as well as for the rest of the world. Since there is no change in the efficiency as a result of these demand adjustment, at base year prices, the cost of a unit of the aggregate commodity remains unchanged, even though there may be a substantial difference in the relative growth rates across countries. A final problem after the adjustment of Armington demand functions is related to assets rather than terms of trade and becomes evident in deviations between baseline and base year consumption. This reflects an inherent difficulty in setting up an equilibrium growth model in which the base year is not on a steady-state growth path. The level of net borrowing does not reflect earnings on assets - some of these capital flows represent ongoing changes in net asset positions as countries move toward the long-run equilibrium. In order to exactly replicate the base year consumption level, the level of net assets in the base year can be treated as a variable which is computed endogenously. These values are adjusted so as to produce a common base year consumption level in all regions.

3.3. Energy (Carbon) intensities

Standard baseline projections for climate or energy policy analysis include not only exogenous information on future GDP, but also detailed accounts on fossil fuel use, world market energy prices, and CO_2 emission profiles. In order to incorporate the energy data, we perform a two-step recalibration. First, we use the baseline intensities for fossil fuel demands to re-scale the baseline cost shares in the production of the electric and non-electric energy aggregates. In order to preserve the initial *total* costs per unit of production, we inversely adjust the capital cost shares, meaning that energy efficiency improvements are not costless but are linked to the increased use of capital services. Within the BaU re-calculation, we endogenously adjust the resource endowments of fossil fuels to calibrate the model to given exogenous target prices for fossil fuels. In a second step, we then recalibrate fossil fuel supply functions locally to match exogenous estimates of fossil fuel supply elasticities.

3.4. Parameterization

As is customary in applied general equilibrium analysis, base year quantities and prices – together with exogenous elasticities – determine the parameters of functional forms. The most comprehensive base year statistics on global trade and energy use are provided by the GTAP5 database that features consistent accounts of regional production and consumption, bilateral trade and energy flows for up to 66 countries/regions and 57 commodities in the year 1997 (Dimaranan and McDougall 2002).

Considering the regional resolution of our climate policy analysis, the binding constraint comes from the availability of long-term baseline projections. Here we make use of the WEC/IIASA database that includes projections for GDP, fossil fuel use and carbon as well as methane emission profiles up to 2100 for eleven geo-politically important world regions and six alternative long-term futures (WEC/IIASA 1998). In order to reduce the computational burden for the numerical analysis, we have further aggregated the eleven regions to seven model regions. The sectoral aggregation in the model has been chosen to distinguish carbon-intensive sectors from the rest of the economy as far as possible given data availability. It captures key dimensions in the analysis of greenhouse gas abatement, such as differences in carbon intensities and the degree of substitutability across carbon-intensive goods. The energy goods identified in the model are coal, natural gas, crude oil, refined oil products and electricity. Important carbon-intensive and energy-intensive non-energy industries that are potentially most affected by carbon abatement policies are aggregated within a composite energy-intensive sector. In order to keep track of the most important source for methane emissions, agriculture forms an explicit sector. The remaining manufacturers and services are aggregated to a composite industry that produces a non-energy-intensive macro good. The primary factors in the model include labor, physical capital and fossil-fuel resources. Table 1 summarizes the regional, sectoral, and factor aggregation of the model.

Among the six possible futures that are provided in the WEC-IIASA database, we use scenario B as our reference case. Scenario B is based on a cautious approach to technological change and energy availability as well as, modest economic growth. Table 2 provides an overview of central indicators for our reference scenario.

Table 1: Model dimensions

Production Sectors	Countries and Regions
Energy	North America (USA and Canada)
Coal	Western Europe
Crude oil	Pacific OECD (Japan, Australia, New Zealand)
Natural gas	Newly independent states of the former Soviet Union
Refined oil products	Central and Eastern Europe
Electricity	Africa, Latin America, and Middle East
Non-Energy	Asia
Agricultural production	
Energy-intensive sectors	*Primary factors*
Other manufactures and services	Labor
Savings good	Capital
	Fixed factor resources for coal, oil and gas

Table 2: Main characteristics of WEC-IIASA scenario B (WEC/IIASA 1998)

	Scenario B ("Middle course")
Carbon emissions (GtC)	9.6 (in 2050) - 11.4 (in 2100)
World economic growth	2.2 % p.a.
Environmental taxes	No
Carbon constraints	No

4. Non- CO_2 Abatement Options

CO_2 is the major anthropogenic greenhouse gas contributing to global warming. However, other greenhouse gases including CH_4, N_2O, and a number of industrial process gases are also relevant to climate change. In our multi-gas simulations below we track energy related emission of CO_2 and energy and non-energy emissions of CH_4 as the most important non-CO_2 greenhouse gas. We endogenously determine the level of CO_2 and CH_4 emissions thereby taking into account the various sources of anthropogenic CH_4 emissions and the technological options to abate them.

Agriculture is a principal source of CH_4 emissions. Especially the livestock sector contributes through enteric fermentation and the (anaerobic) decomposition of manure to the amount of CH_4 emissions from the agriculture sector. An important source of CH_4 emissions in agriculture is rice cultivation. Fugitive CH_4 emissions from natural gas and oil systems, especially from the production, processing, transmission and distribution of natural gas are considerably large. Less important are agricultural residue burning. Coal production (mining and post-mining activities) also produces CH_4 emissions through the process of coal formation which results in CH_4 that is stored in the coal. Municipal and industrial waste (solid waste landfilling and wastewater treatment) leads to anaerobic decomposition of waste and thereby CH_4 emissions. Other CH_4 emission sources include, e.g., stationary and mobile combustion and biofuel combustion.

Table 3: CH_4 sources, emission baseline and corresponding model sectors

CH_4 emission sources	EPA Baseline 2010 (in MMTCE)	Model sector
Rice cultivation	187.4	Agricultural
Enteric fermentation	557.9	Production
Manure management	65.3	
Biomass burning (agricultural residue burning)	75.1	
Coal production (underground and surface mining and post-mining)	140.9	Coal
Crude oil production	19.4	Crude oil
Natural gas systems (production, processing, transmission and distribution)	316.3	Natural gas
Industrial sewage (wastewater)	174.3	Energy-int. sectors
Domestic sewage (wastewater)		Household
Landfills of solid waste	239.0	
Stationary and mobile combustion	19.2	
Biofuel combustion	64.1	
Other	5.5	

Table 3 provides an overview of the CH_4 sources, baseline emissions in 2010 provided by the United States Environmental Protection Agency (EPA) (*see "Reference" in this special issue*) and the mapping of CH_4 sources to the sectors incorporated in our model.

Carbon emissions are directly linked to the combustion of fossil fuels. The key to lower carbon emissions is thus the reduction of fossil fuel combustion. In contrast, emissions of other GHG gases cannot, in general, be tied in fixed proportions to activity (use) as there are technical possibilities to reduce emissions per unit of activity. EPA provides bottom-up estimates of the abatement potential for CH_4 emission sources and the associated marginal abatement costs (*see "Reference" in this special issue*). There are regional marginal abatement cost curves (MAC) available for different activities: rice cultivation, enteric fermentation, manure management, coal production, crude oil production, natural gas systems and landfills of solid waste. More than 80 % of total anthropogenic CH_4 emission are hence supplemented with engineering information about technical options for potential emission abatement. Figure 3 illustrates marginal abatement cost curves for different CH_4 emission sources in the year 2010.

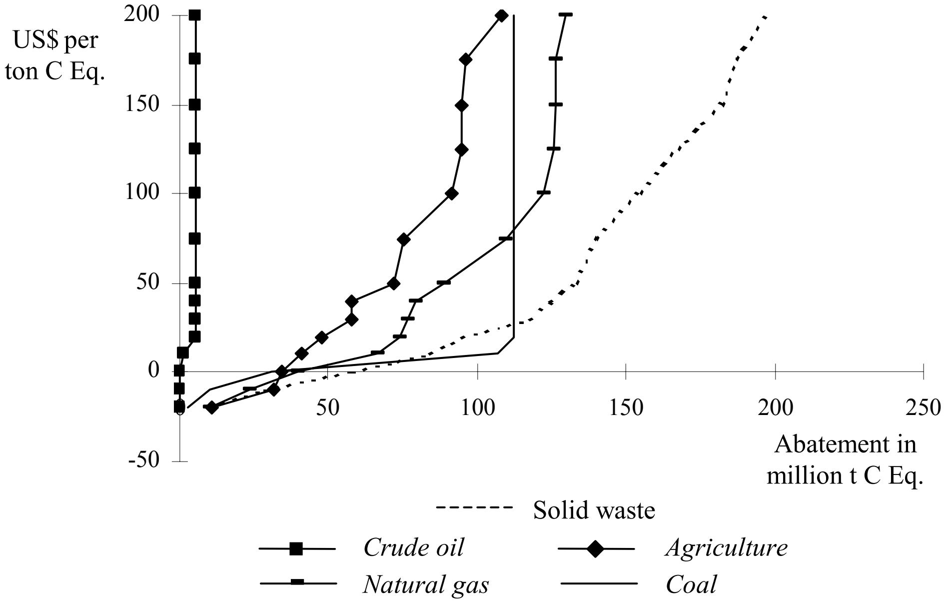

Figure 3: Global marginal abatement cost curves for CH_4 emission sources in 2010 (Source: "Reference" in this special issue)

To incorporate the cascaded marginal abatement cost curves for CH_4 in each sector and region of our model, we first compute an equilibrium path of the counterfactual GHG abatement scenario without CH_4 abatement options. Next, we evaluate the solution with respect to carbon prices. We then assume that all potential cost-effective CH_4 abatement options in each sector and region are implemented. We thus get a point estimate of CH_4 abatement levels, marginal cost of abatement, and the average cost increase of CH_4 abatement, whereby the latter is given by the area under the marginal abatement cost curve divided by the sectoral activity level. We then calculate the new temperature profile with the adjusted CH_4 emissions. Using the new equilibrium path, we can update the CH_4 abatement and cost fractions. The iterative CH_4 abatement algorithm converges quickly to a stable solution.

5. The Climate Sub-Module

In order to assess climate change policy options we combine economic aspects of climate change with scientific knowledge of the dynamics of climate change in an integrated assessment model. Climate-change modeling is introduced through the geophysical module of the RICE-99 (Regional Integrated model of Climate and the Economy) model (Nordhaus and Boyer 2000). It contains a number of geophysical relationships that link together the different forces affecting climate change. The geophysical relations are simplified representations of more complex models and give a reduced form description of emissions, concentrations, and globally averaged temperature change. Economic activity leads to CO_2 emissions which affect climate through their radiative forcing. The accumulation and transportation of CO_2 emissions is modeled as a linear three-reservoir approach calibrated to existing carbon cycle models. The three reservoirs represent the atmosphere, a quickly mixing reservoir in the upper oceans together with the short-term biosphere, and the deep oceans. The accumulation of CO_2 emissions in the atmosphere leads to an increase in radiative forcing. This relationship is derived from large-scale climate models: The radiative forcing equation includes the forcings of other greenhouse gases (CH_4, N_2O, CFCs and ozone) and aerosols as an exogenous component. The climate-change equations link radiative forcing and climate change based on the three-box climate model representation. An increased radiative forcing warms the atmosphere with some time lag due to the thermal inertia of the different ocean layers.

In the RICE-99 environmental module only CO_2 is endogenously modeled. Other greenhouse gases and their radiative forcings are assumed to be exogenous. For our multi-gas analysis we endogenize CH_4 as the most important non-CO_2 greenhouse gas. The calibration of the extended environmental module is based on the MERGE climate module (Manne et al. 1994). Methane emissions result from different sources and are linked to economic activities in the economic model. These emissions build up a CH_4 stock. The base year stock of methane is assumed to be 4.850 billion tons of CH_4 of which 60 % are subject to decay with a yearly retention factor of 8.3 % reflecting the atmospheric lifetime. The increase in the stock of methane leads to an increase in the radiative forcing of methane which is proportional to the logarithm of the ratio of the current to the initial level and takes into account the interaction effects of CH_4 and N_2O. The aggregate radiative forcing is again the sum of the radiative forcing for CO_2, CH_4 and the other exogenous forcings. The temperature equations remain unchanged.

Our algorithm for computing "when-efficient" tax profiles involves iterative computation of the numerical derivatives of temperature with respect to greenhouse gas emissions (CO_2 and CH_4 in our case). It turns out that these partial derivatives are fairly stable, which makes it possible to compute time-efficient tax profiles without resorting to an optimizing framework.

Due to the large uncertainties in damage estimates for climate change, we do not attempt to translate global warming into market impacts (such as productivitiy changes, capital depreciation) and non-market impacts (such as biodiversity losses, natural disasters) (Manne et al., 1995): There is only a one-way link between economic variables and biophysical variables. As a consequence, the welfare analysis is solely driven by economy-wide adjustment costs and restrictive GHG emissions control policies are necessarily welfare decreasing (in the absence of major second-best effects due to initial market distortions). The coupling of the economic system and climate system for our integrated CGE assessment is depicted in Figure 4.

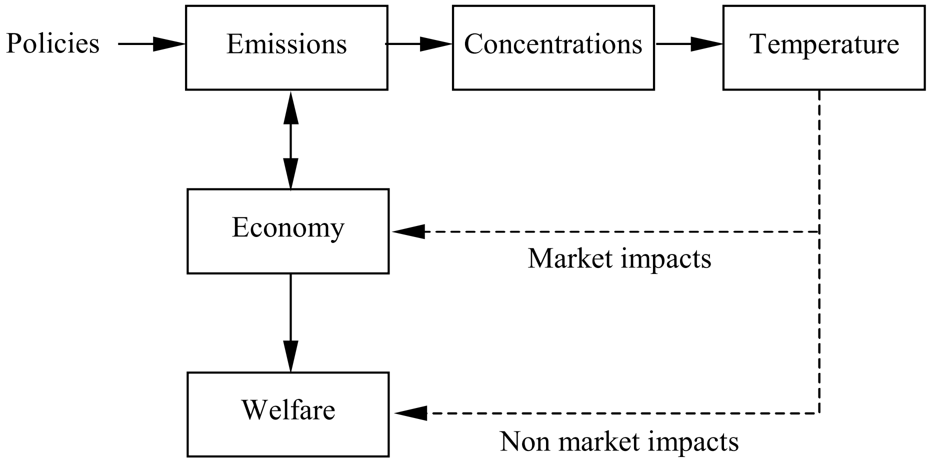

Figure 4: Coupling of economic system and climate system for integrated CGE assessment

6. Scenarios and Results

We distinguish two different climate control schemes. The first control scheme (*Target*) aims at stabilizing the long-term global temperature at an exogenously given level from 2100 onwards. Such a policy reflects the precautionary principle adopted by the UNFCCC to prevent global mean temperature rising beyond a certain threshold that could imply dangerous anthropogenic interference with the climate system. In our central case setting, temperature may not increase more than 90 % of the BaU temperature increase in 2100. The second control scheme (*Rate*) imposes an additional constraint on the rate of temperature change in addition to the long-term temperature stabilization target. This scenario reflects concerns that damages might not be only dependent on absolute temperature change but also on the rate of temperature change (see e.g. Peck and Teisberg, 1994, Alcamo and Kreileman 1996).[5]

In order to assess the importance of "what"-flexibility we combine each of the two control schemes with two alternative assumptions on the scope of greenhouse gases that are explicitly included. Variant CO_2 covers the case where only carbon emissions are subject to direct emission control measures. Variant *Multigas* explicitly includes various greenhouse gas emissions (in our case: CO_2 and CH_4) within the abatement strategy. In total, we thus obtain four scenarios whose characteristics are summarized in Table 4. Across all scenarios, comprehensive "where"-flexibility applies, i.e. emissions will be abated where it is cheapest.

Table 4: Central case scenarios

	Control scheme	Emission s.t. control policy
$CO_2\text{-}T_{Target}$	Temperature target	CO_2 only
$Multigas\text{-}T_{Target}$	Temperature rate	CO_2 and CH_4
$CO_2\text{-}T_{Rate}$	Temperature target	CO_2 only
$Multigas\text{-}T_{Rate}$	Temperature rate	CO_2 and CH_4

Abstracting from external costs of climate change, we simply investigate the least-cost way to satisfy external policy constraints with respect to the choice of the control scheme and the scope of GHG emissions covered. Our scenarios are thus based on a cost-effectiveness paradigm rather than comprehensive cost-benefit analysis. Without accounting for benefits

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[5] We approximate an upper bound on the decadal rate of change by specifying a set of temperature targets for each decade beginning in 2030.

from emission abatement, compliance to the exogenous emission control scheme necessarily involves global adjustment costs vis-à-vis the unconstrained business-as-usual.[6]

In the exposition of results from our large-scale multi-sector, multi-region CGE model PACE, we focus on global cost implications across the different scenarios. At the regional level, compliance costs will to a large extent depend on the allocation of the (endogenous) global emission budget which emerges from the respective emission control policies. This leads to the fundamental issue of burden sharing, i.e. the question how abatement duties - or likewise emission entitlements – shall be allocated across countries. This issue has already dominated climate negotiations under the Kyoto Protocol and proved extremely difficult to resolve. We do not want to enter the controversial and highly subjective debate on equity principles here and adopt the economist's typical device to separate efficiency from equity considerations (handling some exogenous distributional objective by means of hypothetical lump-sum transfers).

Note that, abstracting from secondary income effects, the initial emission entitlement does not affect global efficiency given full flexibility.[7]

Table 5 reports the global compliance costs across our four central scenarios. The qualitative results confirm basic economic intuition: (i) imposition of a decadal rate constraint on top of the temperature target will be more restrictive for the global economy and thus generate larger adjustment costs, and (ii) "what"-flexibility in terms of a multigas abatement approach reduces overall compliance costs for a given control scheme vis-à-vis a CO2-only strategy. The concrete quantitative figures show that global costs are relatively moderate ranging from a loss in lifetime BaU consumption of 0.01 % (scenario: *Multigas-*T_{Target}) up to 0.22 % (scenario: *Multigas-*T_{Rate}). However, the differences across scenarios are quite substantial. First, we see that hedging against "larger" decadal rates of temperature change is quite expensive – in fact the compliance costs are an order of magnitude higher as compared

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[6] In principle, second-best effects such as the interaction of emission control schemes with existing distortionary taxes might offset the direct emission control costs yielding a double dividend (see Goulder 1995, Bovenberg 1999). In our analysis, we deliberately neglect the incorporation of major initial distortions owing to the aggregate nature of our global model that makes it difficult to reflect specific tax and transfer systems as well as institutional constraints – such as labor market rigidities – in an appropriate manner.

[7] In our simulations we assume that in any period the BaU carbon emissions are scaled uniformly across regions to result in the (endogenous) global GHG emissions that are consistent with the temperature constraint. From an equity perspective, such an entitlement rule would reflect a sovereignty approach, where projected BaU emissions constitute a status quo right.

to the respective scenarios that only involve a long-term temperature target. Second, “what”-flexibility provides substantial efficiency gains cutting down the compliance costs vis-à-vis a CO2-only strategy by roughly a half.

Table 5: Global adjustment costs expressed as Hicksian equivalent variation (HEV) in income (% present value of BaU consumption).

	Temperature target		Decadal rate	
	CO_2-T_{Target}	Multigas-T_{Target}	CO_2-T_{Rate}	Multigas-T_{Rate}
	-0.02	-0.01	-0.22	-0.11

Figure 5 depicts the trajectory of the global mean temperature for the central case scenarios. Policies that only aim at limiting the increase in global mean temperature in 2100 at 90 % of the BaU value involve little temperature decreases vis-à-vis the business-as-usual until the mid of the century. Policies that in addition limit the decadal rate of temperature change are much more restrictive and involve distinct temperature decreases from BaU already in initial periods.

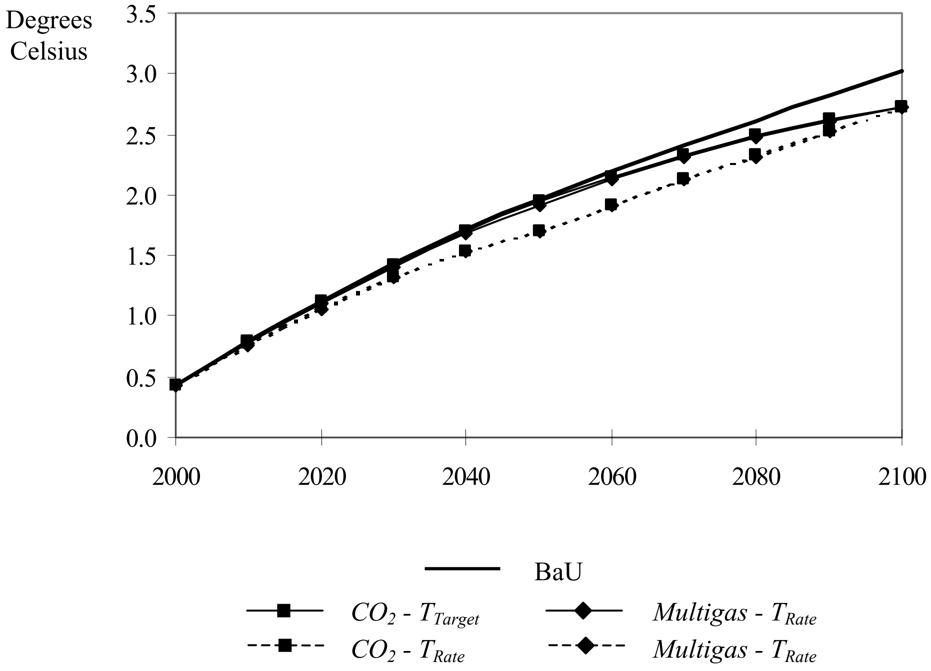

Figure 5: Global mean temperature (degrees Celsius)

Figure 6 illustrates the carbon emission profiles that emerge from the imposition of temperature targets and rate constraints. We see that the long-term temperature targets without decadal rate constraint allow for substantial increases in emission levels from current levels to the mid-century.

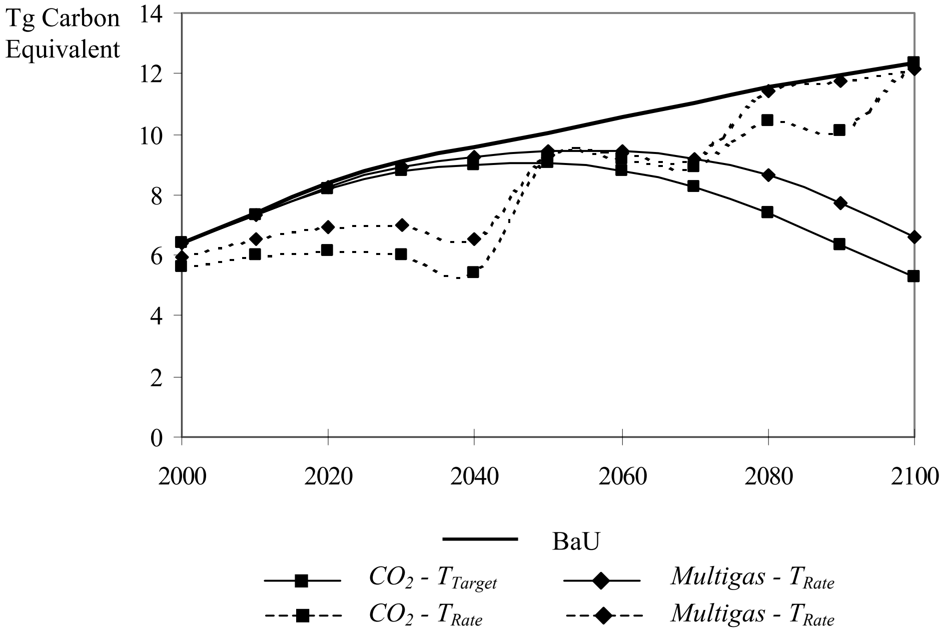

Figure 6: CO_2 Emissions from fossil fuels (Tg of C eq.)

The cutback requirements from BaU are relatively modest till 2050 but thereafter emissions must be reduced substantially to achieve the temperature target. In other words: abatement is shifted to the second half of the century where costs in present value terms simply decrease by discounting. Additional rate constraints imply larger cutbacks from BaU levels already in the initial decades. The climate dynamics reflecting past emissions then allow to increase emissions from 2040 onwards with a steep increase in the period between 2040-2050, some stable emission levels between 2050-2070 and a final increase towards BaU emission levels at the end of the century. The discontinuous step-function type emission trajectories for the scenarios with decadal rate constraints reflect the discrete bounds on rate increase. Due to the latter, there is no leeway for smoothing the carbon profile as is the case for the target-only scenarios. "What"-flexibility allows for higher CO_2 emissions for both climate control schemes (*Target* and *Rate*) since CH_4 abatement will be undertaken whenever it is cheaper.

The carbon emission profiles for the different scenarios are an indicator for the potential magnitude of compliance costs. The less carbon emissions must be cut back and the later in time abatement takes place the less costly the control scheme is – not surprisingly the comparison of profiles along these lines reveal the *Multigas*-T_{Target} as the least-cost scenario.

Figure 7 shows the magnitude of carbon taxes that would be required to achieve the long-term temperature target and - for scenarios *CO_2-T_{Rate}* and *Multigas-T_{Rate}* - to meet the rate constraints.

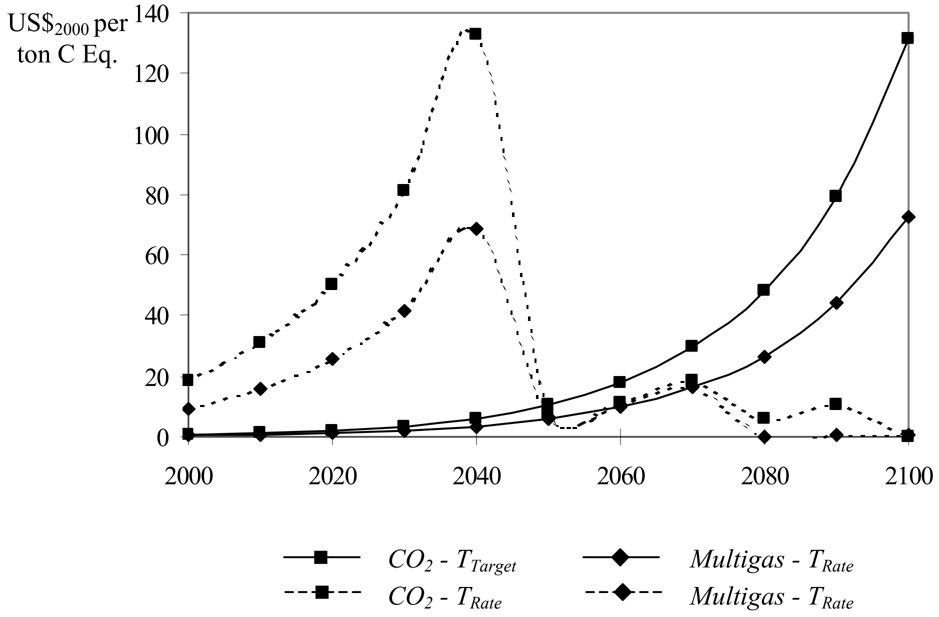

Figure 7: Incremental value of carbon permit / carbon tax (US$$_{2000}$/metric ton C Eq)

The course of the tax trajectories mirror the characteristics of the emission trajectories. When climate policies only aim at long-term temperature targets there is a continuous increase in carbon taxes towards the end of the century reflecting economic rationality to postpone abatement as long as possible. Rate constraints trigger very high shadow prices in the initial periods whereas towards the end of the model horizon prices become very small or even zero (as rate constraints may no longer be binding).

Figure 8 illustrates the tradeoffs between CO_2 and CH_4 based on efficiency prices that is the ratio of shadow values for these gases with respect to the long-term temperature target (scenario: *Multigas-T_{Target}*). As indicated by the natural science of the climate system this ratio increases over time since the impact of an additional emission unit CH_4 on the global mean temperature goes up relatively to the impact of an additional emission unit of CO_2. With its relatively short lifetime, the value of CH_4 increases as one approaches the temperature ceiling. The kink in 2080 reflects the "break-point" where the shorter lifetime of CH_4 vis-à-vis CO_2 does no longer matter with respect to the terminal temperature target. Figure 8 highlights the pitfalls of the Global Warming Potential (GWP) approach for establishing equivalence among greenhouse gases. Price rations may vary substantially over time (in addition they are sensitive to the ultimate temperature goal – see Manne and Richels 2001).

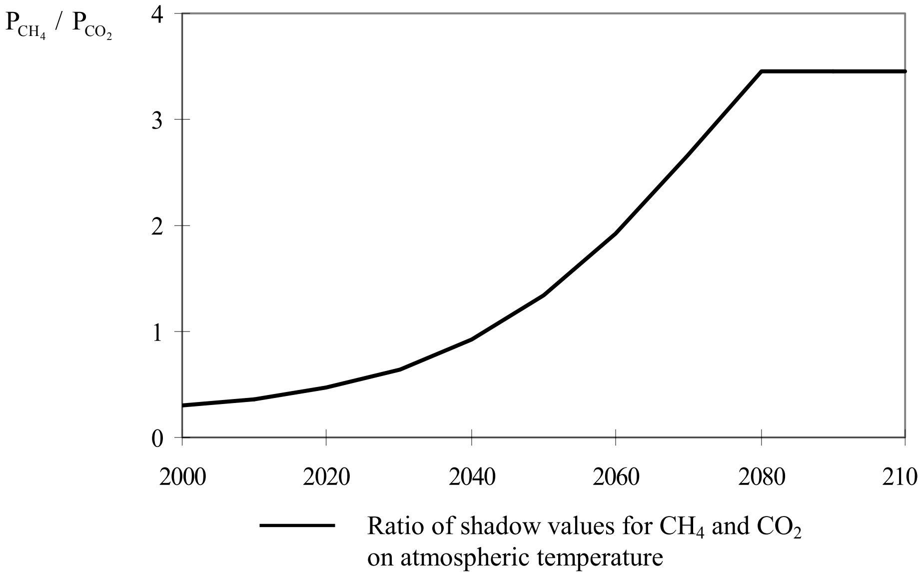

Figure 8: Ratio of shadow values for CH_4 and CO_2 on atmospheric temperature

7. Conclusions

In this paper, we have investigated the importance of "what"-flexibility for alternative emission control schemes that prescribe long-term temperature targets and eventually impose additional constraints on the rate of temperature change. In line with previous analysis, we find that "what"-flexibility can provide substantial global efficiency gains as cost-efficient abatement options for non-CO_2 gases are directly taken into account. In our simulations, we have identified very large insurance premia when hedging against too rapid rates of temperature increase. We have also highlighted the shortcomings of the GWP approach to represent the contribution of different greenhouse gases to radiative forcing.

From a methodological point of view, the primary objective of our paper has been to lay out a multi-sector, multi-region CGE model PACE that entails a careful baseline calibration and provides a self-consistent simple representation of the connection between greenhouse gas emissions and climate change (radiative forcing and temperature).

We close with several caveats. Although our model captures important economic aspects of long-term emission control schemes, it is only a crude approximation of the real world's technologies, preferences, endowments, etc. This applies in particular to longer-term analysis where substantial uncertainties about the future economic development prevail. Furthermore, our reduced from representation of the climate dynamics is very simplistic. Against this background we caution against too literal an interpretation of our numerical results.

Acknowledgements

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Annex II

EMF meeting programmes

Energy Modeling Forum 21
Multi-Gas Mitigation & Climate Change
May 9-10 2002, Joint Global Change Research Institute, University of Maryland

Speakers should plan about 20-25 minutes for presentations and 5-10 minutes for Q&A and discussion.

Thursday, May 9

8:30 am	Welcome / Introduction – Jae Edmonds, PNNL & John Weyant, EMF
9:00 am	EMF 21 Working Group Update – Francisco de la Chesnaye, EPA
9:30 am	Overview of emission projections, concentrations and temperature change
	- Steve Smith, PNNL
10:00 am	Break
10:30 am	Non-CO_2 data development and analyses: Methane & Nitrous Oxide
	- Casey Delhotal
	- Ann Gardiner
11:30 pm	Non-CO_2 data development and analyses: Fluorinated gases
	- Jochen Harnish
	- Deborah Ottinger
12:30 pm	*Lunch*
1:30 pm	Economic modeling teams
	- Rich Richels & Alan Manne, MERGE
	- Richard Tol, FUND
	- Don Hanson, AMIGA
	- Patrick Criqui, POLES
3:30 pm	*Break*
4:00 pm	- John Reilly, EPPA
	- Jesper Jensen, EDGE model
	- Koen Smekens, MARKAL Europe (not confirmed)
5:30 pm	*Working Dinner*
	- Billy Pizer, White House Climate Policy

Friday, May 10

8:30 am	US Domestic sequestration data development and incorporation into economic models - Bruce McCarl, FASOM-GHG
9:15 am	International sequestration data development and incorporation into economic models - Jayant Sathaye & Ken Andrasko, COMAP

10:00 am Economic modeling teams - Continued

- Hugh Pitcher, MiniCAM

10:30 am *Break*

11:00 am

- Tom Kram & Detlef van Vuuren, IMAGE
- Atsushi Kurosawa, GRAPE (not confirmed)
- Kate Woffenden, GTEM (not confirmed)

12:30 pm *Working Lunch*

Group discussion on data priorities, scenarios design, and schedule

- John Weyant & Francisco de la Chesnaye

14:00 Meeting Conclusion

Energy Modeling Forum 21
Multi-Gas Mitigation & Climate Change
December 4-6 2002, The Hotel Washington, Washington, DC

Unless otherwise arranged, speakers should plan about 20-25 minutes for presentations and 5-10 minutes for Q&A and discussion.

Wednesday, December 4 (Modelers Technical Meeting)

8:30 am	Welcome and Introduction – John Weyant, EMF
9:00 am	EMF 21 Update – Francisco de la Chesnaye, USEPA
9:30 am	Sessions on non-CO_2 data development and analyses
	Each will cover baseline emissions, mitigation methodology and options, and results by region and sector.
	1) Methane & Nitrous Oxide
	- Elizabeth Scheehle, USEPA
10:15 am	*Break*
10:45 am	1) Methane & Nitrous Oxide - continued
	- Casey Delhotal, USEPA
	- Chris Henricks, Ecofys
12:00 pm	*Lunch*
1:00 pm	2) Fluorinated gases
	- Dave Godwin, USEPA
	- Jochen Harnish, Ecofys
	- Deborah Ottinger, USEPA
2:30 pm	*Break*
3:00 pm	Discussion on Modeling Multi-gas Mitigation Targets
	- John Reilly, MIT
	- Steve Smith, JGCRI
4:00 pm	Sequestration data development and incorporation into economic models
	- Brent Sohngen, Ohio State Univ.
	- Bruce McCarl, Texas A&M Univ.
	- Jayant Sathaye, LBNL
	- Ron Sands, PNNL
5:30 pm	Conclusion
6:00 pm	*Reception*

Thursday, December 5

8:30 am	Welcome and Introduction to EMF 21 – John Weyant, EMF

Thursday, December 5

9:00 am	Overview of Multi-gas Mitigation – Francisco de la Chesnaye, EPA
9:30 am	Summary of Non-CO_2 analyses
	- Methane and Nitrous Oxide, Casey Delhotal, USEPA & Ann Gardiner, AEA Tech
	- Fluorinated Gases, Deborah Ottinger, USEPA
10:00 am	Break
10:30 am	Economic modeling teams (confirmed)
	- Andy Kydes, Energy Information Agency with SAGE
	- Asbjørn Aaheim, University of Oslo with COMBAT
	- Claudia Kemfert, Oldenburg University
12:00 pm	*Lunch*
1:00 pm	- Daniel Deybe, CIRAD with AGRIPOL
	- Detlef van Vuuren, RIVM with IMAGE
	- Don Hanson, Argonne Nat. Lab. and Skip Laitner, USEPA with AMIGA
	- Guy Jakeman, ABARE with GTEM
3:00 pm	*Break*
3:30 pm	- Hugh Pitcher, JGCRI with SGM/MiniCAM
	- Jesper Jensen, Copenhagen Economics with the EDGE Model
	- John Reilly, MIT with EPPA
	- Jiang Kejun, Energy Research Institute China
5:30 pm	Conclusion

Friday, December 6

8:30 am	Economic modeling teams (confirmed) - continued
	- Junichi Fujino, National Institute for Environmental Studies Japan with AIM
	- Marc Vielle, CEA - IDEI with GEMINI-E3
	- Rich Richels, EPRI & Alan Manne, Stanford Univ. with MERGE
	- Shilpa Rao, IIASA with MESSAGE
10:30 am	*Break*
11:00 am	- Thomas Rutherford, Univ of Colorado and Paul Bernstein & W. David Montgomery, CRAI
	Economic modeling teams (not confirmed)
	- Atsushi Kurosawa, IAE Japan with GRAPE
	- Patrick Criqui, UPMF with POLES
12:30 pm	*Lunch*

1:30 pm Discussion on priority scenarios and new scenarios

- John Weyant, EMF
- Andreas Löschel, Center for European Econ Research-ZEW
- Others

2:30 pm Group discussion on Key Issues, Data Priorities, Scenarios and Planning for Next Meeting

- John Weyant & Francisco de la Chesnaye

3:00 pm Meeting Conclusion

EMF 21: Multi-Gas Mitigation & Climate Change
May 19 - 21 2003, Radisson SAS Royal Hotel
Copenhagen, Denmark

Meeting Organized by the Stanford Energy Modeling Forum and Copenhagen Economics

Presenters should plan for 45 minutes total for presentation and questions.

Day 1: Monday, May 19

8:30 am	Welcome and Introduction – John Weyant, EMF & Jesper Jensen, Copenhagen Economics
9:00 am	EMF 21 Update – Francisco de la Chesnaye, USEPA
9:30 am	Scenario comparisons – John Weyant, EMF
10:00 am	*Break*
10:30 am	Economic modeling team presentations
	– Asbjorn Aaheim, Univ. of Oslo
	– Christoph Böhringer, Center for European Economic Research
12:00 pm	*Lunch*
1:30 pm	Economic modeling team presentations - continued
	– Patrick Criqui, LEPII-EPE
	– Junichi Fujino, National Institute for Environmental Studies
3:00 pm	*Break*
3:30 pm	Economic modeling team presentations - continued
	– Claudia Kemfert, Oldenburg University, SPEED
	– Atsushi Kurosawa, Institute of Applied Energy
5:30 pm	Conclusion
6:00 pm	*Informal Reception*

Day 2: Tuesday, May 20

8:30 am	Sequestration presentations and scenarios
	– Jayant Sathaye, Lawrence Berkeley Laboratory
	– Francisco de la Chesnaye, USEPA
10:00 am	Break
10:30 am	Modeling team presentations - continued
	– Alan S. Manne, Stanford Univ.

- Shilpa Rao, IIASA

12:00 pm *Lunch*

1:00 pm Modeling team presentations - continued

- Steven J. Smith, Univ. of Maryland & Pacific Northwest Natl
- Richard S.J. Tol, Hamburg Univ.
- Detlef van Vuuren & Tom Kram, RIVM

3:15 pm *Break*

3:45 pm Modeling team presentations - continued

- Marc Vielle, CEA-IDEI

4:30 pm Open discussion

5:00 pm Day 2 Conclusion

7:00 pm *Dinner* (To be confirmed – participants will be responsible for their own bill.)

Day 3: Wednesday, May 21

8:30 am Non-CO_2 and Sequestration presentations

- Francisco de la Chesnaye, USEPA
- Casey Delhotal, USEPA
- Ann Gardiner
- Dave Godwin, USEPA & Jochen Harnisch, Ecofys

10:30 am Break

11:00 am Update on EU GHG trading program

- Peter Zapfel, European Commission

Discussion on priority scenarios and new scenarios

12:30 pm *Lunch*

1:30 pm Key Issues, Priorities, Reporting & Planning for Next Meeting

- John Weyant, Francisco de la Chesnaye, & Peter Zapfel

2:30 pm Meeting Conclusion

EMF 21: Multi-Gas Mitigation & Climate Change
December 8 - 9 2003, Stanford University

** Presenters should plan for 45 minutes total for presentation and questions **

Day 1: Monday, December 8

8:30 am **Introduction, Status of overall study, & Scenario comparisons**

- John Weyant, EMF
- Francisco de la Chesnaye, USEPA

9:30 am **Long Term Model Presentations**

- Detlef van Vuuren, RIVM

10:15 am *Break*

10:45 am

- Richard S.J. Tol, Hamburg University
- Steven J. Smith, University of Maryland & Pacific Northwest Natl.

12:15 pm *Lunch*

1:15 pm

- John Reilly, Massachusetts Inst of Technology
- Shilpa Rao, IIASA
- Atsushi Kurosawa, Institute of Applied Energy

3:30 pm *Break*

4:00 pm

- Alan S. Manne, Stanford University & Richard Richels, EPRI
- Kejun Jiang, Energy Research Institute

5:30 pm **Day 1 Conclusion**

6:30 pm *Dinner*

Day 2: Tuesday, December 9

8:30 am **Long Term Model Presentations – continued**

- Claudia Kemfert, Oldenburg University, SPEED
- Odd Godal, CICERO, University of Oslo

10:00 am Break

10:30 am

- Junichi Fujino, National Institute for Environmental Studies
- Andreas Loeschel, Center for European Economic Research

12:00 pm *Working Lunch:*

Study on future architecture of international climate policy, Detlef van Vuuren, RIVM

1:15 pm **Short Term Model Presentations**

- Marc Vielle, CEA-IDEI

- Ron Sands, PNNL & Allen Fawcett, USEPA
- Jesper Jespen, Copenhagen Economics

3:30 pm *Break*

4:00 pm
- Don Hansen, Argonne National Laboratory & Skip Laitner, USEPA
- Guy Jakeman, ABARE

5:30 pm **Day 2 Conclusion**

6:30 pm *Working Dinner – Plans for Final Analyses and Publication*

Day 3: Wednesday, December 10

8:30 am **Sinks and Agricultural Mitigation presentations**
- Francisco de la Chesnaye, USEPA
- Daniel Deybe, European Commission
- Sinks Result Comparisons: Ken Andrasko, USEPA

10:00 am Break

10:30 am
- Brent Sonhgen, Ohio Sate University & RTI
- Detlev van Vuuren, RIVM & Alban Kitous, LEPII-EPE

12:00 pm
- *Lunch*

1:00 pm
- Jayant Sathaye & Willy Makundi, Lawrence Berkeley Laboratory
- Huey-Lin Lee, Purdue University

2:30 pm *Break*

2:45 pm **Completion of EMF21 Study & Continuation of Sub-group work**
- John Weyant & Francisco de la Chesnaye

3:30 pm **Meeting Conclusion**

Annex III

EMF lists of attendees

To avoid repetitions the four lists of attendees were merged in a single list of contacts.

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