

Overview of EMF-21: Multigas Mitigation and Climate Policy

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1. INTRODUCTION

This Special Issue of *The Energy Journal* presents the results of the most recently completed international collaboration under Stanford University's Energy Modeling Forum (EMF)¹. The EMF was started in 1976 as an organized forum for discussion and evaluation of important energy and environmental issues. The EMF operates mainly around organized working groups that focus their work by comparing the results of different economic, market, and planning models. Participants in EMF are leading energy and economics experts and advisors from industry, universities, government, and other research organizations.

On the topic of climate change mitigation, recent EMF working groups include: EMF-16, *The Costs of the Kyoto Protocol: A Multi-Model Evaluation*, which was a comprehensive comparison of 13 international modeling teams of the

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1. See <http://www.stanford.edu/group/EMF/index.htm>

protocol and also published as a special issue of *The Energy Journal* (Weyant, 1999); and EMF-19, which evaluated alternative technology strategies for climate change policy and resulted in a special issue of *Energy Economics* (Weyant, 2004).

This Special Issue provides a comprehensive report on a comparative set of analyses of the economic and energy sector impacts of multigas mitigation of anthropogenic greenhouse gases including carbon dioxide (CO₂) and the non-CO₂ GHGs (NCGGs) covering methane (CH₄), nitrous oxide (N₂O), and a set of fluorinated gases (F-gases: PFCs, HFCs and SF₆). There is greater uncertainty in estimating CO₂ emissions from landuse and CH₄ and N₂O emissions than in estimating CO₂ emissions from fossil fuels. Table 1 provides global estimates for 2000 of all the gases by major emitting sector and reference projections to 2100 for CO₂, CH₄, and N₂O based on the means of all models reporting data. In 2000, out of a global total of about 10,200 million tons of carbon equivalent (MtCe), CO₂ is by far the largest at 74 percent of the total with CH₄ second at 16 percent. Emissions of N₂O and the fluorinated gases are nine and one percent of the total, respectively. By 2050, the mean projection of all gases is about 18,600 MtCe and by 2100 it is over 25,000 MtCe.

The objectives of this study, commonly referred to as EMF-21, were to:

1. Conduct a new comprehensive, multigas policy assessment to improve the understanding of the effects of including NCGGs and sinks (terrestrial sequestration) into short- and long-term mitigation targets. EMF-21 essentially answers the following question: How important are NCGGs & sinks in climate policies?
2. Provide explanations for differences in results from different models and identify high priority areas for future research.
3. Advance the state-of-the-art in integrated assessment and climate economic modeling.
4. Strengthen collaboration between NCGG and sinks experts and modeling teams.

This study differs from previous EMF studies in that data development of NCGG and sinks emissions and mitigation costs and subsequent transfer to the modeling teams were major elements of the study. Data development teams participated directly in the study's design and implementation, and the modeling teams generally used the data provided by these teams to develop the capability to project emissions of NCGGs and the costs of mitigating them in their models. In previous studies the data used in the models was generally not modified during the course of the study. The study's results are illustrative of the effects of including multiples gases in mitigation analysis, especially when stabilization targets are considered.

The volume consists of: (1) papers prepared by NCGG data analysis teams on what data they developed and how they developed it; (2) papers by two forestry modeling teams that analyzed the potential for forest sinks to absorb CO₂

Table 1. Global Anthropogenic GHG Emissions in 2000 and Beyond (MtCe)

Sectors Detail for 2000					
Sector subtotal & Percent of Total	Sub-sectors	CO₂	CH₄	N₂O	F-gases
ENERGY 6,845 67%	Coal	2,218	123		
	Nat Gas	1,309	244		
	Petroleum Systems	2,857	17		
	Stationary/Mobile Sources		16	61	
LUCF and AGRICULTURE 2,608 25%	LUCF and Agriculture (net)	942			
	Soils			711	
	Biomass		134	51	
	Enteric Fermentation		476		
	Manure Management		61	56	
	Rice		177		
INDUSTRY 391 4%	Cement	226			
	Adipic & Nitric Acid Prd			43	
	HFCs				26
	PFCs				29
	SF6				15
	Substitution of ODS				52
WASTE 395 4%	Landfills		213		
	Wastewater		154	22	
	Other		3	3	
TOTAL GHG	10,239	7,552	1,618	947	122
Gas as percent of total		74%	16%	9%	1%
Projections: GHG Total & by Gas					
2025	TOTAL	CO₂	CH₄	N₂O	
	14,403	11,102	2,325	976	
2050	18,643	14,494	2,974	1,176	
2075	21,411	16,874	3,419	1,118	
2100	25,067	20,019	3,858	1,190	

Note: LUCF is Land-use change and forestry. Projections are the means of all models reporting data for those years. F-gas projection are not reported because models used different aggregations of the gases. Sources: papers in this volume.

from the atmosphere and the associated mitigation (or enhanced sequestration) costs; and (3) papers by 19 global energy-economic modeling teams on what they did and what they concluded from the model runs that were undertaken. Table 2 shows the names of data development teams and Table 3 shows the names of the 19 modeling teams that participated in the EMF-21 study. This overview paper for the volume focuses on the motivation for the study, the design of the study scenarios, and the interpretation of results for the core scenarios which almost all teams ran. As a collection, these papers contain ideas and insights drawn by the global modeling teams from applying their models to a mutually selected set of important issues.

Table 2. Data Development Teams

Methane and Nitrous Oxide Emissions	E. Scheehle & D. Kruger (U.S. Environmental Protection Agency)
Methane and Nitrous Oxide Mitigation From Waste, Energy And Industry	K. C. Delhotal & F. de la Chesnaye (U.S. EPA), Ann Gardiner & Judith Bates (AEA Technology, U.K.), Alexei Sankovski (ICF Consulting, U.S.), and John Gale (IEA GHG R&D Programme, U.K)
Methane and Nitrous Oxide Mitigation in Agriculture	B. DeAngelo & F. de la Chesnaye (U.S. EPA) and R. Beach, A. Sommer, & B. C. Murray (RTI International, U.S.)
Emissions and Mitigation of HFCs, PFCs, and SF₆	D. Ottinger-Schaefer & D. Godwin (U.S. EPA), Jochen Harnisch (Ecofys, Germany), and John Gale (IEA GHG R&D Programme, U.K)
Carbon Sequestration Costs in Global Forests	Brent Sohngen (Ohio State Univ., U.S.) and Roger Sedjo (Resources for the Future, U.S.)
Costs and Benefits in Global Forests	J. Sathaye, W. Makundi, L. Dale, & P. Chan (Lawrence Berkeley National Laboratory, U.S.) and K. Andrasko (U.S. EPA)

Table 3. Energy-economic Models in EMF- 21

AIM Asian-Pacific Integrated Model	J. Fujino, R. Nair, M. Kainuma, T. Masui (National Institute for Environment Studies, Japan) and Y. Matsuoka (Kyoto Univ., Japan)
AIM/EU-India AIM - End-Use Component Applied to India	P.R. Shukla (Indian Institute of Management), A. Garg (UNEP/RISO), M. Kapshe (Maulana Azad Inst.of Tech.), and R. Nair (NIES, Japan)
AMIGA All Modular Industry Growth Assessment	D. Hansen (Argonne National Laboratory, U.S.), J. Laitner (U.S. EPA)
COMBAT COMprehensive aBATement	H.A. Aahaim, J.S. Fuglestedt, and O. Godal (CICERO, Norway)
EDGE European Dynamic Equilibrium Model	J. Jensen (TECA TRAINING ApS)
EPPA Emissions Projection and Policy Analysis Model	J. Reilly, M. Sarofim, S. Paltsev, and R. Prinn (Massachusetts Institute of Technology, U.S.)
FUND Climate Framework for Uncertainty, Negotiation, and Distribution	Richard Tol (Economic and Social Research Institute, Ireland and Hamburg, Vrije & Carnegie Mellon Universities)
GEMINI-E3/GEMWTrap General Equilibrium Model of International Interaction for Economy-Energy- Environment	A. Bernard (Min. of Equipment, Transport, and Housing, France), M. Vielle (CEA-LERNA, France), and L. Viguier (HEC Geneva and Swiss Federal Institute of Technology)
GRAPE Global Relationship Assessment to Protect the Environment	A. Kurosawa (Institute of Applied Energy, Japan)

Table 3. Energy-economic Models in EMF- 21 (continued)

GTEM Global Trade and Environment Model	G. Jakeman and B. Fisher (Australian Bureau of Agricultural and Resource Economics)
IMAGE Integrated Model to Assess The Global Environment	D.P. van Vuuren, B. Eickhout, P.L. Lucas and M.G.J. den Elzen (National Institute for Public Health and the Environment, The Netherlands)
IPAC Integrated Projection Assessments for China	K. Jiang, X. Hu, & S. Zhu (Energy Research Institute, China)
MERGE Model for Evaluating Regional and Global Effects of GHG Reductions Policies	A. Manne (Stanford University, U.S.) and R. Richels (Electric Power Research Institute, U.S.)
MESSAGE Model for Energy Supply Strategy Alternatives and Their General Environmental Impact	S. Rao and K. Riahi (International Institute for Applied Systems Analysis, Austria)
MiniCAM Mini-Climate Assessment Model	S. Smith (PNNL/Univ. Maryland, U.S.) and T.M.L. Wigley (National Center for Atmospheric Research, U.S.)
PACE Policy Analysis With Computable Equilibrium	C. Böhringer, (University of Heidelberg), A. Löschel (Centre for European Economic Research – ZEW, and T. Rutherford (University of Colorado)
POLES-GECS Prospective Outlook on Long-Term Energy Systems-Global Emissions Control Strategies	P. Criqui (Institute of Energy Policy and Economics, France), Peter Russ (EC- Institute for Prospective Technological Studies, Spain), and Daniel Deybe (EC Environment DG)
SGM Second Generation Model	A. Fawcett (U.S. EPA) and R. Sands (PNNL/Univ. Maryland, U.S.)
WIAGEM World Integrated Applied General Equilibrium Model	C. Kemfert (German Inst. of Economic Research & Humboldt University), T. P. Truong (Univ. of New South Wales, Australia) and T. Bruckner (Institute for Energy Engineering, Tech Univ, Germany)

2. INTERNATIONAL POLICY FRAMEWORK

Increasing atmospheric concentrations of CO₂ are, by far, the most important element of the enhanced greenhouse effect. Accordingly, most mitigation studies so far have concentrated on this gas only. At the same time, however, human activities cause emissions of several other greenhouse gases (GHGs), including CH₄, N₂O, and the F-gases. In order to “stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system” (UNFCCC, 1992) NCGGs also will need to be reduced. In 1997, policy-makers acknowledged this by formulating the Kyoto Protocol targets in terms of a “basket” of GHGs (allowing full substitution among them), thus making a multigas abatement strategy operational. The gases, referred to as

'Kyoto' gases are CO₂, CH₄, N₂O, and the F-gases (PFCs, HFCs and SF₆). CFCs and HCFCs are not covered by the Kyoto Protocol as their replacement and phase out is dealt with under the Montreal Protocol on ozone depleting substances.

The Kyoto Protocol sets targets for emissions of GHGs from the industrialized countries. These targets are generally specified as a percentage reduction (or in some cases a small maximum increase) in annual average GHG emissions permitted during the first budget period which runs from 2008 to 2012 relative to actual 1990 emissions. The emissions of the different GHGs are to be combined by using Global Warming Potentials (GWPs) to convert the other GHGs into carbon equivalents. The designated GWP factors, which set the contributions to radiative forcing of the other GHGs equal to that resulting from CO₂ over some fixed period of time, are the 100-year GWPs reported by the Intergovernmental Panel on Climate Change in its Second Assessment Report (IPCC, 1996). Interestingly, most studies on the implications of a multigas strategy are more recent. An important reason is that consistent information on reduction potential for the NCGGs was lacking.

3. PREVIOUS STUDIES

The economic literature on the costs of greenhouse gas (GHG) emission reduction has focused on carbon dioxide from industry and electricity given that it is the largest single source of greenhouse gases (Hourcade et al., 2001). However, other sources are important too. Perhaps the explanation for the paucity of studies is that these other sources are hard to include into models that emphasize energy economics. Methane is emitted by coal mining and leakage from gas transport, but also by agriculture. Nitrous oxide originates from agriculture and a range of industrial processes. Another explanation is the lack of data on engineering solutions to CH₄ and N₂O emission abatements and their costs. Although there are a fair number of older partial studies on emissions, options, and costs (van Amstel, 1993; Hogan, 1993a,b,c; de Jager and Blok, 1993; van Ham, et al., 1994, 2002; AEAT, 1998 a, b; IEA GHG, 1998; USEPA, 1999, 2003; Bates and Haworth, 2000), climate economists had to extrapolate country-specific methane emission reduction costs, e.g., from the Netherlands, to the rest of the world Tol (1999) and Tol et al. (2003). Reilly et al. (1999) were the first to report, albeit only graphically, an internally consistent, region specific set of cost curves.

A few previous studies have looked at multigas emission reduction. Tol (1999) looks at CO₂ and CH₄, finding that "how" flexibility is as important as "where" flexibility, with cost savings of up to 70 percent. Reilly et al. (1999) study emission reduction for all GHGs, finding annual cost reductions of about 50 percent. They emphasize that emission reduction targets, if expressed relative to a base year, are sensitive to the gases included. The analysis of Manne and Richels (2001) is restricted to CO₂, CH₄ and N₂O. Their annual cost savings in 2010 are 20-50 percent, smaller than in Reilly et al. (1999). Jensen and Thelle (2001) include all Kyoto gases in a medium-term model; their welfare costs in the OECD fall by

20-35 percent due to the inclusion of other gases, but the countries of the former Soviet Union lose substantial revenue in the emission permit trade. The study by Tol et al. (2003) is restricted to carbon dioxide and methane. In contrast to the other multigas studies (including this one), it emphasizes the differences in the dynamics of the two gases in the economy, a factor that complicates the optimal trade-off between respective emission reductions. Tol et al. (2003) report cost savings of up to 70 percent by including methane only. The current study differs from these previous papers in using a different set of scenarios and sensitivity analyses, and developing and using more reliable data on the costs of emission reduction.

4. EMF- 21 SCENARIOS

Over the course of the EMF-21 study group, one of the major challenges was to collectively define the core scenarios that all the modeling teams would run. This was a challenge due to the significant number of modeling teams that participated in EMF-21, the complexities of including multiple GHGs and accurately associating their emissions to modeled economic activities, and because of the many different model types and related solution concepts. Ultimately, the participants of EMF-21 agreed on the core scenarios that are described below.

4.1 Modeler's Reference

As is customary in EMF studies, each modeling team developed their own reference case. The modeler's reference case was defined by each team's own (exogenous or endogenous) assumptions about economic and population growth, future energy prices, and rates of technological improvement among other key factors. The one requested common assumption for the groups was that the Kyoto Protocol not be included in the reference scenario. The reasons for this assumption were due to modeling practicality: First, at the time when the reference scenarios were developed, it was not clear that the Protocol would come into force; and Second, the focus of the study was on long-term stabilization so that the time frame of the Protocol's first commitment period of 2008 to 2012 was a small section of the long-term analysis.

4.2 Long-term, CO₂-only Stabilization Scenario

The first mitigation or intervention scenario was the benchmark stabilization scenario. It was the most common (but not the only) stabilization scenario run by modelers and the scenario to which other cases would be compared to in order to evaluate the significance of multigas mitigation. In this scenario, the climate change or emissions target was defined as stabilizing radiative forcing at 4.5 Wm⁻² (watts per square meter) relative to pre-Industrial times by 2150 using CO₂-only mitigation. This forcing level corresponds to an equilibrium temperature of 3.0°C, for a 2.5°C per CO₂ doubling climate sensitivity. Some

models also evaluated sensitivities using a range of different forcing targets (see papers by Aahaim et al., Manne & Richels, Rao & Riahi, Tol, and van Vuuren et al., in this volume). From 2100 to 2150, the radiative forcing from all the GHGs was held constant at the 2100 level. This definition of the first mitigation scenario was done specifically to fit the structures of the long-term climate-economic or integrated assessment, models in the study.

The short-term models (those that run out to 2030 or 2050), however, required emissions targets for global total emissions for all GHGs (based on 100-yr GWPs). MIT using the EPPA model and PNNL using MiniCAM provided short-term emissions targets that were consistent with the defined stabilization targets.

4.3 Long-term, Multigas Stabilization Scenario

In contrast to the CO₂-mitigation scenario, this scenario included as many NCGGs options as available in a model to meet the specified radiative forcing stabilization target. The inclusion of sinks mitigation was treated in a separate scenario for comparison purposes. The stabilization target was the same: Stabilize radiative forcing at 4.5 Wm⁻² relative to pre-Industrial times by 2150. As above, long-term models provided short-term emissions targets that were consistent with the defined stabilization target.

4.4 Combined Multigas Scenario

This scenario combined the same long-term target as above and added a decadal rate-of-change target, all under a multigas scenario. It was defined as: Hold the global, mean decadal rate of temperature change from 2030 to 2100 at 0.2°C (two-tenths of a degree) starting in 2030, and meet the long-term target of stabilizing radiative forcing at 4.5 Wm⁻² relative to pre-Industrial times by 2150. Midway through the study, an earlier rate-of-change scenario was attempted that included the same mean decadal rate of temperature change target but started as soon as the models ran and did not include the long-term forcing limit. Two noteworthy insights came out of those early runs: First, given the reference emissions projections for the early part of the century, and owing in part to the inertia in the climate system resulting from the accumulation of past emissions in the atmosphere, most models required an extremely high carbon price to limit the rate of temperature increase (in some cases models could not solve due to the extreme prices); and Second, without an end-of-century temperature limit, the rate of temperature increase was held within 0.2°C per decade but the long-term temperature continued to increase above the stabilization target. As a result, a new combined target was used for this scenario to capture both a short-term rate target with the long-term climate stabilization target. Since results for this scenario are not included in this overview paper, readers are encouraged to review the set of papers that included this analysis (see Böhringer et al., Criqui et al., Kemfert et al., Tol, Kurosawa, Manne & Richels, and Rao & Riahi in this volume).

4.5 Sinks Scenarios

The last core scenario which included sinks data in modeling scenarios was optional for modelers. The reasons this was optional were: (1) the approaches taken by various modeling teams to incorporate sinks into their analysis were very different, more so than with the NCGGs; and (2) the sinks data were developed based on a set of carbon price paths that were not necessarily consistent with the prices resulting from the above mitigation scenarios. In the end, a few models ran the additional sinks scenarios so that comparisons were available between CO₂-only and multigas scenarios, and then to scenarios including sinks. The EMF-21 study helped foster new collaborations between the integrated assessment and forestry modeling teams. After the main work of the study was conducted, a subset of modelers and sinks experts developed a special EMF report on landuse activity and emissions in stabilization modeling (Rose et al., 2006). Readers interested in more details on landuse emissions are encourage to obtain the paper from the EMF-21 website (see RESULTS section below for link).

5. EMF- 21 MODELS

Table 3 shows the names and developers of the 19 models participating in the EMF- 21 study. This study included a comprehensive data set of current NCGG emissions and projections and mitigation opportunities in different regions of the world. The way models include this information depends on the type of model. The models may be distinguished according to four key attributes given in Table 4: Model Type, Representation of non-CO₂ GHG Emissions Sector(s), non-CO₂ Gas Contribution Method, and Solution Concept.

There are three basic types of models: (1) Multi-sector general equilibrium models that include the inputs and outputs to a number of economic sectors in the economy, (2) models that consider only the aggregate economic output produced by the economy, and (3) market equilibrium models that include market supply and demand conditions for a number of energy and non-energy sectors of the economy. The way the non-CO₂ GHG emissions sectors are represented in the models depends directly on the model type. In the multi-sector general equilibrium models the mitigation options are used to modify the input-output coefficients in the sectoral production functions with, for example, more capital, labor and materials inputs substituting for GHG outputs. In the aggregate general equilibrium models, reduced-form Marginal Abatement Cost (MACs) for the NCGGs which consume aggregate economic output and lead to less GHG emissions are included as options for reducing NCGG emissions which allow CO₂ and non-CO₂ GHG emissions to be substituted for each other depending on their relative costs. In the market models, structural models of the sectors that produce NCGGs (e.g., agriculture, oil and gas production) are included. These structural models often allowed individual NCGG mitigation technologies to be represented and implemented in GHG control scenarios.

Table 4. Key Characteristics of EMF- 21 Models

Model	Model Type	Representation of non-CO ₂ GHG Emissions Sector(s)	Non-CO ₂ Gas Contribution Method	Solution Concept
AIM	Multi-Sector General Equilibrium	Reduced Form Adj. to Prod. Fcns.	Radiative Forcing	Recursive Dynamic
AMIGA	Multi-Sector General Equilibrium	Reduced Form Adj. to Prod. Fcns.	GWPs	Recursive Dynamic
GTEM	Multi-Sector General Equilibrium	Reduced Form Adj. to Prod. Fcns.	GWPs	Recursive Dynamic
GEMINI-E3	Multi-Sector General Equilibrium	Reduced Form Adj. to Prod. Fcns.	GWPs	Recursive Dynamic
EU-PACE	Multi-Sector General Equilibrium	Reduced Form Adj. to Prod. Fcns.	Radiative Forcing	Intertemporal Optimization
EDGE	Multi-Sector General Equilibrium	Reduced Form Adj. to Prod. Fcns.	GWPs	Recursive Dynamic
EPPA	Multi-Sector General Equilibrium	Reduced Form Adj. to Prod. Fcns.	GWPs	Recursive Dynamic
IPAC	Multi-Sector General Equilibrium	Reduced Form Adj. to Prod. Fcns.	GWPs	Recursive Dynamic
SGM	Multi-Sector General Equilibrium	Reduced Form Adj. to Prod. Fcns.	GWPs	Recursive Dynamic
WIAGEM	Multi-Sector General Equilibrium	Reduced Form Adj. to Prod. Fcns.	GWPs	Recursive Dynamic
Combat	Aggregate General Equilibrium	Reduced Form MACs	Radiative Forcing	Intertemporal Optimization
FUND	Aggregate General Equilibrium	Reduced Form MACs	Radiative Forcing	Intertemporal Optimization
GRAPE	Aggregate General Equilibrium	Structural Models	Radiative Forcing	Intertemporal Optimization
MERGE	Aggregate General Equilibrium	Reduced Form MACs	Radiative Forcing	Intertemporal Optimization
IMAGE	Market Equilibrium	Structural Models	GWPs	Recursive Dynamic
MESSAGE	Market Equilibrium	Structural Models	GWPs	Intertemporal Optimization
MiniCAM	Market Equilibrium	Structural Models	GWPs	Recursive Dynamic
POLES/AgriPol	Market Equilibrium	Structural Models	GWPs	Recursive Dynamic

The models also differ in whether they aggregate the contributions of the different GHGs via 100-year GWPs or via equations representing directly their contributions to radiative forcing. Several factors influence the choice of methods.

First, these models are mostly economic models, but they all could include enough atmospheric modeling to compute contributions of each of the GHGs to radiative forcing directly, at least using a reduced-form formulation. Second, many of the multi-sector general equilibrium models extend out only to 2030-2050 and obtained GHG emissions tracks that satisfied the 4.5 Wm^{-2} radiative forcing constraint from the longer-term models; this calibration was generally done in terms of GWP carbon equivalents instead of individual gases so as to not override the internal economic tradeoffs contained in the shorter run models. The final model attribute shown in Table 4 is whether the model represents current production and investment decisions based on current prices of inputs and outputs and includes an intertemporal optimization that considers the prices that will prevail over the lifetime of those investments. Since it is generally easier to implement an intertemporal optimization algorithm when economic output is aggregated, these two model attributes are often (but not always) found together in economic models in general and all the models included in this study in particular.

6. RESULTS

Given that this study has produced a significant amount of results and analysis from the data development teams and the global energy-economic models, a special website has been set up for open public access to all the study data. This paper only presents a small set of the results available for the full study. For example, only emissions results for CO_2 and CH_4 for the US, the EU-15, and China are reported here. Many modeling teams reported all gases, including different combinations of F-gases, for 15 different countries or regional groupings. The EMF-21 site can be found at <http://www.stanford.edu/group/EMF/projects/projectemf21.htm>.

6.1 Baseline Emission Projections

Reference case global GHG emission projections are shown for CO_2 , CH_4 , and N_2O in Tables 5, 6, and 7, respectively. All emissions are anthropogenic in origin, i.e., man made. Emissions of CO_2 are from the combustion of fossil fuels and cement manufacturing, unless otherwise noted. Although the models project that CO_2 emissions grow throughout the century, the range of reference case projections is quite large, with projections from some models (e.g., MESSAGE, AIM, IMAGE, and IPAC) showing just a bit more than a doubling in carbon emissions over the century and others (e.g., FUND) showing about a factor of five increase over the century. The reference case growth rate projections for CH_4 emissions from the models are generally much more modest than for carbon dioxide with most models projecting about a doubling, but with projections from one model showing a slight decrease and another a fourfold increase. Nitrous oxide reference case emission projection growth rates are similar to methane emission growth rates with again a couple of models showing much larger emissions increases than the others.

Table 5. Global Fossil Fuel and Cement CO₂ Emissions (GtC)

Model	Scenario	2000	2025	2050	2075	2100
AIM	Reference Case	6.8	9.2	12.4	14.4	15.8
	% Reduction in CO ₂ Only Scenario	0.0%	-20.9%	-39.1%	-49.5%	-56.5%
	% Reduction in Multigas Scenario	0.0%	-16.1%	-30.1%	-39.3%	-45.3%
AMIGA	Reference Case	6.3	8.4	11.0	14.3	17.6
	% Reduction in CO ₂ Only Scenario	0.0%	-9.4%	-32.2%	-46.7%	-59.2%
	% Reduction in Multigas Scenario	0.0%	-8.1%	-26.9%	-37.7%	-47.5%
COMBAT	Reference Case	7.1	10.7	15.0	20.9	28.8
	% Reduction in CO ₂ Only Scenario	-9.3%	-13.1%	-21.8%	-44.8%	-71.3%
	% Reduction in Multigas Scenario	-8.8%	-12.3%	-20.5%	-42.9%	-70.0%
EDGE	Reference Case	6.5	10.1	NA	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-3.5%	NA	NA	NA
	% Reduction in Multigas Scenario	0.0%	-1.5%	NA	NA	NA
EPPA*	Reference Case	6.3	10.2	15.7	20.8	24.7
	% Reduction in CO ₂ Only Scenario	0.0%	-22.0%	-57.3%	-73.1%	-81.3%
	% Reduction in Multigas Scenario	0.0%	-11.5%	-45.2%	-66.0%	-75.1%
FUND	Reference Case	7.5	11.6	17.3	25.7	36.0
	% Reduction in CO ₂ Only Scenario	0.0%	-57.2%	-85.7%	-97.5%	-99.2%
	% Reduction in Multigas Scenario	0.0%	-46.6%	-79.2%	-95.1%	-98.1%
GEMINI	Reference Case	6.7	10.2	11.8	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-27.7%	-48.4%	NA	NA
	% Reduction in Multigas Scenario	0.0%	-17.1%	-33.5%	NA	NA
GRAPE	Reference Case	6.5	9.9	13.1	16.5	21.7
	% Reduction in CO ₂ Only Scenario	0.0%	-2.7%	-16.6%	-64.5%	-81.9%
	% Reduction in Multigas Scenario	0.0%	-1.8%	-6.7%	-49.8%	-73.6%
GTEM	Reference Case	6.3	11.5	19.6	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-37.3%	-69.8%	NA	NA
	% Reduction in Multigas Scenario	0.0%	-26.4%	-58.2%	NA	NA
IMAGE	Reference Case	6.7	11.3	15.5	16.4	15.7
	% Reduction in CO ₂ Only Scenario	0.0%	-18.7%	-47.8%	-62.0%	-70.1%
	% Reduction in Multigas Scenario	0.0%	-10.9%	-39.3%	-52.9%	-60.5%
IPAC	Reference Case	6.4	10.7	15.2	15.4	14.6
	% Reduction in CO ₂ Only Scenario	-9.1%	-23.9%	-39.7%	-56.0%	-67.9%
	% Reduction in Multigas Scenario	0.0%	-18.8%	-34.4%	-51.4%	-61.7%
MERGE	Reference Case	6.6	9.4	13.1	16.9	21.1
	% Reduction in CO ₂ Only Scenario	0.0%	-5.3%	-39.4%	-69.3%	-91.3%
	% Reduction in Multigas Scenario	0.0%	-2.5%	-24.8%	-58.3%	-77.8%
MESSAGE	Reference Case	6.4	9.1	10.7	11.8	14.1
	% Reduction in CO ₂ Only Scenario	0.0%	-14.1%	-37.4%	-71.7%	-85.7%
	% Reduction in Multigas Scenario	0.0%	-8.5%	-25.9%	-57.5%	-72.2%
MiniCAM	Reference Case	7.0	10.6	14.2	17.7	20.6
	% Reduction in CO ₂ Only Scenario	-1.4%	-26.5%	-58.2%	-71.4%	-78.7%
	% Reduction in Multigas Scenario	-1.4%	-14.0%	-40.1%	-58.6%	-70.5%
PACE	Reference Case	6.4	8.7	10.0	11.3	12.3
	% Reduction in CO ₂ Only Scenario	-0.6%	-2.7%	-10.1%	-30.5%	-57.4%
	% Reduction in Multigas Scenario	-0.3%	-1.5%	-6.2%	-21.1%	-46.3%

Table 5. Global Fossil Fuel and Cement CO₂ Emissions (GtC) (continued)

POLES	Reference Case	6.7	11.6	NA	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-15.1%	NA	NA	NA
	% Reduction in Multigas Scenario	0.0%	-10.3%	NA	NA	NA
SGM	Reference Case	6.0	9.7	12.95	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-31.4%	-46.2%	NA	NA
	% Reduction in Multigas Scenario	0.0%	-15.6%	-27.8%	NA	NA
WIAGEM	Reference Case	8.3	10.6	13.0	15.9	20.7
	% Reduction in CO ₂ Only Scenario	-2.2%	-21.6%	-38.9%	-55.2%	-66.1%
	% Reduction in Multigas Scenario	-0.5%	-16.4%	-32.4%	-48.2%	-59.4%
Mean	CO ₂ in Reference Case	6.7	10.2	13.8	16.8	20.3
	% Reduction in CO ₂ Only Scenario	-1.3%	-19.6%	-43.0%	-60.9%	-74.4%
	% Reduction in Multigas Scenario	-0.6%	-13.3%	-33.2%	-52.2%	-66.0%

Note: a. EPPA reports fossil fuel CO₂ only. NA indicates models do not run out to that date.

Table 6. Global CH₄ Emissions (MtCe)

Model	Scenario	2000	2025	2050	2075	2100
AIM	Reference Case	1,720	2,372	2,713	2,592	2,389
	% Reduction in CO ₂ Only Scenario	0.0%	-5.1%	-10.6%	-13.1%	-16.0%
	% Reduction in Multigas Scenario	0.0%	-22.0%	-46.9%	-56.8%	-61.8%
AMIGA	Reference Case	1,600	2,144	2,614	2,295	2,061
	% Reduction in CO ₂ Only Scenario	0.0%	-0.4%	-1.7%	-5.6%	-9.7%
	% Reduction in Multigas Scenario	0.0%	-0.9%	-6.1%	-22.0%	-39.5%
COMBAT	Reference Case	2,006	2,377	2,810	3,407	4,213
	% Reduction in CO ₂ Only Scenario	-2.9%	-5.5%	-11.2%	-27.3%	-48.9%
	% Reduction in Multigas Scenario	-6.9%	-9.4%	-14.7%	-30.2%	-52.2%
EDGE	Reference Case	1,618	2,294	NA	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	0.0%	NA	NA	NA
	% Reduction in Multigas Scenario	0.0%	-5.1%	NA	NA	NA
EPPA	Reference Case	1,659	2,722	3,821	4,512	4,672
	% Reduction in CO ₂ Only Scenario	0.0%	-7.0%	-18.4%	-22.2%	-27.2%
	% Reduction in Multigas Scenario	0.0%	-36.6%	-51.8%	-58.4%	-62.9%
FUND	Reference Case	1,529	2,312	3,023	3,793	4,311
	% Reduction in CO ₂ Only Scenario	0.0%	0.0%	0.0%	0.0%	0.0%
	% Reduction in Multigas Scenario	0.0%	-5.2%	-10.4%	-18.1%	-8.2%
GEMINI	Reference Case	1,619	2,213	2,450	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-6.6%	-7.8%	NA	NA
	% Reduction in Multigas Scenario	0.0%	-20.7%	-26.3%	NA	NA
GRAPE	Reference Case	1,598	2,073	2,565	2,763	3,083
	% Reduction in CO ₂ Only Scenario	0.0%	-0.4%	-3.1%	-24.2%	-47.7%
	% Reduction in Multigas Scenario	0.0%	0.0%	-7.6%	-47.3%	-61.4%
GTEM	Reference Case	1,344	2,073	3,167	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-14.0%	-27.3%	NA	NA
	% Reduction in Multigas Scenario	0.0%	-36.6%	-52.7%	NA	NA

Table 6. Global CH₄ Emissions (MtCe) (continued)

IMAGE	Reference Case	1,908	2,691	2,999	2,883	2,737
	% Reduction in CO ₂ Only Scenario	0.1%	-3.1%	-11.4%	-14.9%	-13.3%
	% Reduction in Multigas Scenario	0.1%	-28.8%	-41.4%	-47.7%	-48.0%
IPAC	Reference Case	1,918	2,497	2,962	3,010	2,860
	% Reduction in CO ₂ Only Scenario	-3.0%	-7.0%	-9.8%	-12.3%	-13.2%
	% Reduction in Multigas Scenario	-2.1%	-32.1%	-33.9%	-35.2%	-38.5%
MERGE	Reference Case	1,685	2,228	2,492	2,947	3,396
	% Reduction in CO ₂ Only Scenario	0.0%	-0.7%	-0.9%	-0.1%	0.1%
	% Reduction in Multigas Scenario	0.0%	-0.3%	0.0%	-27.8%	-48.8%
MESSAGE	Reference Case	1,555	2,165	3,121	3,509	3,727
	% Reduction in CO ₂ Only Scenario	0.0%	-3.3%	-4.9%	-6.8%	-9.4%
	% Reduction in Multigas Scenario	0.0%	-18.1%	-29.1%	-37.3%	-42.3%
MiniCAM	Reference Case	1,617	1,963	1,871	1,744	1,590
	% Reduction in CO ₂ Only Scenario	-0.6%	-8.0%	-13.7%	-21.5%	-21.9%
	% Reduction in Multigas Scenario	-0.6%	-16.4%	-36.0%	-53.6%	-60.6%
PACE	Reference Case	1,294	1,946	2,449	3,070	3,821
	% Reduction in CO ₂ Only Scenario	-0.2%	-0.9%	-3.0%	-8.6%	-14.5%
	% Reduction in Multigas Scenario	-7.3%	-7.6%	-8.6%	-20.3%	-28.1%
POLES	Reference Case	1,633	2,035	NA	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-5.1%	NA	NA	NA
	% Reduction in Multigas Scenario	0.0%	-25.4%	NA	NA	NA
SGM	Reference Case	1,618	2,287	2,957	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-8.0%	-13.0%	NA	NA
	% Reduction in Multigas Scenario	0.0%	-61.1%	-66.3%	NA	NA
WIAGEM	Reference Case	2,046	3,421	5,335	7,924	11,287
	% Reduction in CO ₂ Only Scenario	-8.9%	-43.2%	-61.9%	-73.0%	-80.0%
	% Reduction in Multigas Scenario	-16.0%	-56.6%	-72.8%	-81.5%	-86.6%
Mean	Reference Case	1,665	2,323	2,959	3,419	3,858
	% Reduction in CO ₂ Only Scenario	-0.9%	-6.6%	-12.4%	-17.7%	-23.2%
	% Reduction in Multigas Scenario	-1.8%	-21.3%	-31.5%	-41.2%	-49.2%

Note: NA indicates models do not run out to that date.

Table 7. Global N₂O Emissions (MtCe)

Model	Scenario	2000	2025	2050	2075	2100
AIM	Reference Case	932	1,147	1,348	1,563	1,669
	% Reduction in CO ₂ Only Scenario	0.0%	-0.4%	-2.1%	-4.8%	-5.9%
	% Reduction in Multigas Scenario	0.0%	-3.9%	-11.9%	-26.6%	-45.8%
AMIGA	Reference Case	837	930	981	926	854
	% Reduction in CO ₂ Only Scenario	0.0%	0.0%	0.0%	0.0%	0.0%
	% Reduction in Multigas Scenario	0.0%	-1.4%	-6.0%	-8.7%	-11.9%
COMBAT	Reference Case	765	819	883	971	1,090
	% Reduction in CO ₂ Only Scenario	-1.1%	-2.3%	-5.2%	-14.1%	-27.8%
	% Reduction in Multigas Scenario	-3.9%	-5.1%	-7.8%	-16.3%	-30.2%

Table 7. Global N₂O Emissions (MtCe) (continued)

EDGE	Reference Case	950	1,346	NA	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	0.0%	NA	NA	NA
	% Reduction in Multigas Scenario	0.0%	-1.4%	NA	NA	NA
EPPA	Reference Case	896	1,323	1,756	2,377	3,138
	% Reduction in CO ₂ Only Scenario	0.0%	-2.5%	-8.7%	-11.3%	-10.0%
	% Reduction in Multigas Scenario	0.0%	-32.2%	-46.2%	-55.9%	-65.8%
FUND	Reference Case	477	607	693	782	869
	% Reduction in CO ₂ Only Scenario	4.4%	1.1%	0.5%	0.3%	0.5%
	% Reduction in Multigas Scenario	4.4%	-59.2%	-73.3%	-82.1%	-71.5%
GEMINI	Reference Case	951	1,326	1,559	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-1.2%	-1.3%	NA	NA
	% Reduction in Multigas Scenario	0.0%	-7.6%	-10.2%	NA	NA
GRAPE	Reference Case	941	1,140	1,257	1,302	1,337
	% Reduction in CO ₂ Only Scenario	0.0%	-6.0%	-11.5%	-22.5%	-36.5%
	% Reduction in Multigas Scenario	0.0%	-11.4%	-21.7%	-31.6%	-43.5%
GTEM	Reference Case	613	902	1,270	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-3.2%	-13.3%	NA	NA
	% Reduction in Multigas Scenario	0.0%	-37.8%	-47.7%	NA	NA
IMAGE	Reference Case	685	897	1,000	1,041	1,048
	% Reduction in CO ₂ Only Scenario	0.0%	-0.8%	-1.4%	-1.8%	3.2%
	% Reduction in Multigas Scenario	0.0%	-6.1%	-13.7%	-16.5%	-16.2%
IPAC	Reference Case	494	485	512	541	562
	% Reduction in CO ₂ Only Scenario	-0.4%	-1.6%	-3.9%	-5.1%	-5.4%
	% Reduction in Multigas Scenario	-0.3%	-18.5%	-19.4%	-21.5%	-22.1%
MERGE	Reference Case	949	949	949	949	949
	% Reduction in CO ₂ Only Scenario	0.0%	0.0%	0.0%	0.0%	0.0%
	% Reduction in Multigas Scenario	0.0%	-8.8%	-12.2%	-17.1%	-19.6%
MESSAGE	Reference Case	940	1,319	1,670	1,400	1,090
	% Reduction in CO ₂ Only Scenario	0.0%	-0.7%	-1.0%	-0.8%	-0.5%
	% Reduction in Multigas Scenario	0.0%	-9.4%	-14.8%	-20.9%	-29.0%
MiniCAM	Reference Case	825	927	900	840	780
	% Reduction in CO ₂ Only Scenario	-0.7%	-3.5%	-6.8%	-9.2%	-10.9%
	% Reduction in Multigas Scenario	-0.7%	-10.5%	-21.8%	-30.7%	-36.7%
POLES	Reference Case	352	599	NA	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-0.1%	NA	NA	NA
	% Reduction in Multigas Scenario	0.0%	-0.2%	NA	NA	NA
SGM	Reference Case	950	1,335	1,720	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-1.2%	-2.0%	NA	NA
	% Reduction in Multigas Scenario	0.0%	-23.3%	-26.4%	NA	NA
WIAGEM	Reference Case	373	465	579	722	899
	% Reduction in CO ₂ Only Scenario	-3.3%	-11.2%	-19.9%	-28.3%	-35.2%
	% Reduction in Multigas Scenario	-2.3%	-14.6%	-26.2%	-36.7%	-45.5%
Mean	Reference Case	760	971	1,139	1,118	1,190
	% Reduction in CO ₂ Only Scenario	-0.1%	-2.0%	-5.1%	-8.1%	-10.7%
	% Reduction in Multigas Scenario	-0.2%	-14.8%	-23.9%	-30.4%	-36.5%

Note: Models not listed in table did not report results. NA indicates models do not run out to that date.

These tables also show a comparison between the CO₂-only and multigas mitigation scenarios for projections of CO₂, CH₄, and N₂O as percent reductions from their respective reference cases. In Table 5, the increase in CO₂ indicates that under a multigas mitigation scenario, the required reductions in CO₂ emissions are less than in a CO₂-only mitigation scenario, for the same radiative forcing target. This finding holds across all the models with the decrease in a CO₂ reduction burden differing depending on how many NCGG reduction options are included in each model. Tables 6 and 7 show the complement to the CO₂ reductions in that both the required emission reduction of CH₄ and N₂O increase under the multigas mitigation scenario. Essentially, since the other GHGs are also subject to a total radiative forcing constraint, less costly reductions in those gases are displacing more costly reduction of CO₂ from the energy sector. For models that use GWPs for the NCGGs, the required reductions steadily grow through the century whereas for intertemporal optimization models (e.g., MERGE) that internally calculate the trade offs between gases, reductions in NCGGs (particularly CH₄) increase toward the end of the century and the stabilization target. For complete coverage of all CO₂ emissions, Table 8 provides reference case emissions of global CO₂ from land use change and forestry activities. (As indicated above, more details on landuse activity and emissions in stabilization modeling are available at the EMF-21 website.)

Table 8. Reference Global Land Use Change and Forestry CO₂ Emissions (GtC)

Model	2000	2025	2050	2075	2100
AIM	0.92	(0.05)	(0.24)	(0.45)	(0.58)
FUND	0.91	0.77	0.56	0.25	(0.07)
GRAPE	0.94	1.05	0.42	0.08	(0.08)
IMAGE	1.02	1.64	0.38	0.17	(0.64)
IPAC	0.89	0.21	0.08	0.15	0.22
MESSAGE	1.08	0.82	0.43	(0.07)	(0.65)
MiniCAM	0.83	1.80	1.66	0.66	(0.07)
Mean	0.94	0.89	0.47	0.11	(0.27)

Note: Models not listed in table did not report results.

Projections of CO₂ and CH₄ emissions for the U.S., Western Europe, and China are shown from Table 9 to 14. Emissions growth is projected to be faster in China than in the developed regions. Also evident in these comparisons are regional extremes which drive the high and low global projections of emissions of the two GHGs. For example, the projection of CO₂ for China from the FUND model and for the U.S and Europe from the EPPA model are the highest. The wide range of baseline emission projections also provides an additional sensitivity analysis in interpretations of the model results. This set of tables also shows the

Table 9. U.S. Global Fossil Fuel and Cement CO₂ Emissions (GtC)

Model	Scenario	2000	2025	2050	2075	2100
AIM	Reference Case	1.5	1.8	2.3	2.7	3.0
	% Reduction in CO ₂ Only Scenario	0.0%	-6.5%	-21.5%	-27.3%	-37.6%
	% Reduction in Multigas Scenario	0.0%	-3.9%	-15.3%	-22.4%	-23.1%
AMIGA	Reference Case	1.5	2.0	2.5	3.0	3.6
	% Reduction in CO ₂ Only Scenario	0.0%	-8.1%	-28.6%	-38.6%	-50.6%
	% Reduction in Multigas Scenario	0.0%	-6.6%	-23.1%	-29.0%	-37.2%
EDGE	Reference Case	1.6	1.9	NA	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-1.5%	NA	NA	NA
	% Reduction in Multigas Scenario	0.0%	-0.9%	NA	NA	NA
EPPA ^a	Reference Case	1.6	2.3	3.5	5.0	6.3
	% Reduction in CO ₂ Only Scenario	0.0%	-15.8%	-56.5%	-74.0%	-82.5%
	% Reduction in Multigas Scenario	0.0%	-5.6%	-40.8%	-67.0%	-77.3%
FUND	Reference Case	1.6	2.0	2.6	3.2	3.8
	% Reduction in CO ₂ Only Scenario	0.0%	-28.7%	-72.0%	-98.6%	-99.9%
	% Reduction in Multigas Scenario	0.0%	-20.3%	-57.0%	-94.1%	-99.1%
GEMINI	Reference Case	1.6	2.1	2.3	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-20.6%	-44.6%	NA	NA
	% Reduction in Multigas Scenario	0.0%	-9.5%	-26.3%	NA	NA
GRAPE	Reference Case	1.6	1.9	2.3	2.7	3.2
	% Reduction in CO ₂ Only Scenario	0.0%	-1.6%	-15.9%	-56.4%	-80.3%
	% Reduction in Multigas Scenario	0.0%	-1.2%	-6.1%	-31.8%	-66.1%
GTEM	Reference Case	1.5	2.3	3.2	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-36.2%	-70.2%	NA	NA
	% Reduction in Multigas Scenario	0.0%	-24.3%	-58.8%	NA	NA
IMAGE	Reference Case	1.7	2.0	2.1	1.8	1.5
	% Reduction in CO ₂ Only Scenario	0.0%	-19.7%	-53.9%	-67.3%	-76.9%
	% Reduction in Multigas Scenario	0.0%	-10.9%	-44.4%	-57.5%	-67.8%
IPAC	Reference Case	1.4	1.7	1.8	1.5	1.6
	% Reduction in CO ₂ Only Scenario	-10.1%	-23.0%	-35.7%	-47.8%	-57.0%
	% Reduction in Multigas Scenario	0.0%	-18.6%	-31.0%	-43.7%	-50.5%
MERGE	Reference Case	1.6	1.9	2.1	2.3	2.4
	% Reduction in CO ₂ Only Scenario	0.0%	-2.3%	-36.9%	-64.0%	-100.0%
	% Reduction in Multigas Scenario	0.0%	-0.4%	-24.0%	-54.3%	-74.5%
MiniCAM	Reference Case	1.7	2.1	2.3	2.5	2.8
	% Reduction in CO ₂ Only Scenario	-0.7%	-23.6%	-56.6%	-71.0%	-78.9%
	% Reduction in Multigas Scenario	-0.7%	-12.1%	-37.6%	-56.7%	-69.7%
PACE	Reference Case	1.7	2.0	1.7	1.6	1.0
	% Reduction in CO ₂ Only Scenario	-0.4%	-1.6%	-6.4%	-24.7%	-54.8%
	% Reduction in Multigas Scenario	-0.2%	-0.9%	-3.7%	-15.2%	-40.3%
POLES	Reference Case	1.6	1.9	NA	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-15.6%	NA	NA	NA
	% Reduction in Multigas Scenario	0.0%	-9.7%	NA	NA	NA
SGM	Reference Case	1.6	2.3	3.5	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-26.0%	-46.9%	NA	NA
	% Reduction in Multigas Scenario	0.0%	-9.6%	-19.6%	NA	NA

**Table 9. U.S. Global Fossil Fuel and Cement CO₂ Emissions (GtC)
(continued)**

WIA GEM	Reference Case	1.8	2.0	2.3	2.7	3.2
	% Reduction in CO ₂ Only Scenario	-4.2%	-23.3%	-40.4%	-56.4%	-67.0%
	% Reduction in Multigas Scenario	-2.6%	-18.2%	-34.1%	-49.6%	-60.5%
Mean	CO ₂ in Reference Case	1.6	2.0	2.5	2.6	2.9
	% Reduction in CO ₂ Only Scenario	-1.0%	-15.9%	-41.9%	-56.9%	-71.4%
	% Reduction in Multigas Scenario	-0.2%	-9.5%	-30.1%	-47.4%	-60.6%

Note: Models not listed in table did not report results. a. EPPA reports fossil fuel CO₂ only. NA indicates models do not run out to that date.

Table 10. U.S. CH₄ Emissions (MtCe)

Model	Scenario	2000	2025	2050	2075	2100
AIM	Reference Case	134	184	197	162	127
	% Reduction in CO ₂ Only Scenario	0.0%	-13.7%	-28.0%	-32.7%	-41.7%
	% Reduction in Multigas Scenario	0.0%	-17.5%	-43.4%	-59.2%	-61.6%
AMIGA	Reference Case	177	179	194	202	211
	% Reduction in CO ₂ Only Scenario	0.0%	0.0%	0.0%	-4.2%	-8.1%
	% Reduction in Multigas Scenario	0.0%	0.0%	-2.9%	-11.3%	-18.9%
EDGE	Reference Case	168	179	NA	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	0.0%	NA	NA	NA
	% Reduction in Multigas Scenario	0.0%	-7.5%	NA	NA	NA
EPPA	Reference Case	188	242	281	341	398
	% Reduction in CO ₂ Only Scenario	0.0%	-5.3%	-23.3%	-31.2%	-43.1%
	% Reduction in Multigas Scenario	0.0%	-40.3%	-54.6%	-68.5%	-75.4%
FUND	Reference Case	167	201	224	245	318
	% Reduction in CO ₂ Only Scenario	0.0%	0.0%	0.0%	0.0%	0.0%
	% Reduction in Multigas Scenario	0.0%	-8.2%	-21.7%	-41.2%	-22.9%
GEMINI-E3	Reference Case	168	177	157	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-7.5%	-11.3%	NA	NA
	% Reduction in Multigas Scenario	0.0%	-29.4%	-44.9%	NA	NA
GRAPE	Reference Case	167	201	191	126	76
	% Reduction in CO ₂ Only Scenario	0.0%	0.4%	-3.7%	24.9%	65.2%
	% Reduction in Multigas Scenario	0.0%	0.4%	-2.5%	-46.0%	-26.2%
GTEM	Reference Case	161	191	266	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-9.7%	-26.3%	NA	NA
	% Reduction in Multigas Scenario	0.0%	-34.2%	-45.1%	NA	NA
IMAGE	Reference Case	278	252	207	222	240
	% Reduction in CO ₂ Only Scenario	0.0%	-6.2%	-11.6%	-25.3%	-37.9%
	% Reduction in Multigas Scenario	0.0%	-34.5%	-74.4%	-77.4%	-80.8%
IPAC	Reference Case	205	209	164	156	149
	% Reduction in CO ₂ Only Scenario	-3.9%	-18.1%	-18.2%	-29.0%	-37.3%
	% Reduction in Multigas Scenario	-2.7%	-51.8%	-48.7%	-52.4%	-56.4%

Table 10. U.S. CH₄ Emissions (MtCe) (continued)

MiniCAM	Reference Case	182	169	166	184	182
	% Reduction in CO ₂ Only Scenario	-0.3%	-5.5%	-15.1%	-31.0%	-30.4%
	% Reduction in Multigas Scenario	-0.3%	-17.0%	-48.7%	-64.7%	-71.5%
PACE	Reference Case	130	157	135	139	96
	% Reduction in CO ₂ Only Scenario	-0.2%	-0.9%	-3.6%	-13.5%	-29.5%
	% Reduction in Multigas Scenario	-12.5%	-12.7%	-13.8%	-29.8%	-41.2%
POLES	Reference Case	244	266	NA	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-8.7%	NA	NA	NA
	% Reduction in Multigas Scenario	0.0%	-35.6%	NA	NA	NA
SGM	Reference Case	168	183	199	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-6.2%	-9.9%	NA	NA
	% Reduction in Multigas Scenario	0.0%	-55.4%	-58.6%	NA	NA
WIAGEM	Reference Case	238	338	480	658	843
	% Reduction in CO ₂ Only Scenario	-8.9%	-43.0%	-61.9%	-73.0%	-80.0%
	% Reduction in Multigas Scenario	-16.0%	-56.4%	-72.8%	-81.5%	-86.6%
Mean	Reference Case	185	209	220	244	264
	% Reduction in CO ₂ Only Scenario	-0.9%	-8.3%	-16.4%	-21.5%	-24.3%
	% Reduction in Multigas Scenario	-2.1%	-26.7%	-40.9%	-53.2%	-54.2%

Note: Models not listed in table did not report results. NA indicates models do not run out to that date.

Table 11. EU-15 Global Fossil Fuel and Cement CO₂ Emissions (GtC)

Model	Scenario	2000	2025	2050	2075	2100
AIM	Reference Case	0.9	1.0	1.3	1.5	1.8
	% Reduction in CO ₂ Only Scenario	0.0%	-7.4%	-41.9%	-63.2%	-70.7%
	% Reduction in Multigas Scenario	0.0%	-4.0%	-20.2%	-56.8%	-65.1%
EDGE	Reference Case	0.9	1.0	NA	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-0.4%	NA	NA	NA
	% Reduction in Multigas Scenario	0.0%	-0.3%	NA	NA	NA
EPPA ^a	Reference Case	1.0	1.4	2.0	2.7	3.3
	% Reduction in CO ₂ Only Scenario	0.0%	-14.6%	-46.5%	-65.1%	-77.4%
	% Reduction in Multigas Scenario	0.0%	-6.9%	-32.0%	-56.3%	-68.9%
GEMINI	Reference Case	0.9	1.0	1.1	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-8.1%	-17.2%	NA	NA
	% Reduction in Multigas Scenario	0.0%	-3.7%	-8.2%	NA	NA
GRAPE	Reference Case	0.9	1.1	1.2	1.2	1.3
	% Reduction in CO ₂ Only Scenario	0.0%	-3.0%	-5.9%	-52.8%	-79.0%
	% Reduction in Multigas Scenario	0.0%	-2.8%	-1.4%	-21.0%	-50.6%
GTEM	Reference Case	0.9	1.2	1.6	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-21.7%	-55.9%	NA	NA
	% Reduction in Multigas Scenario	0.0%	-12.9%	-41.2%	NA	NA
IMAGE	Reference Case	1.0	1.1	1.2	1.0	0.8
	% Reduction in CO ₂ Only Scenario	0.0%	-14.6%	-44.3%	-54.9%	-63.4%
	% Reduction in Multigas Scenario	0.0%	-8.2%	-35.4%	-46.9%	-52.5%

**Table 11. EU-15 Global Fossil Fuel and Cement CO₂ Emissions (GtC)
(continued)**

MERGE	Reference Case	0.9	1.1	1.1	0.8	0.6
	% Reduction in CO ₂ Only Scenario	0.0%	-3.6%	-27.4%	-42.9%	-59.7%
	% Reduction in Multigas Scenario	0.0%	-1.3%	-7.0%	-23.2%	-44.1%
MiniCAM	Reference Case	1.1	1.1	1.2	1.0	1.0
	% Reduction in CO ₂ Only Scenario	-0.4%	-18.4%	-56.1%	-69.4%	-78.1%
	% Reduction in Multigas Scenario	-0.4%	-9.5%	-35.5%	-55.0%	-69.4%
PACE	Reference Case	1.0	0.9	0.7	0.5	0.4
	% Reduction in CO ₂ Only Scenario	-0.2%	-0.7%	-2.6%	-13.5%	-34.0%
	% Reduction in Multigas Scenario	-0.1%	-0.4%	-1.5%	-7.9%	-22.8%
POLES	Reference Case	0.9	1.1	NA	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-12.4%	NA	NA	NA
	% Reduction in Multigas Scenario	0.0%	-9.0%	NA	NA	NA
SGM	Reference Case	1.0	1.1	1.0	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-14.4%	-24.0%	NA	NA
	% Reduction in Multigas Scenario	0.0%	-6.4%	-13.2%	NA	NA
WIAGEM	Reference Case	1.3	1.5	1.7	1.8	2.2
	% Reduction in CO ₂ Only Scenario	-4.2%	-23.3%	-40.4%	-56.3%	-67.0%
	% Reduction in Multigas Scenario	-2.6%	-18.2%	-34.1%	-49.6%	-60.5%
Mean	CO ₂ in Reference Case	1.0	1.1	1.3	1.3	1.4
	% Reduction in CO ₂ Only Scenario	-0.4%	-11.0%	-32.9%	-52.3%	-66.2%
	% Reduction in Multigas Scenario	-0.2%	-6.4%	-20.9%	-39.6%	-54.2%

Note: Models not listed in table did not report results. a. EPPA reports fossil fuel CO₂ only. NA indicates models do not run out to that date.

Table 12. EU-15 CH₄ Emissions (MtCe)

Model	Scenario	2000	2025	2050	2075	2100
AIM	Reference Case	97.0	121.4	115.2	91.5	72.0
	% Reduction in CO ₂ Only Scenario	0.0%	-15.9%	-24.7%	-35.4%	-41.0%
	% Reduction in Multigas Scenario	0.0%	-22.1%	-49.7%	-72.0%	-82.3%
EDGE	Reference Case	101.7	90.4	NA	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	0.0%	NA	NA	NA
	% Reduction in Multigas Scenario	0.0%	-3.9%	NA	NA	NA
EPPA	Reference Case	107.2	126.9	141.8	158.7	194.9
	% Reduction in CO ₂ Only Scenario	0.0%	-5.4%	-18.9%	-24.7%	-49.3%
	% Reduction in Multigas Scenario	0.0%	-44.1%	-55.5%	-64.6%	-73.3%
GEMINI-E3	Reference Case	101.7	89.6	78.4	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-2.6%	-3.9%	NA	NA
	% Reduction in Multigas Scenario	0.0%	-15.2%	-19.3%	NA	NA
GRAPE	Reference Case	104.5	119.5	87.8	57.4	48.0
	% Reduction in CO ₂ Only Scenario	0.0%	0.2%	-10.6%	-4.8%	0.8%
	% Reduction in Multigas Scenario	0.0%	0.2%	-9.0%	-45.8%	-51.0%

Table 12. EU-15 CH₄ Emissions (MtCe) (continued)

GTEM	Reference Case	91.1	88.6	86.1	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-6.5%	-13.8%	NA	NA
	% Reduction in Multigas Scenario	0.0%	-19.2%	-28.6%	NA	NA
IMAGE	Reference Case	136.0	126.5	106.0	94.5	88
	% Reduction in CO ₂ Only Scenario	0.0%	-1.6%	-3.8%	-6.3%	-9.1%
	% Reduction in Multigas Scenario	0.0%	-19.8%	-26.4%	-39.7%	-39.8%
MiniCAM	Reference Case	128.5	109.5	100.0	89.2	81.2
	% Reduction in CO ₂ Only Scenario	-0.1%	-7.4%	-17.4%	-27.0%	-35.3%
	% Reduction in Multigas Scenario	-0.1%	-9.9%	-33.1%	-47.0%	-57.4%
PACE	Reference Case	82.7	86.2	77.6	62.4	55.2
	% Reduction in CO ₂ Only Scenario	-0.1%	-0.4%	-1.7%	-4.7%	-9.6%
	% Reduction in Multigas Scenario	-6.4%	-6.8%	-7.4%	-12.8%	-18.5%
POLES	Reference Case	101.9	96.4	NA	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-2.1%	NA	NA	NA
	% Reduction in Multigas Scenario	0.0%	-20.1%	NA	NA	NA
SGM	Reference Case	101.7	88.7	75.7	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-3.0%	-4.8%	NA	NA
	% Reduction in Multigas Scenario	0.0%	-34.1%	-41.7%	NA	NA
WIAGEM	Reference Case	148.3	176.8	274.0	349.4	450.0
	% Reduction in CO ₂ Only Scenario	-8.9%	-43.2%	-61.9%	-73.0%	-80.0%
	% Reduction in Multigas Scenario	-16.0%	-56.6%	-72.8%	-81.5%	-86.6%
Mean	Reference Case	108.6	110.0	114.3	129.0	141.3
	% Reduction in CO ₂ Only Scenario	-0.8%	-7.3%	-16.1%	-25.1%	-31.9%
	% Reduction in Multigas Scenario	-1.9%	-21.0%	-34.4%	-51.9%	-58.4%

Note: Models not listed in table did not report results. NA indicates models do not run out to that date.

Table 13. China Global Fossil Fuel and Cement CO₂ Emissions (GtC)

Model	Scenario	2000	2025	2050	2075	2100
AIM	Reference Case	1.0	1.4	1.7	1.9	2.1
	% Reduction in CO ₂ Only Scenario	0.0%	-24.9%	-39.0%	-57.2%	-67.9%
	% Reduction in Multigas Scenario	0.0%	-18.8%	-32.0%	-36.3%	-64.3%
EDGE	Reference Case	1.1	2.1	NA	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-7.4%	NA	NA	NA
	% Reduction in Multigas Scenario	0.0%	-3.1%	NA	NA	NA
EPPA*	Reference Case	0.8	1.7	2.8	3.4	3.6
	% Reduction in CO ₂ Only Scenario	0.0%	-39.0%	-73.0%	-83.4%	-87.9%
	% Reduction in Multigas Scenario	0.0%	-23.8%	-61.7%	-79.4%	-84.2%
FUND	Reference Case	1.4	2.5	4.3	7.4	11.4
	% Reduction in CO ₂ Only Scenario	-0.1%	-75.7%	-99.6%	-100.0%	-100.0%
	% Reduction in Multigas Scenario	-0.1%	-60.6%	-96.5%	-100.0%	-100.0%
GEMINI	Reference Case	1.0	2.0	2.6	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-62.9%	-79.1%	NA	NA
	% Reduction in Multigas Scenario	0.0%	-48.3%	-68.9%	NA	NA

**Table 13. China Global Fossil Fuel and Cement CO₂ Emissions (GtC)
(continued)**

GRAPE	Reference Case	0.9	1.7	2.3	2.6	3.3
	% Reduction in CO ₂ Only Scenario	0.0%	-3.2%	-24.2%	-80.5%	-93.8%
	% Reduction in Multigas Scenario	0.0%	-2.3%	-8.1%	-68.0%	-89.2%
GTEM	Reference Case	0.9	2.2	4.2	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-55.4%	-79.5%	NA	NA
	% Reduction in Multigas Scenario	0.0%	-44.3%	-70.9%	NA	NA
IMAGE	Reference Case	1.2	2.5	3.2	3.1	2.9
	% Reduction in CO ₂ Only Scenario	0.0%	-19.7%	-50.2%	-63.3%	-70.6%
	% Reduction in Multigas Scenario	0.0%	-10.5%	-42.8%	-55.0%	-62.2%
IPAC	Reference Case	1.0	2.2	3.1	3.3	3.2
	% Reduction in CO ₂ Only Scenario	-8.9%	-26.3%	-46.9%	-64.5%	-76.5%
	% Reduction in Multigas Scenario	0.0%	-20.3%	-40.2%	-59.1%	-70.3%
MERGE	Reference Case	0.8	1.4	2.3	3.3	4.5
	% Reduction in CO ₂ Only Scenario	0.0%	-12.8%	-47.8%	-77.1%	-100.0%
	% Reduction in Multigas Scenario	0.0%	-8.5%	-38.0%	-68.0%	-85.6%
MiniCAM	Reference Case	1.0	2.2	2.6	3.0	3.4
	% Reduction in CO ₂ Only Scenario	-0.4%	-40.2%	-68.9%	-78.8%	-83.9%
	% Reduction in Multigas Scenario	-0.4%	-22.5%	-53.2%	-68.9%	-78.0%
POLES	Reference Case	1.1	2.5	NA	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-18.0%	NA	NA	NA
	% Reduction in Multigas Scenario	0.0%	-11.7%	NA	NA	NA
SGM	Reference Case	0.8	1.9	2.7	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-52.7%	-64.4%	NA	NA
	% Reduction in Multigas Scenario	0.0%	-32.0%	-50.4%	NA	NA
WIAGEM	Reference Case	1.1	1.6	2.0	2.7	3.3
	% Reduction in CO ₂ Only Scenario	-4.2%	-23.4%	-40.4%	-56.4%	-67.0%
	% Reduction in Multigas Scenario	-2.6%	-18.3%	-34.1%	-49.6%	-60.5%
Mean	CO ₂ in Reference Case	1.0	2.0	2.8	3.4	4.2
	% Reduction in CO ₂ Only Scenario	-1.0%	-33.0%	-59.4%	-73.5%	-83.1%
	% Reduction in Multigas Scenario	-0.2%	-23.2%	-49.7%	-64.9%	-77.1%

Note: Models not listed in table did not report results. a. EPPA reports fossil fuel CO₂ only. NA indicates models do not run out to that date.

Table 14. China CH₄ Emissions (MtCe)

Model	Scenario	2000	2025	2050	2075	2100
AIM	Reference Case	288.5	416.0	487.4	475.4	428.7
	% Reduction in CO ₂ Only Scenario	0.0%	-7.1%	-11.9%	-24.2%	-32.2%
	% Reduction in Multigas Scenario	0.0%	-11.6%	-35.4%	-48.7%	-47.1%
EDGE	Reference Case	253.5	362.5	NA	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	0.0%	NA	NA	NA
	% Reduction in Multigas Scenario	0.0%	-2.9%	NA	NA	NA

Table 14. China CH₄ Emissions (MtCe) (continued)

EPPA	Reference Case	235.7	476.3	804.9	945.0	844.8
	% Reduction in CO ₂ Only Scenario	0.0%	-13.5%	-23.8%	-25.8%	-30.7%
	% Reduction in Multigas Scenario	0.0%	-56.1%	-67.2%	-71.1%	-74.8%
FUND	Reference Case	207.3	286.4	431.0	609.3	747.6
	% Reduction in CO ₂ Only Scenario	0.0%	0.0%	0.0%	0.0%	0.0%
	% Reduction in Multigas Scenario	0.0%	-1.6%	-3.4%	-5.5%	-2.1%
GEMINI	Reference Case	253.5	383.1	514.6	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-14.8%	-10.6%	NA	NA
	% Reduction in Multigas Scenario	0.0%	-32.1%	-37.0%	NA	NA
GRAPE	Reference Case	252.0	349.6	450.8	521.0	668.9
	% Reduction in CO ₂ Only Scenario	0.0%	-0.7%	-6.9%	-29.6%	-51.8%
	% Reduction in Multigas Scenario	0.0%	1.6%	-35.9%	-50.9%	-62.9%
GTEM	Reference Case	213.1	409.4	644.7	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-29.5%	-37.3%	NA	NA
	% Reduction in Multigas Scenario	0.0%	-59.1%	-69.3%	NA	NA
IMAGE	Reference Case	265.0	346.5	387.0	398.0	375.0
	% Reduction in CO ₂ Only Scenario	0.4%	-5.8%	-10.9%	-18.0%	-13.6%
	% Reduction in Multigas Scenario	0.4%	-24.7%	-43.4%	-59.9%	-54.9%
IPAC	Reference Case	310.4	534.7	665.1	604.7	451.4
	% Reduction in CO ₂ Only Scenario	-2.2%	-6.9%	-9.7%	-13.1%	-15.1%
	% Reduction in Multigas Scenario	-1.6%	-26.6%	-30.3%	-33.2%	-38.7%
MiniCAM	Reference Case	229.6	275.9	294.2	293.3	254.8
	% Reduction in CO ₂ Only Scenario	-0.7%	-8.5%	-9.8%	-12.4%	-4.7%
	% Reduction in Multigas Scenario	-0.7%	-24.0%	-46.4%	-60.4%	-63.4%
POLES	Reference Case	184.4	230.4	NA	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-9.2%	NA	NA	NA
	% Reduction in Multigas Scenario	0.0%	-31.2%	NA	NA	NA
SGM	Reference Case	253.5	362.8	472.2	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-15.4%	-20.9%	NA	NA
	% Reduction in Multigas Scenario	0.0%	-76.5%	-81.9%	NA	NA
WIAGEM	Reference Case	295.9	480.8	738.5	1140.0	1491.0
	% Reduction in CO ₂ Only Scenario	-8.9%	-43.2%	-61.9%	-73.0%	-80.0%
	% Reduction in Multigas Scenario	-16.0%	-56.6%	-72.8%	-81.5%	-86.6%
Mean	Reference Case	249.4	378.0	535.5	623.3	657.8
	% Reduction in CO ₂ Only Scenario	-0.9%	-11.9%	-18.5%	-24.5%	-28.5%
	% Reduction in Multigas Scenario	-1.4%	-30.9%	-47.5%	-51.4%	-53.8%

Note: Models not listed in table did not report results. NA indicates models do not run out to that date.

comparison between the CO₂-only and multigas mitigation scenarios, again as percent reductions from reference case projections, for emissions of the two main gases for the U.S., Western Europe, and China.

The last two tables provide economic cost comparisons across most of the EMF- 21 economy-energy models. Table 15 shows carbon prices (2000

\$US/tCe) for both the CO₂-only and Multigas scenarios. For all models except one², the inclusion of NCGGs in the multigas scenarios decreases the marginal costs through the century of meeting the stabilization target. In 2025, the carbon price reduction in the multigas scenarios as a percentage of the price in the CO₂-only scenario ranges from a low of 15 percent in COMBAT to over 70 percent in SGM. The average carbon price reduction across 18 models for 2025 is 48 percent showing that climate mitigation under a multigas policy leads to an appreciable reduction in marginal costs versus a CO₂-only mitigation policy. In 2100, there are 12 models reporting results given a range from a low of almost zero percent in FUND to 56 percent in EPPA with an average price reduction of 39 percent for all 12 models. Table 16 provides another economic cost comparison between the CO₂-only and multigas scenarios in terms of percentage reduction from reference global GDP. These cost estimates are overly optimistic because the scenario implementations assume perfect global GHG emissions trading starting immediately (in some cases in 2000) and continuing for the rest of the century which is very unrealistic. The result of this assumption is to produce a global, least-cost estimate where there is an equal marginal cost across all regions and countries. Any restriction in the number of countries or regions participating this system would increase both the carbon permit price and the GDP costs. However, the percentage reductions in costs resulting from controlling multiple

Table 15. Carbon Permit Price (2000 \$US/tCe)

Model	Scenario	2000	2025	2050	2075	2100
AIM	CO ₂ Only Scenario	0.0	112.0	485.9	721.5	770.2
	Multigas Scenario	0.0	65.0	302.7	492.3	524.1
	% Reduction	-	42%	38%	32%	32%
AMIGA	CO ₂ Only Scenario	0.0	72.5	114.0	135.0	147.0
	Multigas Scenario	0.0	49.0	77.0	91.0	99.0
	% Reduction	-	32%	32%	33%	33%
COMBAT	CO ₂ Only Scenario	39.1	79.2	129.5	246.9	531.1
	Multigas Scenario	33.2	67.2	109.9	209.5	450.9
	% Reduction	15%	15%	15%	15%	15%
EDGE	CO ₂ Only Scenario	0.0	5.5	NA	NA	NA
	Multigas Scenario	0.0	2.9	NA	NA	NA
	% Reduction	-	47%	NA	NA	NA
EPPA*	CO ₂ Only Scenario	0.0	110.7	522.3	1,607.1	4,693.3
	Multigas Scenario	0.0	42.2	326.2	754.9	2,056.0
	% Reduction	-	62%	38%	53%	56%

2. FUND has lower short run carbon prices in the multigas case, but this switches to lower prices in the CO₂-only case as the scenario continues out to 2100. However, the net present value of total costs is still lower with the multigas case than in the CO₂-only case. See Tol in this volume for more details.

Table 15. Carbon Permit Price (2000 \$US/tCe) (continued)

FUND	CO ₂ Only Scenario	0.0	482.2	210.5	21.1	0.0
	Multigas Scenario	0.0	394.0	320.5	54.0	0.3
	% Reduction	-	18%	-52%	-156%	-
GEMINI-E3	CO ₂ Only Scenario	0.0	88.9	301.7	NA	NA
	Multigas Scenario	0.0	31.5	112.6	NA	NA
	% Reduction	-	65%	63%	NA	NA
GRAPE	CO ₂ Only Scenario	0.0	12.4	67.2	459.5	2,018.7
	Multigas Scenario	0.0	6.9	36.7	312.5	1,285.0
	% Reduction	-	45%	45%	32%	36%
GTEM	CO ₂ Only Scenario	0.0	219.7	1,806.8	NA	NA
	Multigas Scenario	0.0	119.6	642.0	NA	NA
	% Reduction	-	46%	64%	NA	NA
IMAGE	CO ₂ Only Scenario	0.0	101.8	191.9	319.8	626.6
	Multigas Scenario	0.0	53.1	139.0	208.5	288.9
	% Reduction	-	48%	28%	35%	54%
IPAC	CO ₂ Only Scenario	0.0	87.5	180.0	266.5	350.0
	Multigas Scenario	0.0	37.5	100.0	168.5	210.0
	% Reduction	-	57%	44%	37%	40%
MERGE	CO ₂ Only Scenario	0.0	22.8	81.4	300.9	1,000.0
	Multigas Scenario	0.0	10.7	38.2	139.6	484.9
	% Reduction	-	53%	53%	54%	52%
MESSAGE	CO ₂ Only Scenario	0.0	42.1	209.0	703.1	422.9
	Multigas Scenario	0.0	13.1	75.0	396.8	270.7
	% Reduction	-	69%	64%	44%	36%
MiniCAM	CO ₂ Only Scenario	0.0	25.1	146.4	314.1	489.0
	Multigas Scenario	0.0	10.2	79.9	228.5	401.8
	% Reduction	-	59%	45%	27%	18%
PACE	CO ₂ Only Scenario	0.7	2.8	10.3	38.9	131.2
	Multigas Scenario	0.4	1.5	5.7	21.6	72.8
	% Reduction	44%	44%	44%	44%	45%
POLES	CO ₂ Only Scenario	0.0	86.1	NA	NA	NA
	Multigas Scenario	0.0	53.9	NA	NA	NA
	% Reduction	-	37%	NA	NA	NA
SGM	CO ₂ Only Scenario	0.0	231.0	483.7	NA	NA
	Multigas Scenario	0.0	65.2	136.6	NA	NA
	% Reduction	-	72%	72%	NA	NA
WIAGEM	CO ₂ Only Scenario	9.4	41.5	86.5	146.1	221.0
	Multigas Scenario	2.5	16.2	37.2	65.3	99.7
	% Reduction	73%	61%	57%	55%	55%
Mean	CO ₂ Only Scenario	2.7	101.3	314.2	406.2	877.0
	Multigas Scenario	2.0	57.8	158.7	241.8	480.3
	% Reduction	44%	48%	41%	23%	39%

Note: ^a EPPA reported data in 1997 \$US. NA indicates models do not run out to that date.

Table 16. Global GDP (2000 \$US Trillions)

Model	Scenario	2000	2025	2050	2075	2100
AIM	Reference Case	31.2	49.6	76.0	112.1	155.5
	% Reduction in CO ₂ Only Scenario	0.0%	-0.2%	-1.4%	-4.6%	-9.6%
	% Reduction in Multigas Scenario	0.0%	-0.1%	-0.7%	-2.2%	-5.1%
AMIGA	Reference Case	33.0	61.2	111.1	185.1	295.9
	% Reduction in CO ₂ Only Scenario	0.0%	0.0%	0.0%	0.0%	0.0%
	% Reduction in Multigas Scenario	0.0%	0.0%	0.0%	0.0%	0.0%
COMBAT	Reference Case	26.7	43.1	62.0	88.6	125.5
	% Reduction in CO ₂ Only Scenario	-1.0%	-1.9%	-3.3%	-7.2%	-12.0%
	% Reduction in Multigas Scenario	-1.0%	-1.8%	-3.0%	-6.8%	-11.7%
EDGE	Reference Case	32.2	68.2	NA	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-0.1%	NA	NA	NA
	% Reduction in Multigas Scenario	0.0%	0.0%	NA	NA	NA
EPPA*	Reference Case	32.1	72.0	150.0	267.4	427.5
	% Reduction in CO ₂ Only Scenario	0.0%	-0.8%	-3.3%	-6.6%	-10.6%
	% Reduction in Multigas Scenario	0.0%	-0.4%	-2.0%	-4.5%	-7.7%
FUND	Reference Case	41.0	77.6	126.4	201.1	306.5
	% Reduction in CO ₂ Only Scenario	0.0%	-3.5%	-7.3%	-9.2%	-10.4%
	% Reduction in Multigas Scenario	0.0%	-1.9%	-5.1%	-7.2%	-8.2%
GEMINI-E3	Reference Case	33.3	71.0	118.8	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-0.2%	-0.6%	NA	NA
	% Reduction in Multigas Scenario	0.0%	-0.1%	-0.2%	NA	NA
GRAPE	Reference Case	31.1	55.0	88.8	138.6	224.8
	% Reduction in CO ₂ Only Scenario	0.0%	-0.1%	-0.9%	-3.9%	-11.7%
	% Reduction in Multigas Scenario	0.0%	-0.1%	-0.4%	-2.4%	-8.2%
GTEM	Reference Case	34.1	73.1	148.1	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-1.2%	-7.1%	NA	NA
	% Reduction in Multigas Scenario	0.0%	-0.5%	-3.3%	NA	NA
IMAGE ^b	Reference Case	32.3	71.9	129.5	195.9	279.5
IPAC	Reference Case	28.0	54.9	106.2	175.8	248.0
	% Reduction in CO ₂ Only Scenario	-0.3%	-0.8%	-1.2%	-1.6%	-2.4%
	% Reduction in Multigas Scenario	-0.2%	-0.6%	-1.0%	-1.4%	-1.8%
MERGE	Reference Case	33.4	65.1	116.3	212.1	382.7
	% Reduction in CO ₂ Only Scenario	0.0%	-0.1%	-0.5%	-0.4%	-0.7%
	% Reduction in Multigas Scenario	0.0%	0.0%	-0.2%	-0.3%	-0.3%
MESSAGE ^b	Reference Case	34.0	70.1	131.4	208.7	281.9
MiniCAM ^b	Reference Case	34.2	68.4	132.5	204.2	275.2
POLES ^b	Reference Case	45.2	99.3	NA	NA	NA
SGM	Reference Case	32.3	58.9	91.2	NA	NA
	% Reduction in CO ₂ Only Scenario	0.0%	-0.6%	-0.9%	NA	NA
	% Reduction in Multigas Scenario	0.0%	-0.1%	-0.2%	NA	NA
WIAGEM	Reference Case	26.4	58.8	162.6	343.6	542.4
	% Reduction in CO ₂ Only Scenario	-0.1%	-0.2%	-0.3%	-0.4%	-0.5%
	% Reduction in Multigas Scenario	-0.1%	-0.1%	-0.2%	-0.2%	-0.4%

Table 16. Global GDP (2000 \$US Trillions) (continued)

Mean	GDP in Reference Case	33.0	65.8	116.7	194.4	295.4
	% Reduction GDP in CO ₂ Only Scenario-0.1%	-0.7%	-0.7%	-2.2%	-3.8%	-6.4%
	% Reduction GDP in Multigas Scenario-0.1%	-0.4%	-0.4%	-1.4%	-2.8%	-4.8%

Notes: a. EPPA reported data in 1997 \$US. b. Models did not report changes in GDP. NA indicates models do not run out to that date.

GHG gas emissions rather than just carbon are still meaningful. In 2025 for the multigas scenario, 13 models report a range of GDP reduction from less than 0.01 percent in AMIGA to 1.9 percent in FUND with an average across the models of 0.4 percent. In 2100, when greater emission reductions are needed, the percent reduction in global GDP across nine models that reported data is from less than 0.01 percent again in AMIGA to 12 percent in COMBAT with an average of 4.8 percent. The reduction in GDP in the CO₂-only scenario is greater than the multigas scenario for all models showing similar cost-saving in GDP effects for a multigas strategy.

7. UNDERSTANDING MODEL DIFFERENCES

The contributions of the different GHGs change sharply over time – but there is considerable spread among the different models. This can be seen in Tables 5 to 7. Many models project relatively early reductions of CH₄ in the multigas case. However, the subset of models that do not use GWPs as metrics for the relative contributions of the different gases to the overall target, but do assume intertemporal optimization in minimizing abatement costs, do not start to reduce CH₄ emissions substantially until the end of the period. The reason for this result is that in aiming at the long-term target, it does not pay to engage in early CH₄ emission reductions because CH₄ has a short atmospheric life-time (about ten years). That is, since the benefits to reducing a radiative forcing in the atmosphere are more immediately felt with CH₄ mitigation, these models “wait” to reduce these emissions as the target approaches. In their calculations, there is not much benefit in reducing CH₄ early in the simulation.

In the GWP-based models, however, CH₄ emission reductions are attractive early based on the availability of low cost emission reduction options. It should be noted that for N₂O, reductions in the first decades also seem to be substantial – and here the results do not differ among the different categories of models. This is due to the fact that, for N₂O, the use of GWPs versus direct contributions to radiative forcing as a way of weighing the contributions of the different gases to climate change does not make much difference because both gases have similar (medium length) lifetimes in the atmosphere.

8. OVERVIEW OF SPECIAL ISSUE

8.1 Data Development Papers

There are four data development papers in this volume. Methane and nitrous oxide emissions contribute significantly to greenhouse gas emissions globally, with an estimated total of about 1,600 and 950 MtCe in 2000, respectively. Scheehle and Kruger incorporate detailed country prepared inventories and projections of methane and nitrous oxide emissions into an overall global estimation framework. Delhotal, de la Chesnaye, Gardiner, Bates, and Sankovski develop regionally adjusted costs per mitigation option and marginal abatement cost curves for NCGGs by region for use in economic models. The result is worldwide cost estimates for methane and nitrous oxide from waste, energy, and the industrial sectors. Ottinger Schaefer, Godwin, and Harnisch estimate global emissions of HFCs, PFCs, and SF₆ from twelve source categories from 1990 to 2020, and provide guidance for projecting emissions beyond 2020. They also present 2010 and 2020 marginal abatement cost curves for the same source categories. Finally, DeAngelo, de la Chesnaye, Beach, Sommer and Murray presents cost estimates for mitigating nitrous oxide from cropland soils, and methane from livestock enteric fermentation, manure management and rice cultivation for major world regions.

8.2 Biological Sinks Papers

There are two papers focused on terrestrial sinks in this volume. These papers present stand alone analyses of terrestrial sink potentials as well as inputs to the global economic modeling teams represented in the study. Sohngen and Sedjo consider how sequestration fits into a global program to reduce net emissions of GHGs. Because forestry has the potential to sequester substantial carbon at prices consistent with current estimates of potential greenhouse gas abatement policies, it is useful to ask how forestry fits within the set of available policy tools. Sathaye, Makundi, Dale, Chan, and Andrasko report on the global potential for carbon sequestration in forest plantations and the reduction of carbon emissions from deforestation, in response to six carbon price scenarios from 2000 to 2100. Three mitigation options—long- and short-rotation forestry, and the reduction of deforestation—were analyzed using a global dynamic partial equilibrium model (GCOMAP).

8.3 Global Model Papers

There are 19 energy-economic model based analyses papers (see Table 3) in this volume. Most of these papers³ include at least three of the core scenarios

3. Two exceptions are the papers by Reilly, et al. that analyzes an interesting NCGG-only policy option (results for the EMF- 21 core scenarios were in fact provided for the EPPA model and are included in this overview) and the paper by Shukla, et al. that focuses on reference case GHG emissions and mitigation options in India in considerable detail.

– the modelers’ reference scenario, the CO₂-only mitigation target, and the multigas mitigation target. In addition, as indicated in Table 4, six of these papers include analyses of the GWP versus radiative forcing methods for aggregating the contributions of the different GHGs.

A large number of additional topics are addressed in the individual papers. For example, Criqui, Russ and Deybe derive agricultural sector Marginal Abatement Cost curves 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. Bernard, Vielle, and Viguié look at how the process of allocating initial emission quotas affects the distribution of costs across regions even with the introduction of NCGGs and international emission trading. Tol examines how the inclusion of SO₂ and sulfate aerosols makes policy targets substantially harder to achieve. The costs of emission reduction vary greatly with the choice of stabilization target.

Manne and Richels find that mitigation costs are substantially higher when the focus is on the rate of change rather than on absolute change. The timing of costs is also significantly changed. Correspondingly, Jensen shows that multigas flexibility may be particularly important if climate policies reflect not only long-term stabilization, but also the rate at which the climate changes, as the latter may require large reductions in emissions in the short term. Rao and Riahi identify a portfolio of measures in the energy, industry and agricultural sectors for achieving the proposed forcing target.

Van Vuuren, Eickhout, Lucas and den Elzen present a set of multigas mitigation scenarios that aim for stabilization of greenhouse gas radiative forcing in 2150 at levels from 3.7 to 5.3 Wm⁻². Within the assumptions used in this study, the NCGGs contribution to total reduction is very large under less stringent targets (up to 60 percent), but declines under stringent targets. Reilly, Sarofim, Paltsev, and Prinn consider instead a policy that is less comprehensive in term of GHGs, including only the NCGGs, but one that is geographically comprehensive. Abating NCGGs may be seen as less of a threat to economic development and therefore it may be possible to involve developing countries in such a policy even though they have resisted limits on CO₂ emissions. Böhringer, Löschel, and Rutherford identify very large insurance premia when hedging against too rapid rates of temperature increase.

Hansen and Laitner examine the impact of technology policies on the full basket of worldwide greenhouse emissions over the 21st century. Jakeman and Fisher analyze the economic impact of meeting a radiative forcing target using policies that focus on carbon dioxide emissions only and policies that focus on all major greenhouse gases and sources, including land use change and forestry emissions. Smith and Wigley examine the role of climate forcing agents other than carbon dioxide using the MiniCAM integrated assessment model. Non-CO₂ greenhouse gas forcing is dominated by methane and tropospheric ozone. Assumptions about the prevalence of methane recovery and local air pollution controls are a

critical determinant of reference forcing from these two gases. Fawcett and Sands develop an extension of the Second Generation Model (SGM) including advanced fossil generating technologies with CO₂ capture and storage in the US region of the SGM and use it to analyze the GHG mitigation policies.

Shukla, Garg, Kapshe, and Nair analyze future trends (2000-2030) in methane and nitrous oxide emissions across four scenarios that have been developed for India. The major sources of methane emissions are livestock, but the share of emissions from municipal solid waste is expected to rise with increasing urbanization. Nitrous oxide emissions arise chiefly from synthetic fertilizer use and from field burning of agricultural residue. The paper also presents mitigation analysis for CO₂ and CH₄ and long-term, hundred-year analysis for CO₂, CH₄ and N₂O.

Jiang, Hu, and Songli also show, using an energy-economy model with a focus on China, that multigas mitigation policies could have lower cost compared with CO₂-only mitigation policies. They estimate there could be a 30 percent lower carbon price for multigas mitigation which results in reduced GDP losses by 23 percent in 2100.

Fujino, Nair, Kainuma, Masui, and Matsuoka, use a multi-regional, multi-sectoral and multigas computable general equilibrium model combined with a simple climate model to simulate long-term climate stabilization emission paths. In addition to demonstrating the cost effectiveness of a multigas policy, they show that even a CO₂-only mitigation scenario will reduce not only CO₂ emissions but NCGGs emissions simultaneously due primarily to changes in the energy system. Kurosawa analyzes the flexibility in implementing climate change mitigation policies through an evaluation of three key mitigation dimensions; space, time and gas species. The paper also discusses the implications on gas life as well as abatement timing uncertainty on costs and technological availability.

Aahaim, Fuglestedt and Godal take on the debate on the use of Global Warming Potentials (GWPs) used in current climate policies and evaluate the efficiency of alternative methods. They show that a multigas approach with GWPs reduces the costs by eight percent when compared with CO₂-only reductions, whereas the costs may be reduced by an additional 2 percent by using flexible metrics. If compared with the use of GWPs, they find that efficient weights increase the cost savings of including non-CO₂ gases in climate policy by 15-40 percent, depending on the stabilization goal. Finally, Kemfert, Truong, and Bruckner investigate the long-term economic consequences of both climate change impacts and mitigation efforts by applying the multi-regional, multi-sectoral integrated assessment model based on the GTAP data coupled with the reduced-form multigas climate model.

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Methane and Nitrous Oxide Mitigation in Agriculture

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This analysis presents cost estimates for mitigating nitrous oxide from cropland soils, and methane from livestock enteric fermentation, manure management and rice cultivation for major world regions. Total estimated global mitigation potential is approximately 64 MtCeq. in 2010 at negative or zero costs, 141 MtCeq. at \$200/TCeq., and up to 168 MtCeq. at higher costs. Costs for individual options range from negative to positive in nearly every region, depending on emission, yield, input, labor, capital cost, and outside revenue effects. Future assessment requires improved accounting for multiple greenhouse gas effects, heterogeneity of emissions and yields, baseline management conditions, identification of options that generate farmer and societal benefits, adoption feasibility, and commodity market effects into mitigation decisions.

1. INTRODUCTION

Agriculture represents a significant source of the world's total anthropogenic greenhouse gas (GHG) emissions, and emissions from this sector are projected to increase for the foreseeable future. To date, representation of agriculture in multi-sectoral GHG mitigation analyses has been crude or absent. It is challenging to assess GHG mitigation in agriculture at the aggregated national and international scales due to (1) the high degree of spatial and temporal heterogeneity in farming practices and resultant emissions that are rarely directly

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monitored; (2) paucity of regionally-specific cost data to implement identifiable mitigation options; and (3) difficulty in estimating the expected level of response to financial incentives (e.g., carbon price), as there are implementation barriers to GHG mitigation in agriculture that are often unforeseen and difficult to quantify.

Only a few studies have estimated the GHG mitigation potential and associated costs for agriculture across world regions, and these address only some emission sources and some regions. The Intergovernmental Panel on Climate Change (IPCC) (see Table 3.36 in Moomaw et al. 2001) synthesized the existing literature to make the following general statements: (1) for soil nitrous oxide (N_2O), there is the potential to mitigate less than 20 million metric tons of carbon equivalent (MtCeq.) by 2010 and 50-100 MtCeq. by 2020 globally, with costs in US\$ per tonne carbon equivalent (TCeq.) ranging from roughly -\$100 to +\$50/TCeq. (reviewing Kroeze and Mosier, 1999 and IPCC, 2000); (2) for enteric methane (CH_4), there is the potential to mitigate 20-50 MtCeq. in 2010 and 2020 in OECD, and less than 20 MtCeq. in 2010 and 2020 in developing countries, with costs ranging from -\$50 to +\$200/TCeq. (reviewing Kroeze and Mosier, 1999; OECD, 1998; Riemer and Freund, 1999; and Chipato, 1999); and (3) for rice paddy irrigation and fertilizers, there is the potential to mitigate 50-100 MtCeq. in 2010 and over 200 MtCeq. in 2020 globally, all at negative costs (reviewing Riemer and Freund, 1999; and IPCC, 2000).

This paper presents results from an ongoing project to assess the mitigation potential of the largest agricultural GHG sources— N_2O emissions from cropland soils and CH_4 emissions from livestock management and rice cultivation—with data and methods that are generally consistent across emission sources and regions. Changes in GHG emissions other than the primary GHG emitted from each category (e.g., N_2O emissions from rice cultivation) are not currently included in the analysis. In addition, estimates of options that increase soil carbon, reduce fossil fuel carbon dioxide (CO_2) emissions from agricultural operations, and use bioenergy crops as fossil fuel offsets are currently not included (see IPCC, 2000, chapter 4).

2. SOURCES AND BASELINE EMISSIONS OF AGRICULTURAL CH_4 AND N_2O

Agricultural N_2O and CH_4 emissions from croplands, livestock and rice cultivation account for approximately 14 percent of global anthropogenic GHG emissions (Prentice et al., 2001; Scheehle and Kruger, 2006).¹ Of the world's total

1. Total estimate includes CO_2 emissions due to fossil fuel combustion, cement manufacturing, and land-use change, all CH_4 and N_2O sources, as well as the synthetic gases (HFCs, PFCs and SF_6). IPCC (2001) estimates agriculture contributes to over 20 percent of global anthropogenic GHG emissions, because agricultural fossil fuel CO_2 emissions are included in that estimate. To convert from N_2O and CH_4 to C equivalent, 100-year Global Warming Potentials (GWPs) from the 1996 IPCC Second Assessment Report are used (GWP for N_2O = 310; GWP for CH_4 = 21) to convert to CO_2 , which is then converted to C by multiplying by (12/44). GWPs from the IPCC Third Assessment Report (2001) are not used because international GHG reporting guidelines are still based on the Second Assessment Report.

anthropogenic N_2O and CH_4 emissions, agriculture is responsible for almost 90 and over 50 percent, respectively (Scheehle and Kruger, 2006). Agricultural GHG emissions are projected to increase for the foreseeable future due to continued increases in demand for agricultural products, population growth, increases in per capita caloric intake, and changes in diet preferences (FAO, 2002). Changes in these emission drivers are occurring most rapidly in developing countries.

Figure 1 shows the magnitude and projected increases (from 2000 to 2010 and 2020) in global emissions of soil N_2O , enteric fermentation CH_4 , manure CH_4 and rice CH_4 , the emission sources included in this analysis. Figure 2 shows these same emission sources for key regions—the US, EU-15, China, India and Brazil—for the year 2010.

Figure 1. Global Baseline Emissions of Soil N_2O , Enteric CH_4 , Rice CH_4 , and Manure CH_4 for Years 2000, 2010, and 2020 (MtCeq.)

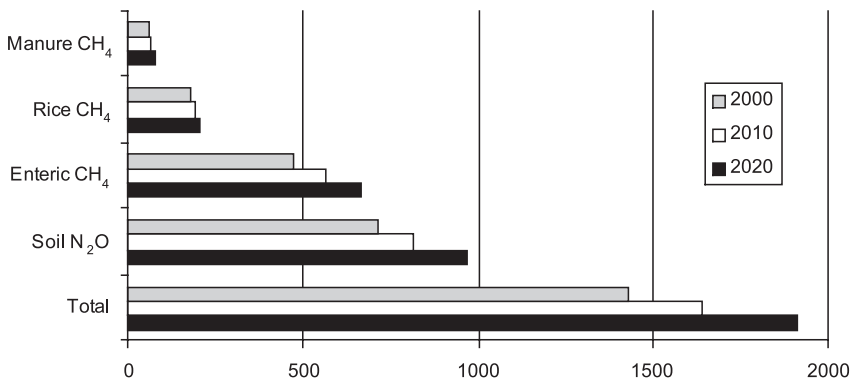
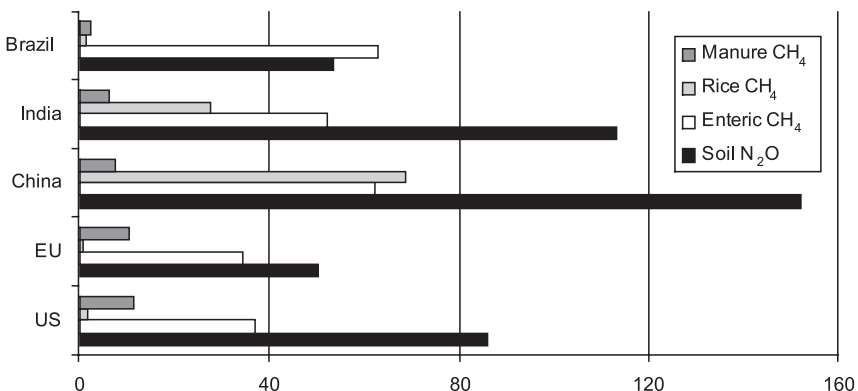


Figure 2. Baseline Emissions of Soil N_2O , Enteric CH_4 , Rice CH_4 , and Manure CH_4 for US, EU-15, China, India and Brazil for Year 2010 (MtCeq.)



Soil N_2O emissions are the largest agricultural GHG source globally, and primarily result from the processes of nitrification (aerobic microbial oxidation of ammonium (NH_4) to nitrate (NO_3)) and denitrification (anaerobic microbial reduction of nitrate to dinitrogen (N_2)). Application of nitrogen (N)-based fertilizers to croplands is a key determinant of N_2O emissions, as excess N not used by the plants is subject to gaseous emissions, as well as leaching and runoff. Mosier et al. (2002) generalize that plant uptake of fertilizer N seldom exceeds 50 percent. Therefore, a viable mitigation option to reduce soil N_2O emissions is to identify where and when N-based fertilizers can be used more efficiently while maintaining yields.

Methane emissions from enteric fermentation are the second largest global agricultural GHG source (Figure 1). Methane emissions occur through microbial fermentation in the digestive system of livestock. The amount of CH_4 emitted depends primarily on the animal's digestive system, and the amount and type of feed. Ruminant livestock such as dairy cattle, beef cattle, and buffalo emit the most CH_4 per animal, while non-ruminant livestock such as swine, horses and mules emit less (EPA, 2003). Because CH_4 emissions represent an economic loss to the farmer—where feed is converted to CH_4 rather than to product output—viable mitigation options can entail efficiency improvements to reduce CH_4 emissions per unit of beef or milk.

Methane emissions from rice cultivation are the third largest global agricultural GHG source (Figure 1). Emissions of CH_4 occur through the anaerobic decomposition of organic matter in flooded rice fields. Approximately 90 percent of the world's harvested rice area is grown under flooded conditions for some period of time (Wassmann et al., 2000). Emission rates depend on soil type, climate, water management regime, fertilizer use, and rice cultivar. For this reason, key mitigation options include changes in water management regime, the use of inorganic fertilizers and possibly different cultivar selection.

CH_4 and N_2O emissions from livestock manure are the fourth largest global agricultural GHG source. The current analysis only assesses the CH_4 emissions from livestock manure because only the CH_4 effects of the mitigation options were quantified in the underlying, supporting literature. Methane emissions occur through the anaerobic decomposition of manure. Anaerobic conditions are created when livestock or poultry manure is treated and stored as a liquid in lagoons, ponds, tanks, or pits. Anaerobic digesters that cover and capture the CH_4 emitted from collected manure, and then flare it (converting it to the less-effective global warming gas, CO_2) or use it as an on-farm energy source, represent a major mitigation option.

3. GENERAL DATA AND METHODS

The current analysis uses a static, bottom-up engineering-economic approach with input parameters from the available agricultural GHG mitigation studies in the literature, FAOSTAT (<http://apps.fao.org/default.htm>), baseline

emission and activity data constructed by EPA (see Scheehle and Kruger, 2006), and, in some cases, IPCC default emission factors. Mitigation options, described in more detail below, are selected for cropland soil N₂O (from Bates, 2001 and EC, 1998), enteric CH₄ (from Johnson et al., 2003; Bates, 2001; and Gerbens, 1998), rice CH₄ (from Wassmann et al., 2000 and Van der Gon et al., 2001), and manure CH₄ (from Bates, 2001 and EPA AgStar, 2003).

3.1 Applicability Factors

The extent to which each mitigation option is applied to baseline emissions or agricultural lands in different regions is determined by:

$$\text{Applicability (A}_{\text{nrt}}) = \text{AV}_{\text{nrt}} \times \text{TA}_{\text{nrt}} \times \text{OCF}_{\text{nrt}} \times \text{AF}_{\text{nrt}} \quad (1)$$

Using Eq. 1 to estimate the applicability of each mitigation option (n) in region (r) at time (t) represents the ongoing direction of this project but in some cases the current analysis could not obtain estimates for certain parameters. In those cases, simplifying assumptions were necessary as discussed below.

AV = availability of the mitigation option, based purely on technical grounds, where yes = 1, and no = 0. This analysis does not change the availability, nor any of the performance characteristics, of options over time. This means options must be considered technically feasible in a region currently to be included in the 2010 mitigation estimate; furthermore, how the mitigation options affect emissions, yields, labor and other factors, discussed further below, is assumed constant over time, such that there is no accounting for (t) in the current analysis.

TA = technical applicability fraction of the option, calculated as a percentage of either the baseline emissions to which the option is applicable or the percentage of underlying activities (e.g., cropland hectares) to which the option can be applied, as determined through either FAOSTAT or EPA baseline data. For example, if a mitigation option for enteric CH₄ applies to dairy cattle only, the TA for this option in a particular region will be the percentage of the region's enteric CH₄ emissions due to dairy. Likewise, if a soil N₂O mitigation option applies only to croplands of winter wheat, then the TA for this option will be the region's percentage of total cropland in winter wheat.

OCF = overlap correction factor of the option, as percentage of TA, taking into account overlap or exclusivity relative to other technically available mitigation options. The current analysis assumes that all mitigation options, with the exception of enteric CH₄ options outside the U.S. (see discussion of adoption feasibility fraction below), are potentially overlapping and that only one mitigation option can be applied to a given fraction of baseline emissions or agricultural production. Therefore, absent any further information on technology overlap for each option, baseline emissions (or the underlying data such as cropland hectares) are uniformly segmented according to the number of available mitigation options

(i.e., OCF = 20 percent where five options are available).² This approach avoids double counting among options, but could either over- or under-estimate the mitigation potential for a given option. Segmenting the baseline uniformly according to the number of mitigation options currently represents a mathematical convenience; further research will be required to change this approach such that the most viable mitigation options, of the fully technically available portfolio, are ‘allowed’ to mitigate a disproportionate share of emissions.

AF = adoption feasibility fraction, as percentage of OCF, taking into account implementation barriers (e.g., infrastructure, field extension services, risk aversion, culture). In nearly all cases, AF was not quantified in the current analysis due to paucity of data, and we chose not to include subjective judgments of our own for AF for different options in different regions. AF is estimated for the enteric CH₄ options applied outside of the US, where underlying literature (Gerbens, 1998) provided quantitative AF estimates for the year 2010.³ Therefore, most results represent technical and economic mitigation potential without policy implementation considerations, and will produce high-end estimates in this regard, at least for the 2010 decade. However, other factors discussed in this paper will tend to result in conservative mitigation estimates.

3.2 Emission Reduction Factors

Once applicability (A) for a mitigation option in a particular region is determined, the absolute emission reduction (ER), expressed in MtCeq., is determined by:

$$ER_{nrt} = A_{nrt} \times RE_{nrt} \times \text{baseline emissions or activity data} \quad (2)$$

where RE = reduction efficiency of the mitigation option, as percentage reduction of applicable baseline emissions or as percentage reduction of underlying activities (e.g., N applied to cropland soils). RE for each mitigation option is taken directly from the underlying literature, and applies only to the primary GHG reduced by the option (soil N₂O, enteric CH₄, rice CH₄ and manure CH₄). Specific RE’s are shown in the “Mitigation Options” section. Other potential effects, such as changes in soil carbon, fossil fuel CO₂, and N₂O emissions for manure management and rice cultivation, are not captured. RE is assumed to be representative of the region from which the underlying study originated, and is also applied uniformly to other regions (i.e., emissions are reduced by X% wherever mitigation n is applied). This is obviously a simplification given the high degree of emissions heterogeneity in agriculture, but it is a necessary assumption to allow for a first approximation of

2. The exception is for enteric fermentation mitigation options in the U.S., where additional information allowed for unequal weighting of OCF, but the OCF shares do still sum to 100%.

3. Based on these estimates and information from Gerbens (1998) and others indicating that multiple options to control methane emissions from enteric fermentation can be adopted simultaneously on the same farm, AF for these options sums to more than 100 percent in some regions.

mitigation potential at the international scale. Further work will be necessary to apply the appropriate RE regionally (r) and often sub-regionally.

3.3 Break-even Price of Mitigation Options

The price at which each mitigation option becomes economic is calculated according to Eq. (3), which sets total benefits equal to total costs, and solves for the present-value, break-even price (P), expressed in 2000 US\$/TCeq.

$$\sum_{t=1}^T \left[\frac{(P \cdot ER) + R}{(1 + DR)^t} \right] = CC + \sum_{t=1}^T \left[\frac{(RC)}{(1 + DR)^t} \right] \quad (3)$$

ER is the absolute emission reduction as determined above. R is the revenue effect as a result of the mitigation option (e.g., yield changes, electricity generation). CC is capital costs taken from the literature which remain fixed across regions, but only apply to the manure CH₄ options and one enteric CH₄ option. RC includes O&M costs (scaled to different regions using agricultural labor wage data from the World Bank (2003)⁴) and input costs such as fertilizers. T is the assumed useful life of capital equipment used for mitigation, which applies only to the small number of options identified that involve purchases of capital. DR is the discount rate, assumed to be 5 percent in all cases.⁵

3.4 Regional Application of Mitigation Estimates

For soil N₂O, enteric CH₄ and manure CH₄, 11 core regions (including US, EU, Russia, China, India, Brazil, and Africa), consistent with EMF regional categories, were selected for direct application of the mitigation options. A proxy method was used to mitigate emissions for remaining EMF regions, where their baseline emissions were reduced by the same percentage as a similar core region's baseline emissions, at corresponding TCeq. prices (e.g., Canada's baseline emissions are reduced proportionately to correspond with U.S. emission reductions). Rice CH₄ mitigation options are only applied to China, India, and Rest of Asia.

4. THE MITIGATION OPTIONS: DATA AND METHODS

Though there is ample literature on agricultural N₂O and CH₄ emissions, as well as potential mitigation options, very few studies include cost data for implementing mitigation options. For this reason, our analysis applies

4. Agricultural wage data were only available from the World Bank (2003) for selected countries. Wage rates for other countries and regions were assumed to be equal to the most similar area for which data were available.

5. The choice of discount rate affects the estimated breakeven cost only for those options that have capital costs.

mitigation options from the small number of studies that either provided cost data or information from which cost data could be derived, and extrapolates their assumptions regarding emission reductions, yield changes, labor requirements and other factors across regions.

4.1 Cropland Soil N₂O Options

A number of reasons may contribute to farmers’ over-application of N-based fertilizers in different regions of the world. The most predominant reason is usually the view that the costs associated with over-application outweigh the risk of lost revenue if yields decline as a result of sub-optimal application.

Options have been identified that could decrease N₂O while maintaining yields, and thus potentially address a farmer’s dominant concern (see Mosier et al., 2002). The soil N₂O mitigation options in this analysis (Table 1) represent a subset of all feasible options, and involve the more efficient or simply reduced application of N-based fertilizers. All five options are assumed to be technically available in all regions (i.e., AV = 1 for all regions in Eq. 1). The technical applicability fraction (TA in Eq. 1) varies by region and is quantified by only including those crop hectares (ha) on which N-based fertilizers are applied, as reported for each region in FAOSTAT. The overlap correction factor (OCF in Eq. 1) is quantified by uniformly segmenting the applicable cropland area by the number of mitigation options, which avoids overlap among the options and allows the implementation of only one mitigation option per unit land area. Adoption feasibility (AF in Eq. 1) for these options could not be estimated with confidence, but will be an important consideration in future assessments.

Table 1. Cropland Soil N₂O Mitigation Options

Mitigation Option	Reduction Efficiency (RE) in N applied*
Spreader maintenance: more uniform spreading to increase efficiency; avoid over-application and under-application	22%
Fertilizer free zone: avoid fertilizer loss by leaving fertilizer free zone at field edges	4%
Spreader maintenance + fertilizer free zone: combination of above two options	26%
Suboptimal application for winter wheat: N-based fertilizer reduced by 50kg/ha for winter wheat only**	26%
Suboptimal application for winter wheat: N-based fertilizer reduced by 100kg/ha for winter wheat only**	51%

*Percent reductions in applied N are converted to percent reductions in N₂O. Reductions in N also incur cost savings.

**There could potentially be numerous similar options included that each apply to specific crops. However, the only crop-specific option identified in Bates (2001) examined winter wheat.

Source: Bates (2001)

The reduction efficiency (RE in Eq. 2) for each option listed in Table 1 is from Bates (2001), and refers to percent reductions in baseline application of kg of N per ha, rather than reductions in N_2O . These percent reductions in N are applied uniformly across regions. Baseline N application rates per ha are estimated by using the applicable cropland base from FAOSTAT and total N consumption that is either projected for the year 2010 (for the US, China, India and Brazil taken from EPA baseline data) or historic (for all other regions), depending on data availability. Reductions in N are converted to N_2O through IPCC (1997) Tier I default factors—which remain uniform regardless of crop type or climate—for both direct emissions and indirect emissions due to volatilization and leaching and runoff.

Four of the five N_2O options incur revenue losses (included as lost revenue in Eq. 3) due to declines in crop yields that result from sub-optimal application of N. We note that this may be a conservative view of the implications of soil N_2O mitigation options, as declines in crop yields need not necessarily decline if less N-based fertilizer is applied, as discussed above. On the other hand, these estimates may be optimistic in some regards, by assuming that farmers would implement those options that decrease yields when the carbon price makes it economic to do so, when in fact that may not be the case due to risk aversion and other production concerns. The percentage declines in yields are taken from Bates (2001) and applied uniformly across regions. The revenue loss is calculated by multiplying the percentage yield decline by the weighted average of crop yields per ha and weighted average of crop prices (converted to 2000 \$US), for each region as currently reported by FAOSTAT. All the N_2O options incur cost savings due to less fertilizer applications (included as a negative RC in Eq. 3). Savings are calculated by multiplying total regional reductions in N (described above) by the weighted average price for all N-based fertilizers in that region from FAOSTAT. No data on required capital costs for these options were available.

4.2 Enteric CH_4 Options

The enteric CH_4 mitigation options (see Table 2) fall into four general categories: (1) improvements to food conversion efficiency by increasing energy content and digestibility of feed; (2) increased animal productivity through the use of natural or synthetic compounds that enhance animal growth and/or lactation (e.g., bovine somatotropin (bST), antibiotics); (3) feed supplementation to combat nutrient deficiencies that prevent animals from optimally utilizing the potential energy available in their feed (e.g., providing molasses/urea multi-nutrient blocks); and (4) changes in herd management (e.g., use of intensive grazing).⁶ In each case, the production of CH_4 per unit of product (meat, milk, or work (for draft animals)) is decreased, but emissions of CH_4 per animal often increase.

6. Emissions can also be mitigated through other methods, such as improving genetic characteristics, feeding compounds that inhibit methane formation in the rumen, improving reproduction efficiency, and better disease control, among others. However, there is currently insufficient information to include estimates of mitigation potential or costs for these options.

Table 2. Enteric CH₄ Mitigation Options

Mitigation Option Categories	Ranges for CH ₄ Reduction Efficiency (RE)*
Improvements to food conversion efficiency by increasing energy content and digestibility of feed (7 options)	4.3 – 51.7%
Increased animal productivity through the use of natural or synthetic compounds that enhance animal growth and/or lactation (2 options)	0.4 – 10.1%
Feed supplementation to combat nutrient deficiencies that prevent animals from optimally utilizing the potential energy available in their feed (3 options)	0.1 – 61.7%
Changes in herd management (5 options)	1.9 – 10.6%

*Ranges represent differences from option to option and also regional differences for the same option.

Source: Bates (2001); Gerbens (1998); Johnson et al. (2003)

Emission reductions at the national or regional level are calculated assuming that total production of meat, milk, or work remain constant after implementation of the mitigation options.

Technical availability, adoption feasibility, reduction efficiency, and incremental net cost per TCEq. for each option in each region are drawn directly from, or calculated based on, either Gerbens (1998), Bates (2001), Johnson et al. (2003), personal communication with Johnson, or professional judgment. Options from Johnson et al. are applied to the U.S. only, because many are not applicable to other regions with less concentrated animal production systems, and options from Gerbens and Bates are believed to be more appropriate for other regions.

Technical applicability for each option in each region is calculated using 2010 baseline data (Scheehle and Kruger, 2006) on regional enteric CH₄ emissions by species (cattle are subdivided into dairy and non-dairy). For instance, an option that applies only to dairy cattle would have a technical applicability equal to the share of regional emissions from enteric fermentation that come from this source (e.g., 21.8 percent for the U.S.). All options with sufficient quantitative information available to include in this analysis are applicable to dairy cattle, non-dairy cattle, and/or buffalo. Although some of these options may potentially be used to reduce emissions from other ruminants, there was insufficient data on these species to include them in this analysis. Technical applicability of a particular option varies across regions based on the distribution of emissions across species (e.g., the share of total enteric CH₄ emissions, by region, ranges from approximately 3 to 49 percent for dairy cattle).

For countries outside the U.S., the Gerbens and Bates studies provide information to estimate adoption feasibility for each option by region in 2010 (whereas for other mitigation categories quantifiable adoption feasibility information is not available). Adoption feasibility of individual options ranges from 0 to 50 percent for non-U.S. regions and may sum to greater than 100

percent for some regions based on indications that multiple mitigation options are expected to be applied jointly (e.g., options to increase feed energy content, enhance feed digestibility, and provide production-enhancing compounds such as BST can potentially be adopted simultaneously). For the options from Johnson et al. applied in the U.S., adoption feasibility is not quantified. These options were assumed to have overlap factors summing to 100 percent, but the factors are not uniform across options and were adjusted based on information from Gerbens for similar technologies and personal communication with Johnson.

Reduction efficiencies for options from Gerbens vary across regions because animal nutrition and management vary across regions in the baseline. Generally, reduction efficiencies are higher for developing countries because those regions tend to have relatively high baseline CH₄ emissions per unit of product, largely due to low quality feed. For options from Johnson et al., reduction efficiencies are equal to the percentage reduction in emissions per unit of milk or beef achieved. The reduction efficiencies for options from Bates are taken directly from that study. Overall, CH₄ reduction efficiencies range from 0.3 to 62 percent across individual options and regions.

Costs per TCeq. (the majority of which are negative due to efficiency gains for the same amount of output) are calculated for options from Gerbens and Bates by converting the reported net cost per tonne of CH₄ into a cost per TCeq. (see footnote 2). Additional detail for Johnson et al. options allowed calculation of changes in both costs and revenue per TCeq. under each option.

4.3 Rice CH₄ Options

All the rice CH₄ mitigation options listed in Table 3 are taken from Wassmann et al. (2000) and Van der Gon et al. (2001), and involve a change in either water management regime (to reduce anaerobic conditions), fertilizers or amendments (to inhibit methanogenesis), or rice variety. All options are assumed available in and applied to China, India and Rest of Asia only; these regions

Table 3. Rice CH₄ Mitigation Options

Mitigation Option Categories	Ranges for CH ₄ Reduction Efficiency (RE)*
Changes in water management regime (10 options)**	6 – 92%
Changes in amendments and/or fertilizer (13 options)	11 – 60.5%
Changes in planting practice (1 option, direct wet seeding)	19%
Changes in rice cultivar (3 options)	18 – 31.5%

*Ranges represent differences from option to option and also baseline differences for the same option.

**Some options included in this category combine change in water management regime with changes in amendments and/or planting practice.

Source: Wassmann et al. (2000); Van der Gon et al. (2001)

comprise approximately 90 percent of the world's rice production (Wassmann et al., 2000). Many values, described below, for Rest of Asia are calculated by averaging values for China and India.

Each option is applied to a segment of each region's 2010 rice CH₄ baseline (through TA and OCF factors in Eq. 1). The technical applicability fraction for these options is determined by (1) categorizing the baseline conditions for which the options apply: irrigated (continuous flooding with organic amendments; continuous flooding without organic amendments; and midseason drainage), rainfed, and deepwater rice, based on Wassmann et al. and Van der Gon et al.; (2) using the percentage of rice lands in these categories for each region (IRRI, 2001)⁷; (3) weighting these percentages by the corresponding IPCC CH₄ default factor; and (4) applying these final percentages to rice area from FAOSTAT. The overlap correction factor for each option is a uniform percentage based on the number of options that apply to a particular baseline condition, which presumes no overlap among options. For example, in China, the applicability of mitigation options for irrigated rice crops under continuous flooding with organic amendments is TA (32.6 percent) × OCF (12.5 percent; because 8 options are available for these conditions) × 2010 baseline (68.7 MtCeq.). Adoption feasibility for these options could not be quantified with confidence.

Methane reduction efficiencies, yield changes, and changes in fertilizers or amendments are taken directly from Wassmann et al. and Van der Gon et al. Methane reduction efficiencies range from 6 to 92 percent, and represent the averages of the statistically significant values reported in Wassmann et al. where there are results from multiple experiments. Reduction efficiencies decrease the applicable segment of 2010 baseline emissions, as determined above.

Yield changes due to the individual mitigation options range from -37.5 percent to +12 percent. As with the soil N₂O options, it is assumed for purposes of this analysis that all options, regardless of their yield effects, are implemented to the same extent, but obviously yield considerations will be the key factor in adoption feasibility (and a subject of subsequent assessments). Baseline yields are from FAOSTAT and assumed to be the same across irrigated, rainfed and deepwater rice crops. Revenue changes are estimated by using the percentage yield changes, and baseline yield and rice prices from FAOSTAT. Some options require the addition of amendments (e.g., phosphogypsum) or an alternative fertilizer (e.g., replacing urea with ammonium sulfate). These additional input costs are included by using baseline application rates from Wassmann et al. and regional prices from FAOSTAT.⁸

7. IRRI data do not disaggregate the area of irrigated rice. Thus, the proportion of rice grown under irrigated conditions in each region was divided evenly between the three subcategories used in this analysis.

8. The price for phosphogypsum was only available for the U.S. and was scaled to China and India (with the average of China and India used for Rest of Asia) using the regional fertilizer price index available from FAOSTAT.

Labor requirements to implement the mitigation options are not included in Wassmann et al. and Van der Gon et al., and therefore an outside study on labor requirements for adopting rice intensification practices (Moser and Barrett, 2002) is used as a rough proxy for each mitigation option. Relative to baseline conditions (assuming 1000 hours/ha/year; IEA, 1999), labor requirements range from +38 percent to -27 percent. The cost implications of any labor requirement changes are calculated using agricultural wages for China, India, and Rest of Asia based on World Bank (2003) data.

4.4 Manure CH₄ Options

All manure CH₄ mitigation options shown in Table 4 involve the capture and use of CH₄ through anaerobic digesters. Anaerobic digesters are used currently, primarily as a means of controlling odor and pathogen contamination (e.g., through *Salmonella* and *Cryptosporidium*). Centralized digesters (where multiple farms supply waste to one digester) are only applied in the EU as a mitigation option. The availability of farm-scale digesters in the EU and all other non-U.S. regions depends on climate, where cool- and warm-climate digesters are applied, respectively, in temperate and tropical or humid countries or regions within countries. Adoption (as percentage of manure CH₄ baselines) is assumed to be low for most digesters in most regions (e.g., 1.1 – 18.6 percent), at least by the 2010 timeframe, and was determined by expert judgement.⁹ Whereas farm-scale digesters outside the U.S. were categorized only by climate, data from EPA's AgSTAR program allowed for much more disaggregated information on farm-scale digesters for the U.S. (five types of digesters for swine manure and 11 for dairy cattle manure; EPA AgStar, 2003). Applicability of these options was further refined by allocating the share of baseline emissions to swine and dairy cattle. Methane reduction efficiencies and capital costs are taken directly from Bates (2001) for regions outside the U.S. Capital costs are based on a small number of representative systems in the EU, and remain fixed across regions. Each digester is assumed to have an operational life of 15 years. Higher emission reduction efficiencies for warm- vs. cool-climate digesters (75 vs. 50 percent) reflect the fact that baseline emissions are assumed to be greater in warm conditions. For the U.S., capital costs are available from

Table 4. Manure CH₄ Mitigation Options

Mitigation Option Categories	Ranges for CH ₄ Reduction Efficiency (RE)
Farm-scale anaerobic digesters (4 options)	50 – 75%*
Centralized anaerobic digesters (1 option)	50%

*Range represents differences in regional climate.

Source: Bates (2001)

9. Kurt Roos, EPA AgStar Program, personal communication, 2002.

AgSTAR, but the CH₄ reduction efficiency is the average of the cool- and warm-climate digesters from Bates. Revenues are generated from the use of captured CH₄ (essentially natural gas) for either heat or electricity on the farm. Revenues are scaled for other non-U.S. regions based on a U.S. Energy Information Agency (EIA, 2003) electricity price index relative to the EU. For the U.S., information on electricity benefits is available directly from AgSTAR.

5. RESULTS

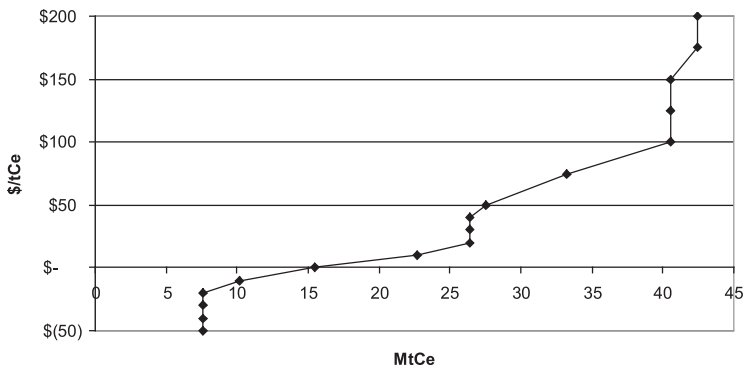
Figures 3-6 show globally aggregated marginal abatement curves for soil N₂O, enteric CH₄, rice CH₄ and manure CH₄ for the year 2010, in terms of estimated mitigation (MtCeq.) over the cost range of -\$50 to +200/TCeq.. Table 5 shows the regional breakout of estimated mitigation in both absolute terms and relative to 2010 baseline emissions.

Total global mitigation for soil N₂O emissions, the largest agricultural GHG source, is estimated to be almost 16 MtCeq. at negative or zero cost, over 42 MtCeq. at \$200/TCeq. (Figure 3), and 63 MtCeq. at much higher costs. The maximum global N₂O mitigation represents a reduction in 2010 baseline emissions of roughly 8 percent, with similar percent reductions in the U.S. and EU but slightly higher in China and India. The relatively low proportionate decrease in soil N₂O can largely be explained by the fact that the mitigation options are addressing only

Table 5. Maximum Agricultural CH₄ and N₂O Mitigation Results in 2010 by Region (over entire cost range, <-\$50/TCeq. to >\$200/TCeq.)

	Soil N ₂ O		Enteric CH ₄		Rice CH ₄		Manure CH ₄	
	MtCeq.	% 2010 Baseline	MtCeq.	% 2010 Baseline	MtCeq.	% 2010 Baseline	MtCeq.	% 2010 Baseline
United States	7.8	9%	1.8	5%	--	--	1.8	16%
EU-15	4.3	9%	3.7	11%	--	--	1.6	16%
Japan	0.2	61%	0.2	11%	--	--	0.03	16%
Russia	1.8	12%	2.9	13%	--	--	0.3	13%
CIS	1.4	12%	1.5	13%	--	--	0.2	16%
Brazil	1.1	2%	0.6	1%	--	--	0.5	19%
Other Latin America	1.0	2%	0.6	1%	--	--	0.4	19%
China	15.6	10%	3.7	6%	24.1	35%	1.5	19%
India	14.1	13%	5.3	10%	10.2	37%	1.6	19%
Other Asia	7.1	13%	3.2	6%	25.7	38%	1.4	19%
Africa	0.2	0.1%	2.7	3%	--	--	0.8	19%
Global Total*	62.9	8%	33.9	6%	61.0	33%	11.4	17%

* Global Total includes all regions listed here in addition to other regions for which these EMF regional results were extrapolated.

Figure 3. 2010 Global Marginal Abatement Cost Curve for N₂O Emissions from Cropland Soils

a portion of total N₂O baseline emissions, i.e., emissions due to application of N-based fertilizers, but not emissions from N-fixing crops, agricultural residues and manure applications. The full range of estimated costs for the soil N₂O options is from negative or very low to highly positive across regions (e.g., for the U.S., -\$55 to \$1,560/TCEq.; for EU, -\$124 to \$2,560/TCEq.; for China, \$3 to \$430/TCEq.). Negative costs result from options where there are net cost savings due to lower applications of fertilizers while maintaining yields, whereas high-cost options are those where revenues decline as yields decline in response to sub-optimal fertilizer applications. A greater portion of mitigation is estimated at the higher cost range due to the assumptions that most mitigation options result in crop yield declines; however, it seems feasible that equivalent levels of mitigation could be estimated at much lower costs, since a different set of mitigation options, or ones tailored more to regionally-specific conditions, could reduce N₂O with less adverse effects on yields.

Total global mitigation for enteric CH₄ is estimated to be 29 MtCeq. at negative or zero cost, almost 31 MtCeq. at \$200/TCEq. (Figure 4), and 34 MtCeq. at even higher costs. The maximum mitigation here represents a reduction in the 2010 global baseline of 6 percent. This is a conservative estimate because many of the mitigation options are not considered feasible, or are assumed to have limited penetration—at least by the 2010 timeframe—in regions where livestock herds are large and there is significant room for improved efficiency (e.g., Africa, Brazil, China and India). Furthermore, if other GHG benefits were included (e.g., soil C increases, cropland N₂O reductions for less feed) the estimates would be higher, but non-primary GHG effects were intentionally removed for this version of the analysis because it was unclear to what extent that would cause double counting among mitigation categories. For nearly all enteric CH₄ options, costs are estimated to be negative due to increased efficiency for an assumed constant level of regional milk or beef production.

Figure 4. 2010 Global Marginal Abatement Cost Curve for CH₄ Emissions from Enteric Fermentation

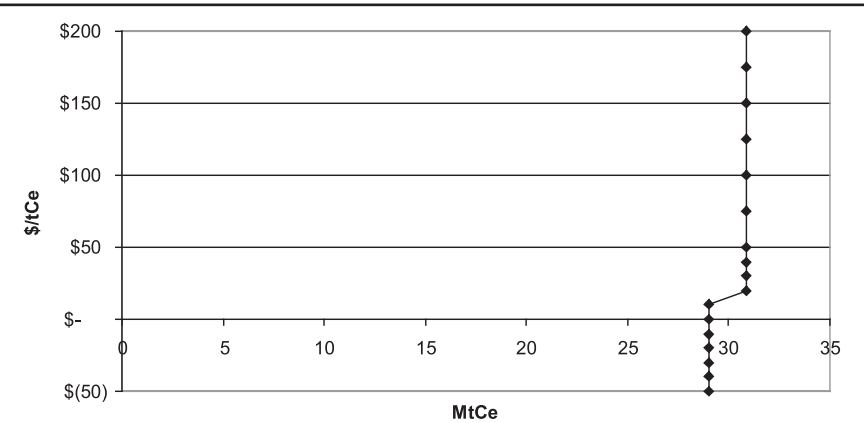
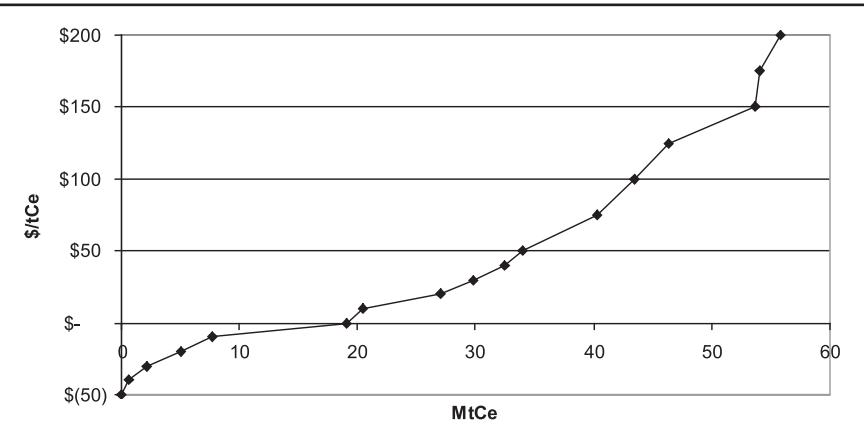
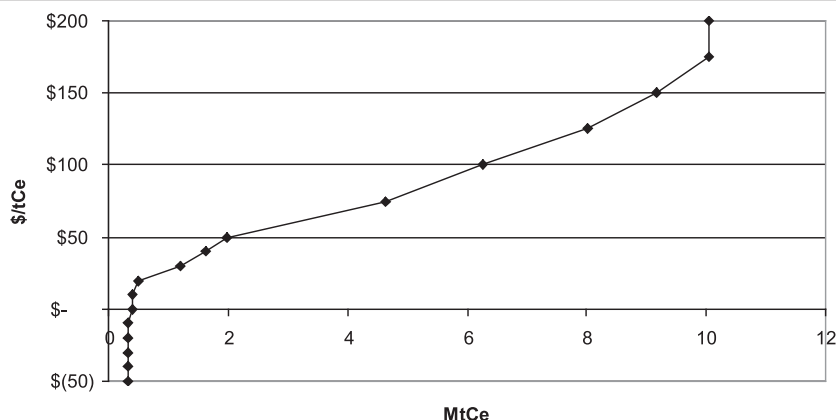


Figure 5. 2010 Global Marginal Abatement Cost Curve for CH₄ Emissions from Rice Cultivation



Total global mitigation for rice CH₄ is estimated to be 19 MtCeq. at negative or zero cost, almost 56 MtCeq. at \$200/TcEq. (Figure 5), and 61 MtCeq. at higher costs. The maximum mitigation estimate is a reduction in the global 2010 baseline of 33 percent. These estimates can be considered high-end values because, unlike the enteric CH₄ category, there were no quantitative data available to quantify adoption feasibility, and therefore the rice CH₄ mitigation estimates represent full-scale adoption. The full range of estimated costs per option is similar across the three regions: for China, -\$37 to 760/TcEq.; for India, -\$46 to 993/TcEq.; and for Rest of Asia, -\$46 to 973/TcEq.. Low-cost options include those with no or little additional labor requirements and increased or steady yields (e.g., midseason drainage and replacing urea with ammonium sulfate), whereas

Figure 6. 2010 Global Marginal Abatement Cost Curve for CH₄ Emissions from Manure Management



high-cost options require significant increases in labor and/or result in yield declines (e.g., direct wet seeding). It should be noted here again that options that both increase and decrease rice yields, as found in the literature, were included for purposes of this analysis, but do not necessarily represent recommended options. Further work will need to focus on those options that hold promise for both GHG reductions and farmer and societal benefits.

Total global mitigation for manure CH₄ is estimated to be roughly 0.4 MtCeq. at negative or zero cost, almost 10 MtCeq. at \$200/TCeq. (Figure 6), and over 11 MtCeq. at even higher prices. This maximum estimated mitigation represents a reduction of 17 percent of the global 2010 baseline. In the EU, estimated mitigation is 1.6 MtCeq., or roughly 16 percent of 2010 baseline emissions, with costs ranging from -\$166 to 642/TCeq. In the U.S., the magnitude of estimated mitigation is similar, with costs ranging from -\$121 to \$156/TCeq.

6. DISCUSSION AND NEXT STEPS

The estimated global emissions mitigation levels presented here appear to be generally within the range of estimates reviewed by IPCC discussed above; however, the range of break-even cost estimates is larger here: for soil N₂O, our estimates show higher positive costs beyond \$50/TCeq.; for enteric CH₄, we appear to have more negative-cost options; and for rice CH₄, we estimate greater positive-cost options. It is beyond the scope of this paper to rigorously compare these estimates with those reviewed by IPCC.

Mitigation estimates for agricultural N₂O and CH₄ will continue to evolve as data regarding baseline management practices, resultant emissions, net GHG effects of mitigation options, implementation costs, implementation barriers, and agricultural commodity effects are refined. Improved data and assumptions for

these factors need to consider how such factors vary spatially and temporally, as it is challenging to capture the heterogeneity of the agricultural sector at the aggregated national and international scales. An overarching caveat to this analysis is that many key assumptions for the mitigation options (e.g., percent emission changes, percent yield changes, percent labor changes) originate from a limited number of studies and are then held constant as these assumptions are applied to regions around the world. This approach allowed for a first approximation of emissions mitigation estimates at the international scale with generally consistent data and methods.

The authors are working to improve upon the current analysis along the following lines:

(1) Net GHG effects: The current analysis assumes only the primary CH₄ and N₂O gas is affected by the mitigation options. Other GHG effects to possibly incorporate include soil carbon, fossil fuel CO₂, and N₂O emissions for the rice and manure management mitigation options. Including these other GHG effects will likely increase estimates of GHG benefits for the enteric and manure management options (due to increases in soil C and decreased N₂O as well), decrease estimates for rice (due to offsetting N₂O emissions), and have effects in both directions for cropland soils.

(2) Heterogeneity of GHG emissions and yields: The current analysis assumes percent changes in emissions and yields—as a result of implementing the mitigation option—remain constant across regions, which is obviously a simplification compared to actual agricultural conditions. Capturing this heterogeneity is especially important, and challenging, for soil N₂O and rice CH₄. For these agricultural GHG sources, process models such as DAYCENT (Del Grosso et al., 2002) and DNDC (Cai et al., 2003) may be able to provide data to improve the underlying biophysical assumptions in the mitigation analysis (and help to determine net GHG impacts as mentioned above).

(3) Baseline management practices: With current data, including the underlying activity data for the EPA baseline estimates, it is often difficult to know baseline management practices (now and in 2010), and therefore difficult to know the extent to which the mitigation options identified here are already being carried out and thus would not contribute to mitigation from the baseline. Improved data in this area will help refine the technical applicability factors in the analysis.

(4) Incorporation of additional mitigation options: Many feasible mitigation options identified in the literature were not included in the current analysis, due to lack of data that would enable their application across regions. Incorporating additional options, such as those described by Mosier et al. (2002), seems most important for soil N₂O emissions.

(5) Adoption feasibility of mitigation options: Rarely does the literature on agricultural GHG mitigation options identify adoption feasibility of the options, and how this feasibility may vary over time and across regions. In most cases, the current analysis assumes the identified mitigation options are adopted

in all regions and to the fullest technically feasible extent. Improved regional data and methods and more expert consultation will be necessary to include and refine adoption feasibility estimates for mitigation options identified in the literature. Tools such as IMPACT (International Model for Policy Analysis of Agricultural Commodities and Trade; Rosegrant et al., 2002) that incorporate trends in agricultural practices, technology and extension services for medium- and long-term projections for food supply and demand may be able to provide useful insights in this regard.

(6) Agricultural commodity market effects: The current analysis, as a static, bottom-up approach, cannot capture agricultural commodity market effects that may result when mitigation options that increase or decrease crop yields are implemented. Such effects will likely alter crop prices which in turn can affect choices of crop mix, management practice and land use, and thus further influence GHG emissions. Here too, models that represent agricultural markets, such as ASMGHG for the U.S. (McCarl and Schneider, 2001) and IMPACT for global markets, may provide useful tools to refine the analysis here.

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Global Anthropogenic Methane and Nitrous Oxide Emissions

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Methane and Nitrous Oxide emissions contribute significantly to greenhouse gas emissions globally, with an estimated total of 1,618 and 950 million metric tons of carbon equivalent in 2000, respectively. The estimates of these gases are highly dependent on country specific activity data and emission factors. Most countries are presently or are in the process of developing greenhouse gas inventories and projections. Developed countries are using more in-depth, detailed methodologies, activity data, and emissions factors and are passing on this knowledge to other countries through bilateral and multilateral processes. In order to take advantage of this newly available information, we have incorporated the detailed country prepared inventories and projections into an overall global estimation framework. The source and country level estimation methodology presented in this study allows for more accurate anthropogenic emission level estimates at a global level. The results show a slow growth in the recent historical period with quicker growth to 2020, under a without measures scenario.

1. INTRODUCTION

This study provides consistent and comprehensive, country-specific emission estimates for anthropogenic sources of methane (CH₄) and nitrous oxide (N₂O). Although country level estimates of carbon dioxide (CO₂) are readily available, this information has been less available for methane and nitrous oxide. In

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this study, methane emissions are estimated at 1,553 million metric tons of carbon equivalent (MtCe)¹ in 1990 with a slow increase to 1,618 MtCe in 2000 and a projected 2,153 MtCe in 2020, under a without measures scenario. The slow growth in the historical period may have various reasons, which include emission reduction programs, and economic and sectoral restructuring. The increased growth rate out to 2020 is due, in part, to the exclusion of the effects of non-regulatory climate programs. Nitrous oxide emissions show a similar trend with emissions of 865 MtCe in 1990, 950 MtCe in 2000 and a projected 1,259 MtCe in 2020.

Historical estimates are reported for 1990, 1995, and 2000 and projections of emissions in the absence of climate measures are provided for 2005 through 2020, in five year increments. The emission estimates presented here are derived from country-reported estimates, when they are available and consistent with the *Revised 1996 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories* (IPCC, 1997). In specific cases, the available estimates are revised to ensure overall consistency in approach. Additionally, estimates were developed where unavailable from country-submitted reports.

In addition to the bottom-up method used for this analysis, global anthropogenic methane and nitrous oxide emissions can be developed using top-down methods. The two methods are not exclusive, as the bottom up estimates may be used as inputs to top-down models. The top-down approach for estimating both methane and nitrous oxide is based on atmospheric measurements. A series of assumptions, inputs, or both is necessary to estimate the natural sinks and distinguish between anthropogenic and natural sources. Using this method, combined with bottom up inputs, the IPCC Special Report on Emission Scenarios (SRES) reports an estimate of 310 Tg of CH₄ and 6.7 Tg N (or 10.2 Tg N₂O) in 1990 from anthropogenic sources (IPCC, 2000). Since the total emissions are estimated at 598 Tg, the natural sources of methane are thus estimated at approximately 290 Tg in 1998. Given the wide variability in nitrous oxide, the IPCC does not provide an estimate for natural nitrous oxide emissions, though a range is shown from 4.6 to 16.8 Tg N. Natural emissions of both gases are given in Table 2. The analysis presented in this paper, based on national activity data and emission factors, reveals a total of anthropogenic emissions of 271 Tg CH₄, and 6.5 Tg N, 13 and 3 percent smaller than the IPCC estimate, respectively.

All anthropogenic sources of methane and nitrous oxide are included, with the major sources considered individually, as listed in Table 1. More detailed

1. The emissions are converted to a carbon dioxide equivalent basis using the global warming potentials of 21 for methane and 310 for nitrous oxide, as published by the Intergovernmental Panel on Climate Change (IPCC) and recognized by the United Nations Framework Convention on Climate Change. The data is then converted to carbon equivalents by multiplying by (12/44). Although the GWPs have been updated by the IPCC in the Third Assessment Report, estimates of emissions in this report continue to use the GWPs from the Second Assessment Report, in order to be consistent with international reporting standards under the UNFCCC (IPCC, 2001; IPCC, 1997).

Table 1. Sources Included with Emissions and Percent of Methane or Nitrous Oxide Emissions in 2000

Anthropogenic Methane (Emissions in MtCe)			Anthropogenic Nitrous Oxide (Emissions in MtCe)		
ENERGY			ENERGY		
Coal Mining	123	8%	Fossil Fuel Combustion	61	9%
Natural Gas & Oil Systems	261	16%	Biofuel Combustion	10	1%
Fossil Fuel Combustion	16	1%	INDUSTRY		
Biofuel Combustion	59	4%	Adipic and Nitric Acid Production	43	4%
AGRICULTURE			AGRICULTURE		
Livestock Manure Management	61	4%	Agricultural Soils	711	75%
Livestock Enteric Fermentation	476	29%	Livestock Manure Management	56	6%
Rice Cultivation	177	11%	Other Agricultural Sources:	41	4%
Biomass Burning:	76	5%	• Agricultural Residue Burning		
• Agricultural Residue Burning			• Prescribed Burning of Savanna		
• Prescribed Burning of Savanna			WASTE		
WASTE			Human Sewage	22	2%
Solid Waste Management	213	13%	Other Non-Agricultural	3	0.3%
Wastewater Treatment	154	10%	• Solvent Use		
Other	3	0.2%	• Waste Incineration		
TOTAL	1,618	100%	TOTAL	950	100%

NOTE: Totals may not sum due to rounding.

Table 2. Natural Sources of Methane and Nitrous Oxide Emissions

Natural Methane (Emissions in MtCe)		Natural Nitrous Oxide (Emissions in MtCe)	
Wetlands	659 – 1357	Ocean	132 – 757
Termites	114	Atmosphere (NH ₃ oxidation)	40 – 159
Ocean	57 – 85	All Soils	438 – 1315
Hydrates	29 – 57		

Source: IPCC, 2001.

information on the inventory of each gas and source can be found in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 through 2001* (USEPA, 2003) and the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, 1997). Natural Sources are listed in Table 2.

Emissions of methane and nitrous oxide contribute significantly to total greenhouse gas emissions and radiative forcing because each gas is more effective at trapping heat than CO₂. The concentrations of both gases have increased since 1750, with methane and nitrous oxide at 1750 parts per billion (ppb) and 314 ppb, respectively in 1998 (IPCC, 2001). Nitrous oxide has been steadily increasing in concentration since pre-industrial times, however, the increase in the methane concentration in the atmosphere has been slowing in recent years, with a plateau in

the concentration between 1999 and 2002 (Dlugokencky et al, 2003). The changes could be due to many reasons, both natural and anthropogenic, including a near stabilization in anthropogenic emissions since 1990 due in part to voluntary and regulatory programs and economic and sectoral restructuring. Future emissions of both natural and anthropogenic emissions will play a role in whether this is a permanent or temporary phenomenon. The historical estimates presented within this study, though not level or declining, are not contradictory to the measurement data as the estimates only account for the anthropogenic portion of total methane emissions. Additionally, the historical trend for the study's methane emissions shows a small growth rate of only 4 percent from 1990 to 2000.

Global emissions of methane and nitrous oxide account for over 20 percent of the enhanced greenhouse effect since pre-industrial times (IPCC, 2001).² Additionally, a National Academy of Sciences article concludes that the climate forcing of direct and indirect non-CO₂ greenhouse gases equals that of CO₂ and, at this current forcing level, has contributed to at least 0.5 degrees of future temperature increase (Hansen et al, 2000).

In addition to contributing significantly to radiative forcing and potentially to climate change, non-CO₂ greenhouse gases can play an effective part of climate mitigation strategies. Methane in particular has great potential. In fact, successful methane reduction strategies are in place in many countries and due to methane's potential use as an energy source, the options are cost effective (USEPA, 2001). Additionally, the relatively short lifetime of methane, 8-12 years, means that it can have an impact on greenhouse gas concentrations in the near term. Finally, these gases are important if a climate strategy is to exist globally. "Any cost-effective effort to engage developing countries in climate mitigation will need to give even greater attention to the non-CO₂ greenhouse gases since these gases account for a higher percentage of overall emissions", in terms of MtCe (Reilly, 2003).

2. APPROACH

Previous efforts to determine global methane emissions by country relied exclusively on IPCC default methodologies, international data sets, and default emission factors. While these default approaches are useful for arriving at a global total quickly with relatively little data collection, they lack the accuracy and national specificity necessary for improving our understanding of how bottom-up methane estimates compare with global top-down estimates. First, the IPCC default methodologies (Tier 1) used in these compilations are frequently not the preferable approach for estimating emissions from key sources.³ The IPCC

2. Not including aerosols.

3. "A key source category is one that is prioritized within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of absolute level of emissions, the trend in emissions, or both" (IPCC, 2001).

thus encourages countries to use state-of-the-art Tier 2 or Tier 3 methodologies, which take into account complicated emission processes and disaggregated data, for major emission sources. Second, default emission factors do not account for variations across countries or regions, and may lead to significant bias (e.g., default emission factors typically come from a small number of developed countries). Finally, country level statistics may be more accurate than statistics gathered by international organizations. In most cases, the best that can be hoped for is that international data sets match national statistics.

National greenhouse gas inventories have improved significantly over the last few years in both the number of countries reporting and the quality of those reports. Many countries that previously prepared only Tier 1 estimates are now using more advanced methodologies. Additionally, through the efforts of national experts from developed countries and with assistance from multilateral and bilateral donors, developing countries are making great strides at collecting new data and improving their inventories. The analysis in this study has relied upon the global improvement in inventories in order to compile state-of-the-art methane and nitrous oxide estimates.

This analysis provides estimates for 24 countries and regions.⁴ In addition to the country and region data, USEPA presents overall trends by gas and sector. The four sectors are Energy, Industrial Processes, Agriculture, and Waste. The sources within each of the four sectors are shown in Table 1. This analysis is based on a much larger dataset with estimates for over 80 individual countries (USEPA, 2004).

Current and projected emission estimates to 2020 are obtained primarily from referenced documents. Preferred data sources include the individual National Communications (available from www.unfccc.org), *Asia Least-Cost Greenhouse Gas Abatement Strategy* (ALGAS) (ADB/UNDP, 1998), or parts of various country-specific reports. Preference is given to the latest published estimates. For example, the preferred sources for Annex I countries are the 3rd National Communications, documents submitted by each Party to the UNFCCC containing current emissions and projections to 2020. Other sources include European Union and country specific studies such as the United Kingdom's report on emissions and projections of greenhouse gases (AEA 2001 a-c, UK DEFRA, 2000). Estimates from the various National Communications and other country reports should be comparable in that they rely on the IPCC methodologies (or similar methods) and country-specific activity data.

If historical or projected emission estimates are not available from the literature, we developed estimates using IPCC default methodologies and emission drivers such as population or energy consumption. This estimation has been performed infrequently however, as the country-prepared estimates provide

4. The definitions of regions can be found on the EMF website at <http://www.stanford.edu/group/EMF/>

significant coverage. For example, they currently account for over 95 percent of both rice production and coal production for 1990.

As noted above, baseline (reference) projections for Annex I countries are largely based on publicly available reports produced by the countries themselves⁵.

Baseline scenarios do not include climate change mitigation efforts, though they do include non-climate-based policies that indirectly reduce greenhouse gases. For consistency, if a country's reported projections included planned climate mitigation efforts, i.e., "with policies and measures", the reductions due to those efforts were added back into the emission projections where identified. If climate policy reductions could not be identified, a country's emissions projections were estimated by continuing trends from previous years as reported in historical inventories, using analogous countries, or activity data drivers such as animal population, energy consumption, or population growth.

When the emissions data did not cover the entire historical or projected time series of 1990 to 2020, estimated emissions are obtained using the following procedures:

- 1) For countries reporting estimates from 1990 to 2020 in 10-year intervals, a linear interpolation is used to estimate values in 5-year increments.
- 2) For countries not reporting all historical years, emission growth rates are estimated based on US Environmental Protection Agency (US EPA) - developed Tier One estimates for the country for 1990 through 2000. The growth rates are applied to reported inventories since 1990 and used to estimate the remaining years up to 2000.
- 3) If a country reports an estimate for an individual source for one year, but reports aggregate estimates for other years, we disaggregate the estimates using the percent contribution of the individual source in that one year.
- 4) After assessing the estimates from the National Communications, we determine if a more recent historical inventory was submitted to the UNFCCC. If more recent estimates for a country are available for 1990, 1995, 2000, or some combination of those years, these historical estimates are included and the projections are scaled to reflect the change.

3. RESULTS

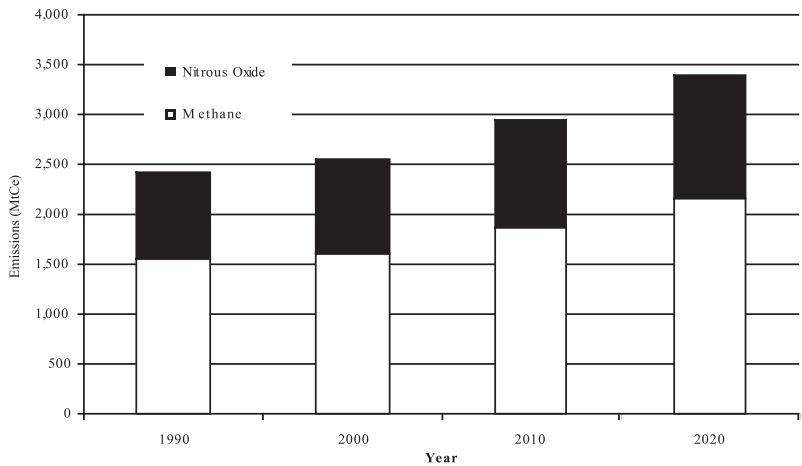
Global methane and nitrous oxide emissions are projected to be 3,411 Million Metric Tons of carbon equivalent (MtCe) in 2020, an increase in emissions of approximately 41 percent from 1990. Table 3 provides data in MtCe and Tg for

5. Annex 1 countries are those countries listed in Annex 1 to the United Nations Framework Convention on Climate Change. Annex 1 parties include the industrialized nations that were members of the Organization for Economic Co-operation and Development (OECD) in 1992 and fourteen countries with economies in transition.

Table 3. Anthropogenic Methane and Nitrous Oxide Emissions

	Methane (Tg)	Methane (MtCe)	Nitrous Oxide (Tg)	Nitrous Oxide (MtCe)
1990	271	1553	10	865
2000	283	1618	11	950
2010	327	1872	13	1082
2020	376	2153	15	1258

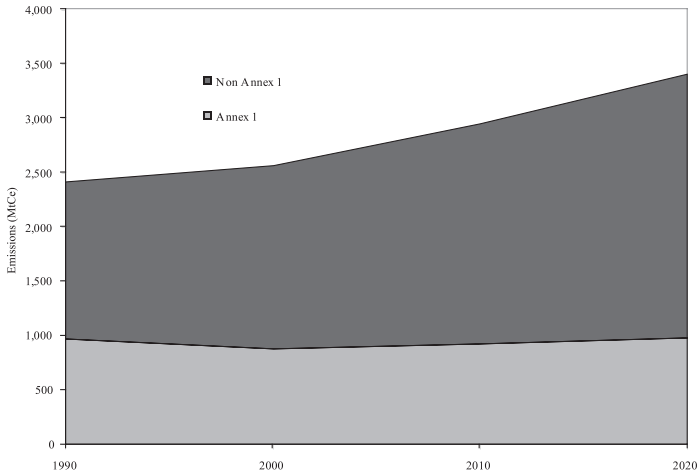
Figure 1. Global Anthropogenic CH₄ and N₂O Emissions (MtCe)



both gases. As Figure 1 shows, methane and nitrous oxide emissions grow slowly early in the period and are expected to increase more rapidly between 2005 and 2020. Over the entire time period, methane is expected to increase around 39 percent and nitrous oxide around 45 (insert percentage) percent.

As shown in Figure 2, the non-Annex 1 countries contribute over half of the total methane and nitrous oxide emissions over the time period, with 60 percent in 1990 and estimated at above 70 percent by 2020. Figure 3 illustrates the regional trends that underlay the global picture. From 1990 to 2020, emissions of methane and nitrous oxide are projected to increase in every region except Eastern Europe, the European Union (EU-15), and the Commonwealth of Independent States (CIS), which show a decrease from 1990 to 2000 and then a subsequent increase to return to near 1990 levels by 2020. As discussed below, the decline is due, in large part, to changes in the economy and policy regime in the CIS, Eastern Europe, and EU-15. On the other hand, developing countries such as China, India, and Brazil are projected to show the large absolute increases in emissions under this without measures scenario. The consistently large increases in global emissions from the developing world are due to several factors, including rapid

Figure 2. Combined CH₄ and N₂O Emissions by Major Region (MtCe)



industrialization, expanding economies, and a large and growing population base. Developed regions' emissions tend to increase at much slower rates, with the EU-15, Japan, and US either declining or growing less than 10 percent from 1990 to 2020. Among the reasons for this phenomenon are methane recovery programs, sectoral restructuring, and near saturation for a few sources. It is important to note that even in regions and countries with a low or negative growth rate in the recent historical period, emissions are expected to grow in the future, under a without measures scenario.

The main EU-15 trends can be explained in part through the restructuring of several industries in key countries or regions. In the 1990s, the coal industry in the United Kingdom and Germany went through changes that resulted in decreased emissions. In the agriculture sector, the EU-15 introduced reforms to the Common Agricultural Policy (CAP). These reforms provided for ceilings on cattle populations as well as incentives to optimize use of agricultural inputs. Finally, the EU-15 implemented a waste directive that limits the disposal of organic waste. This regulation has had a major impact on the current and projected methane emissions from landfills in that region. The historical decrease in emissions from 1990 to 2000 was also partially a result of methane emissions recovery practices in sources including landfills and coal mining.

In Eastern Europe and the CIS, there are two main driving forces behind declines in methane and nitrous oxide emissions. First, the economic transitions during the early 1990s resulted in an emissions decline in almost every source. Emissions are expected to start increasing around 2000 to 2005, as economic recovery widens. Second, the coal industry restructured in a number of countries, resulting in a sustained decrease in emissions. Despite the impact of major

economic and sector restructuring, in the absence of climate mitigation policies, total methane emissions are projected to recover to 1995 levels by 2020.

Globally, methane shows small growth until 2000 but is projected to grow more quickly out to 2020, in this without measures scenario. The historical slow growth can be attributed to many reasons. The decline of emissions in Eastern Europe and the former Soviet countries in the early 1990s accounted for a reduction of over 74 MtCe. The EU-15 also had an impact with reductions in many source categories, noted above, and an overall reduction of 18 MtCe. On a source level, the decline in coal production and increase in coal mine methane recovery efforts in many countries including China resulted in a reduction of 32 MtCe. In the waste sector in the US, the prevalence of landfill methane recovery practices, along with regulations for landfills have an impact with steady overall source emissions despite growing populations and increased waste generation. Overall, methane emissions in the US are below 1990 levels in 2000. The same phenomenon can be seen in other developed countries. Some of the changes lead to permanent decreases in methane emissions, such as the EU regulation on organics in solid waste sites, however, many are temporary. Overall, the changes will not lead to long term stabilization as countries in transition grow and the reductions due to sectoral restructuring are overcome by increases in the underlying activity. On the other hand, the projections do not account for non-regulatory programs and if such programs continue, the emissions will be lower than projected in this “without measures” scenario.

Examining methane emissions by source, the two largest methane sources, enteric fermentation and natural gas systems, have variant trends. Enteric fermentation increased by over 8%, though Russia, Ukraine, and the EU achieved significant decreases from 1990 to 2000. Again, the EU Common Agricultural Policy changed the agricultural sector and Russia and Ukraine underwent an economic downturn. A few additional regions made smaller decreases. Natural gas has a small growth rate with Annex I countries achieving a reduction of 147 MtCe, mainly in Russia, which is counteracted by the non-Annex I emission increase of around 166 MtCe. This stabilization does not continue into the future as the emissions in Russia and other economies in transition will increase as the economies grow.

Nitrous oxide emissions grow at a quicker pace than methane emissions and although the historical growth is at a lower rate than the projections, the differences are not large. Agricultural soils are the largest source and have a growth rate of between 5 and 9 percent every five years. The only source level decrease is in the industrial sector, where adipic and nitric acid production emissions have decreased due to pollution control technologies currently in place to reduce NO_x.

Figure 4 reveals that agricultural sources are the largest source globally of non-CO₂ emissions. In absolute terms, emissions from agricultural sources are projected to increase by 644 MtCe by 2020. Energy sector emissions also increase significantly during this period – by 213 MtCe. The only sector that

Figure 3. Global Anthropogenic CH₄ and N₂O Emissions by Region (MtCe)

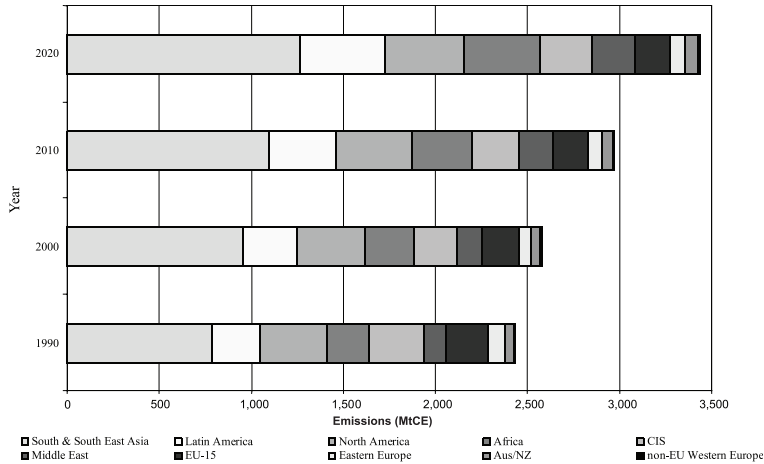
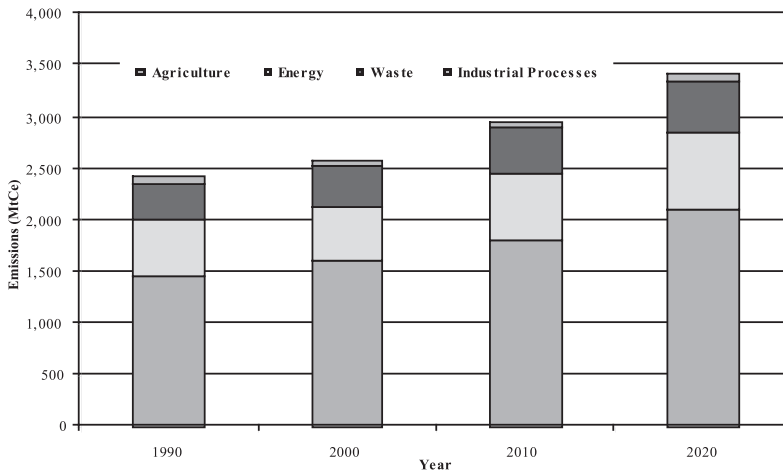


Figure 4. Global CH₄ and N₂O Emissions by Sector and Year Emissions (MtCe)



decreases is industry, which consists almost exclusively of nitric and adipic acid production. As mentioned earlier, the decrease is due to changes in technology not due to climate measures.

Another significant change is occurring as the second largest source of N₂O emissions shifts from industrial processes to mobile sources. Industrial process emissions dropped dramatically between 1990 and 2000 and are expected to stay near 2000 levels out to 2020. However, total N₂O emissions show

an overall increase due to a dramatic increase in mobile source emissions and steadily increasing emissions from agricultural soils after 2000.

In summary, both methane and nitrous oxide emissions are expected to increase significantly from 1990 to 2020, under a without measures scenario. This increase is despite the slower and, in some cases, negative growth seen in methane emissions for many regions and sources. Even with some sources expecting to show little growth as land becomes scarce, methane emissions are still expected to rise by 40 percent by 2020. Nitrous oxide, with more agricultural sources, shows a lower growth rate of 17 percent. The agricultural sources tend to grow at a slower pace due to less land availability, production efficiency gains, and near saturation on fertilizer use per hectare.

4. LIMITATIONS

The projections in this report provide a consistent baseline to compare opportunities and costs of mitigation options across countries. In some cases, the report adjusted national projections in order to remove the effects of climate policies. This step was necessary to ensure that the estimates are consistent. For this reason, actual emissions over time are likely to be lower than these without measures forecasts because many businesses and governments plan to implement additional actions to reduce emissions. Alternative definitions of the baseline or without measures activities could lead to different estimates for some sources.

While the latest available information is reflected in these estimates, the projections are sensitive to changes in key assumptions. Additionally, in some cases the without measures baseline includes incidental greenhouse gas reductions originating from climate related actions or government policies. For consistency, we deducted the effects of planned mitigation efforts. The assumptions may not hold true for all countries to which it was applied. Finally, data gaps existed in emissions data for several countries. To fill gaps, we used methods ranging from interpolation to growth patterns based on analogous countries.

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Carbon Sequestration in Global Forests Under Different Carbon Price Regimes

Brent Sohngen and Roger Sedjo***

This paper examines the potential role of carbon sequestration in forests under a range of exogenously chosen carbon price paths. The price paths were chosen to simulate several different climate change policies. The results indicate that global sequestration could range from 48–147 Pg C by 2105 for carbon prices ranging from \$100 to more than \$800 per t C by the end of the century. The timing of sequestration is found to be sensitive to the assumed carbon price path. Low initial carbon prices (\$10 - \$20 per t C in 2010) followed by rapid price increases, as might occur if policy makers try to stabilize future concentrations, suggest little, if any, sequestration during the next 20 years (-0.2 to 4.5 Pg C). If policy makers develop policies that support higher initial carbon prices, ranging from \$75 to \$100 per t C, 17 to 23 Pg C could be sequestered in forests over the next 20 years. Overall, our results indicate that forestry is not an efficient stop-gap measure for long-term policy goals, but that it is instead an important long-term partner with other mitigation options.

1. INTRODUCTION

Numerous studies have estimated the cost of carbon sequestration in forests and land-use. Richards and Stokes (2004) assess a range of studies and conclude that 2 Pg C (1 Pg C = 1×10^{15} g C; C = Carbon equivalents) per year could be sequestered globally for up to \$200 per t C (1 t C = 1000 Kg C). Most of the studies reviewed in Richards and Stokes (2004) estimate costs in specific regions and for specific types of projects. Previous studies tend to assume that sequestration will occur as soon as

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carbon prices exceed the estimated marginal costs. The Intergovernmental Panel on Climate Change concludes that forest carbon sequestration can be used in the short-term to buy society some time to allow other technological advances to develop to reduce greenhouse gases (Metz et al., 2001).

Forest management, however, is dynamic, and landowners could put off sequestration if they anticipate higher carbon prices in the future. Future carbon prices obviously will depend on the actual climate policies adopted, but the current suite of energy models used by policy makers implies a wide range of potential prices and price paths. Given this range of possible future carbon prices, it is important to develop more thorough analysis that investigates when and how forest carbon sequestration should efficiently enter the suite of policy options for mitigation of climate change damages.

This paper uses a global forestry model to consider this question. A set of carbon price paths have been generated for use in this study so that they encompass a range of the potential price paths generated by energy models used in the Energy Modeling Forum EMF-21 Study. The global forestry model used in Sohngen and Mendelsohn (2003) is adapted for the analysis in this paper. The model is dynamic and global. Dynamic analysis is important in forestry because the age of forests matters to carbon sequestration. Low cost options for sequestration could result from adding new forestland, reducing deforestation, holding forests longer than the market rotation period, or setting aside forests from harvesting activities. The dynamic analysis conducted pays for each of these potential deviations from baseline activities. Global analysis is important because timber markets are linked across regions by prices. Increasing the area of forests in one region causes supply to expand and lowers prices. Lower prices can reduce incentives to manage forests elsewhere. Accounting for global price effects can be important if sequestration programs become large and cause large shifts in land uses.

One limitation in the approach utilized in this study is that we do not formally model agricultural markets. Although the model includes upward sloping land supply functions in all regions, the supply of land in forestry is sensitive only to timber prices. This limitation of the model will be addressed in future versions of the model that include an agricultural sector model. However, it is still possible to test the sensitivity of the results to alternative assumptions about land supply. In particular, the largest effects of land use change on the global carbon budget currently result from land use change in the tropics (Dixon et al., 1994; Intergovernmental Panel on Climate Change, 2000; and Houghton, 2003). To account for uncertainty in potential future land use change in tropical regions, we assess potential carbon sequestration under two alternative assumptions about agricultural land rental values in tropical regions: the original assumptions in Sohngen and Mendelsohn (2003) versus a set of assumptions that mimic results from the SRES scenarios (Intergovernmental Panel on Climate Change, 2000).

The paper is constructed as follows. The next section describes the forestry model used in the analysis. The third section describes the results of the baseline case, and the policy scenarios across different of carbon price paths. The

third section also gives the results for the alternative baseline case using different forest rental functions for tropical regions. The last section is our conclusion.

2. FOREST MODEL DESCRIPTION

The model used in this analysis is built upon the earlier Timber Supply Model originally developed by Sedjo and Lyon (1990). The model was updated and expanded in Sohngen et al. (1999) to incorporate additional regions as responsive to timber market prices. Sohngen and Sedjo (2000) detail the methods used for carbon accounting within the model. Most recently, the model has been integrated with the DICE model (Nordhaus and Boyer, 2000), and used to assess optimal carbon sequestration policy (Sohngen and Mendelsohn, 2003).

We begin with the global demand for industrial timber harvested from all stocks of forests, $D(Q(\bullet), Z_t)$, where $Q(\bullet)$ is global industrial timber harvest, and Z_t , the consumption of all other goods. The demand function is specified as:

$$P(t) = A(Z_t, t) - BQ(\bullet) \quad (1)$$

$A(Z_t, t)$ shifts the demand function outward as a function of global economic growth. All industrial timber feeds into this single global demand function. Industrial timber from each region is quality adjusted to account for differences in the value of timber from different forest stocks on world markets.

Within the forestry model, there are three types of forest stocks. Stocks in i are managed in economically optimal rotations. These include most temperate forests, as well as some stocks in other parts of the world. Stocks in j represent high value timber plantations that occur mainly in subtropical countries. These stocks have additional establishment costs relative to stocks in i , and they too are managed in economically optimal rotations. Stocks in k represent currently inaccessible timber types that are assumed to be old growth and therefore are not defined in age classes. Large areas of boreal and tropical forests are classified in k . If inaccessible forests are harvested (which occurs if timber prices exceed the marginal access costs), they convert to accessible forests and they are subsequently managed in age classes.

The model chooses the area of land to harvest in each age class of each timber stock in each year, the management intensity in each timber stock (determined when the stand is regenerated), and the area of land to regenerate in each timber stock in order to maximize the net present value of consumers surplus minus the costs of managing and holding each forest stock. Formally, the maximization is:

$$\text{Max} \sum_0^{\infty} \rho^t \left\{ \int_0^{Q^*(t)} \{D(Q(\bullet), Z_t) - C^i(\bullet) - C^j(\bullet) - C^k(\bullet)\} dQ_t - \sum_i C_G^i(G_t^i, m_t^i) - \sum_j C_j^N(N_t^j, m_t^j) - \sum_{i,j,k} R^{i,j,k} (L_t^{i,j,k}) + CC(t) \right\} \quad (2)$$

where

$$Q(\bullet) = \sum_{i=1}^I \sum_{a,t}^A H_{a,t}^i V_{a,t}^i + \sum_{j=1}^J \sum_{a,t}^A H_{a,t}^j V_{a,t}^j + \sum_{k=1}^K H_t^k V_t^k \quad (3)$$

$$C^i(\bullet) = \sum_{i=1}^I \sum_{a,t}^A (ch^i + ct^i + cg^i) H_{a,t}^i V_{a,t}^i \quad (4)$$

$$C^j(\bullet) = \sum_{j=1}^J \sum_{a,t}^A (ch^j + ct^j + cg^j) H_{a,t}^j V_{a,t}^j \quad (5)$$

$$C^k(\bullet) = \sum_{k=1}^K (\beta_0 + \beta_1 \sum_{i=1}^I H_t^i V_t^i) H_t^k V_t^k \quad (6)$$

$Q(\bullet)$ in equation (3) sums the product of area harvested in each age class, $H_{a,t}^{i,j}$, and timber volume in each age class $V_{a,t}^{i,j}$ for forest stocks i and j , plus the harvest area times volume for forest stock k . Note that forest stock k is not managed in age classes. $C^i(\bullet)$ and $C^j(\bullet)$ are the sum of marginal harvesting (ch^i or ch^j) and transportation costs (to mills, ct^i or ct^j , and to major market regions, cg^i or cg^j) for the stocks in i and j . Marginal harvesting and transportation costs are assumed to be constant for stocks in i and j . $C^k(\bullet)$ is the cost of harvesting stocks in k . Marginal costs for harvesting these stocks are assumed to be an upward sloping function of the sum of historical harvesting from the initial model period, with parameters β_0 and β_1 .

$C_G^i(\bullet)$ in equation (2) is the cost function for regenerating stocks in i , and $C_N^j(\bullet)$ is the cost function for planting stocks in j . G_t^i is the area of land planted in stocks i , and N_t^j is the area of land planted in highly valuable plantation forests. The term m_t^i is management intensity determined at planting time in stocks i , and m_t^j is management intensity determined at planting time in stocks j .

The planting cost functions are given as:

$$C_G^{i,k}(\bullet) = p_m^i m_t^i G_t^i \quad (7a)$$

$$C_N^j(\bullet) = p_m^j m_t^j N_t^j + f(N_t^j, L_t^j) \quad (7b)$$

Each unit of management intensity can be purchased at price p_m^i or p_m^j . The function $f(N_t^j, L_t^j)$ represents establishment costs for new plantations only. The cost function for establishing new plantations rises as the total area of plantations expands, so these costs are a function not just of area planted this year, N_t^j , also the total area of plantations, L_t^j , in each stock j .

To see how management intensity influences the stock of trees, note that each hectare of land is assigned a yield function that describes the merchantable yield of timber for each age class. For stocks in i , for example, let $V_{a,t}^i = Y^i(a_t, m_t^i(t_0))$, where a_t is the age of the hectare at time t , and $m_t^i(t_0)$ is the management intensity applied to the stand at the time of regeneration, t_0 . The yield function is assumed to be typical for ecological species in that region, so that $dY^i/da_t > 0$ and $d^2Y^i/da_t^2 < 0$. Management intensity determined at the time of regeneration influences the stock of merchantable products at the time of harvest (see Sedjo and Lyon, 1990). The following two conditions hold for trees in stock i planted at time t_0 and harvested at time $a = t_a$:

$$\frac{dY^i(t_{a_i} - t_0)}{dm^i(t_0)} \geq 0 \text{ and } \frac{d^2Y^i(t_{a_i} - t_0)}{dm^i(t_0)^2} \leq 0 \quad (8)$$

In equation (2), the total area of land in each forest stock is given as $L^{ij,k}_t$, which is defined for each stock as:

$$L^i_t = \sum_1^A X^i_{a,t} \quad (9a)$$

$$L^j_t = \sum_1^A X^j_{a,t} \quad (9b)$$

$$L^k_t = X^k_t \quad (9c)$$

where $X^{ij,k}_{a,t}$ is the area of land in each forest stock of i or j in age class a and time period t . X^k_t is the area of inaccessible forests. Annual rent for forestland is a function of land area in each stock of forest, $R^{ij,k}(L^{ij,k}_t)$. The form of the rental function for each forest stock is:

$$R^{ij,k}(L^{ij,k}_t) = \gamma^{ij,k} L^{ij,k}_t + \delta^{ij,k} (L^{ij,k}_t)^2 \quad (10)$$

This function is applied to all stocks in i , j , and k , and $\gamma^{ij,k}$ and $\delta^{ij,k}$ are parameters specific for each stock.

Land in each age class of each forest stock adjusts over time according to:

$$X^i_{a,t} = X^i_{a-1,t-1} - H^i_{a-1,t-1} + G^i_{a=1,t-1} + H^{k=1}_{a=1,t-1} \quad \text{for all } i \quad (11a)$$

$$X^j_{a,t} = X^j_{a-1,t-1} - H^j_{a-1,t-1} + N^j_{a=1,t-1} \quad \text{for all } j \quad (11b)$$

$$X^k_t = X^k_{t-1} - H^k_{t-1} \quad \text{for all } k \quad (11c)$$

Once land is harvested from inaccessible stocks it converts to a corresponding accessible stock i and is managed in age classes. This can be seen through the term H^k_{t-1} in equation (11c), which indicates harvests of inaccessible stocks, and $H^{k=1}_{a=1,t-1}$ in equation (11a) which represents the conversion of this harvested land into the corresponding type in stock i .

Because we are interested in paying for carbon sequestration in order to assess sequestration along different carbon price paths, the term CC_t in equation (2) represents payments for carbon sequestration. For this model, we assume that landowners are paid for sequestration when they store carbon, and that they are taxed for emissions when they harvest forests or convert them to other uses. The price of a ton of carbon sequestered or the tax on carbon emitted in any given year is the marginal cost of energy abatement. The price for a ton of sequestration in an efficient program is paid in the year in which it occurs and a tax is paid in the year in which the emission occurs. This differs from the carbon rental approach in Sohngen and Mendelsohn (2003), in that different property rights are assumed.

This difference in property rights lies in the effects of the subsidy/tax program investigated here on current owners of forestland. They will be taxed under the subsidy/tax program if those forests emit carbon through harvesting or land use changes. Under a system of rental payments, landowners with current forests are not penalized for harvesting or converting lands from forests, they only lose rental for the period when the biomass stock is low. With discounting, the rental method or the tax and subsidy method result in the same marginal value for sequestration (and hence both are efficient). The particular method of subsidizing or taxing does affect the flow of money to and from forestry.

Sequestration is measured as a reduction of net annual baseline emissions. If baseline emissions are E_t^b ,¹ emissions in the sequestration scenario are E_t^s , and carbon prices are P_t^c , then the model credits sequestration according to:

$$\text{Carbon credit in time } t = CC_t = P_t^c [E_t^b - E_t^s] \quad (12)$$

Emissions are treated as positive numbers indicating that emissions enter the atmosphere (the most common method of handling carbon emissions in energy models), and sequestration is treated as a negative number. In equation (12), note that if carbon prices induce sequestration for a period, but carbon is emitted in the future, carbon emissions in the future will be “taxed” at whatever the current carbon price is at that time. E_t^s in this case is determined endogenously, and will depend on the price of carbon sequestration.

The model is programmed into GAMS and solved with the MINOS solver. The model is solved in 10 year time increments, and terminal conditions are imposed on the system after 180 years. The choice of terminal conditions is complicated because many stocks with long rotation periods (i.e., more than 50 or 100 years in some cases) could take many centuries to achieve steady state rotations, and there is debate about whether steady state rotations will even evolve. Our strategy is to choose a terminal period far in the future, 180 years, so that the terminal conditions chosen have little effect on the model solution for the first 100 years, which is the time period of interest for the simulations below. The terminal conditions chosen for this analysis calculate the value for each age class of timber in each stock assuming that steady state conditions have evolved and then apply this value to the stock in the terminal period.

For the baseline case, $P_t^c = 0$, so the term CC_t has no effect on the model. Baseline carbon emissions are then estimated, and used for E_t^b in the carbon scenarios. The scenarios assume an exogenous path for P_t^c , and solve for optimal management. E_t^s under the scenarios is determined endogenously. For the version of the model considered in this paper, there are 53 different stocks of forests distributed across 9 regions. The regions and a brief description of the timber stocks is shown in Table 1. The underlying data and a full description of its

1. $E_t^b = -(S_t^b - S_{t-1}^b)$, where S_t^b is the baseline stock of carbon in forests in period t . The stock includes carbon stored in aboveground biomass, as well as roots, soil, and marketed products.

Table 1. Description of Timber Stocks in 9 Regions Modeled^a

Regions	Description
North America	14 total timber stocks: 11 in stock i, 0 in stock j, and 3 in stock k.
South America	5 total timber stocks: 2 in stock i, 2 in stock j, and 1 in stock k.
Europe	8 total timber stocks: 6 in stock i, 1 in stock j, and 1 in stock k.
Former Soviet Union (includes Central Asia)	5 total timber stocks: 4 in stock i, 0 in stock j, and 1 in stock k.
China	7 total timber stocks: 4 in stock i, 1 in stock j, and 2 in stock k.
India	2 total timber stocks: 0 in stock i, 2 in stock j, 0 in stock k.
Oceania (Australia and New Zealand only)	4 total timber stocks: 1 in stock i, 2 in stock j, and 1 in stock k.
Southeast Asia	4 total timber stocks: 1 in stock i, 2 in stock j, and 1 in stock k.
Africa	4 total timber stocks: 1 in stock i, 2 in stock j, and 1 in stock k.

a. Stock i is managed in economically optimal rotations. Stock j is subtropical plantation forests, which are also managed in economically optimal rotations. Stock k is inaccessible forests, which are assumed to be old growth.

development is available on-line at: <http://aede.osu.edu/people/sohngen.1/forests/GTM/index.htm>.

3. CARBON SEQUESTRATION ANALYSIS

3.1 Baseline Case

The baseline for the timber model assumes that the demand function in (1) shifts outward at 1% per year initially, falling to 0% per year demand growth in 2100 and beyond. Global harvests rise from approximately 1.6 billion m³ per year initially to 2.2 billion m³ per year by 2100.² Prices rise at an average of 0.4% per year during the century, although they are stable for the last few decades.³ Most timber harvests are derived from temperate regions initially, with over 70% of timber harvests in 2000–2010 coming from North America, Europe, and the Former Soviet Union. Aggregate harvest from these regions is relatively constant

2. These results represent growth rates in total timber harvests of about 0.3% per year for the coming century. In comparison, global industrial timber harvests expanded by 1.1% per year between 1961 and 2000, although most of this growth occurred during the period 1960–1990 (FAO, 2003). Global timber harvests have remained fairly stable since 1990.

3. The price in the model represents a numeraire good for timber, with each type quality adjusted relative to the numeraire. The numeraire is U.S. Southern or Pacific Northwestern timber. Historically, U.S. stumpage prices have risen at about 3.5% per year over the past century (Sohngen and Haynes, 1994), so the future price projections in our model are substantially lower in comparison to the past century because the model projects that future forestry is sustainable on a global basis and production gains from plantation forests keep pace with future demand growth.

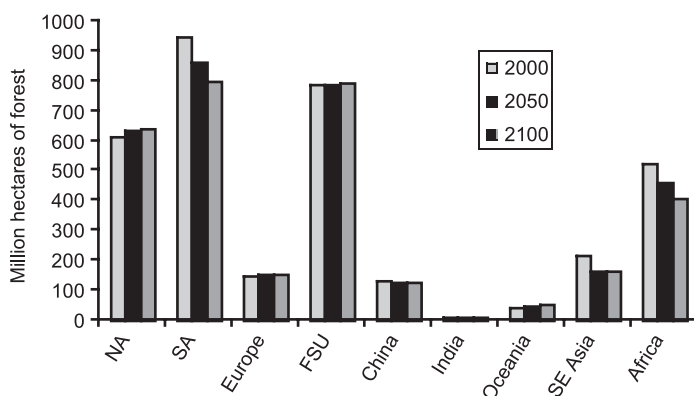
over the century, although some regions experience reductions in timber harvests during some time periods when the area of merchantable timber is low.⁴ Most growth in harvests in the long-term occurs in regions with substantial subtropical plantation forestry (South America and Oceania in particular).

The total area of forestland in the model falls from 3.4 million to 3.1 million hectares of land in forests over the century. The regional changes follow general trends of the recent years, where temperate regions are experiencing afforestation and tropical regions are experiencing deforestation (Figure 1). The estimates of land use change for tropical regions in the baseline differ from historical estimates in the literature. The UN Food and Agricultural Organization (FAO, 2003) suggests that in the 1990's, net forest loss in Africa, South and Central America, and Asia was 12.2 million hectares per year, while in our baseline, the projected rate of net forest loss in those regions is 7.2 million hectares lost per year for the period 2000–2010. Our sensitivity analysis below uses assumptions for the rental functions that more closely mimics FAO (Houghton, 2003) estimates in initial periods.

Initial carbon stocks are estimated to be 811 Pg C, which is close to that estimated by Dixon et al. (1994) if peatlands are removed from the forest inventory (Brown, 1998). Approximately 53% of the carbon is stored in temperate and boreal regions, with the remaining 47% stored in tropical regions. In addition, 35% of total carbon is maintained in vegetation, and 65% in soil.

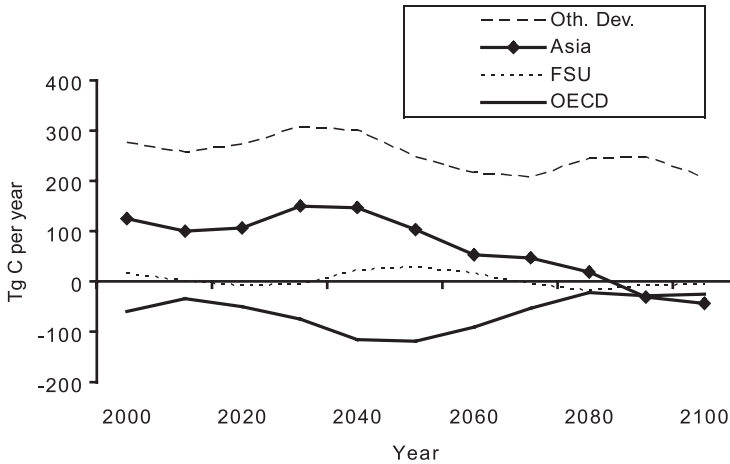
As a result of deforestation, the world's forests are projected to emit carbon over the coming century. Annual global forest emissions are projected to be 368 Tg C per year ($1 \text{ Tg C} = 1 \times 10^{12} \text{ g C}$) during the period 2000–2010, with most of the emission arising from deforestation in tropical regions (Figure 2). These estimates are lower than other estimates of annual emissions from deforestation for recent periods, such as Dixon et al (1994), although estimates of net global terrestrial

Figure 1. Baseline Area of Forestland in each Region in 2000, 2050, and 2100



4. For additional discussion trends in global timber markets see Daigneault et al. (2005).

Figure 2. Trends in Carbon Emissions (+) or Sequestration in Aggregated Regions (-) of the World under the Baseline. (OECD = North America, Europe, and Oceania; FSU = Russia and Central Asia; Asia = China, India, SE Asia; Oth. Dev. = South America and Africa)



fluxes have been revised downward in recent years (Houghton, 2003 and Plattner et al., 2002). The most recent estimates from Houghton (2003) suggest net fluxes of 700 Tg C per year rather than 1400 Tg C per year as previously believed.

3.2 Scenario Analysis

For the scenario analysis on carbon prices, 6 different price paths are considered. Carbon prices are assumed to be exogenous to the timber model and are introduced into equation (2) above through CC_t . The price paths were developed in conjunction with the EMF-21 process to simulate a range of potential energy model responses to climate policy. The scenarios used in this analysis are as follows:

- Scenario 1: $P_{2010}^C = \$5$ per ton C; rising at 5% per year
- Scenario 2: $P_{2010}^C = \$10$ per ton C; rising at 5% per year
- Scenario 3: $P_{2010}^C = \$10$ per ton C; rising at 3% per year
- Scenario 4: $P_{2010}^C = \$20$ per ton C; rising at 3% per year
- Scenario 5: $P_{2010}^C = \$100$ per ton C; remaining constant over time.
- Scenario 6: $P_{2010}^C = \$75$ per ton C; rising by \$5 per year through 2050.

Scenarios 1–4 simulate alternative mitigation policies that attempt to meet long term stabilization goals (i.e., stabilizing the radiative forcing from greenhouse gases at 4.5 Watts per square meter). Different initial prices are used to address

different assumptions from energy models regarding abatement costs, and the inclusiveness of different greenhouse gases. Higher initial prices could arise when only carbon measures are included in policy, and the lower initial prices could occur when other greenhouse gases, such as methane, can also be used to reduce net global emissions. Different rates of growth in carbon prices capture different assumptions about the discount rates used in energy models. In a world with efficient allocation of a cumulative cap without backstop technologies, the price of greenhouse gas abatement will rise at the rate of discounting (Herzog et al., 2003). Our scenarios include two rates of growth in carbon prices (3% and 5%) in order to assess the effects of different discount rate assumptions used in energy models.

Scenarios 5 and 6 examine how carbon sequestration enters global policies that attempt to meet stringent near term objectives. For instance, EMF 21 energy modelers address the possibility of trying to meet targets that limit the rate of warming over the century. Such targets would likely raise near term greenhouse gas abatement prices substantially relative to the price paths in scenarios 1–4. We consider a constant price path of \$100 per t C, and a price that is initially \$75, rising at \$5 per year through 2050. For results from a wider range of potential carbon price paths, see Sedjo et al. (2001).

Over the century, prices in the scenarios rise to levels ranging from \$100 to \$807 per t C in 2100, and cumulative sequestration ranges from 59 to 146 Pg C (Table 2) on 588 to 1527 million hectares of additional forestland (Table 3). Cumulative sequestration is the increase in carbon above the baseline case. Two key results emerge from reviewing the paths of carbon sequestration over the century in Figure 3. First, when carbon prices start at a relatively low level but rise at 3–5% per year, most carbon sequestration occurs later in the century. More rapid increases in carbon prices make it more valuable to wait until later periods to store carbon, so the 5% annual increases in carbon prices sequester little initially,

Figure 3. Path of Cumulative Carbon Sequestration above the Baseline for the Scenarios

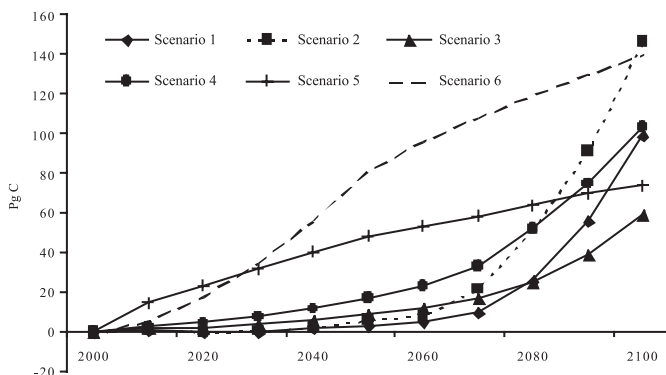


Table 2. Cumulative C Sequestration Above Baseline in Each Region of the Model for the Years 2020 and 2100

Original Land Use Change Assumptions						
Scenario →	1	2	3	4	5	6
Pg C Cumulative Sequestration in 2020						
<i>Temperate</i>						
North America	0.2	0.4	0.4	0.9	4.0	2.7
Europe	0.1	0.0	0.1	0.3	0.8	0.9
FSU	0.1	0.3	0.3	0.6	3.2	3.0
China	0.1	0.1	0.1	0.2	1.1	0.9
Oceania	0.0	0.0	0.0	0.1	0.3	0.3
<i>Tropical</i>						
South America	-0.2	0.0	0.3	0.8	4.9	4.4
India	0.0	0.0	0.0	0.0	0.1	0.1
SE Asia	-0.5	-0.9	0.4	0.8	5.2	3.0
Africa	0.1	0.0	0.4	0.8	3.5	3.0
Total	-0.2	0.0	2.1	4.5	23.1	18.2
Pg C Cumulative Sequestration in 2100						
<i>Temperate</i>						
North America	13.2	21.4	6.0	14.9	8.8	22.3
Europe	4.2	8.9	2.0	3.8	3.5	6.4
FSU	8.3	12.0	4.7	8.1	8.7	11.5
China	4.8	8.9	2.1	4.5	1.8	9.7
Oceania	2.2	5.5	0.7	1.3	0.5	1.7
<i>Tropical</i>						
South America	24.7	34.5	17.4	26.7	20.0	30.6
India	0.6	1.1	0.2	0.6	0.3	1.8
SE Asia	22.4	29.1	13.1	23.5	15.5	29.9
Africa	18.2	25.2	12.9	20.2	14.8	26.1
Total	98.6	146.6	59.1	103.6	73.9	139.8

but substantial carbon by the end of the century. Under long term stabilization policies with annual emissions caps and efficient allocation of trades across time, carbon sequestration does not substitute for energy mitigation in early periods. Energy models that use higher interest rates will place less emphasis on carbon sequestration in early periods than models using lower interest rates.

Second, policies that emphasize near term policy goals, such as limiting the rate of growth in emissions, or limiting decadal temperature changes over the century, will tend to have higher initial carbon prices. These higher initial prices will in turn increase the role of carbon sequestration in abatement policy. The results in scenarios 5 and 6 show that if there is high willingness to pay for mitigation in early periods (> \$75 - \$100 per t C), then 35–80 Pg of carbon could be stored in forests by 2050. Furthermore, because forestry involves some actions that have long-term consequences (i.e. afforestation on old agricultural land), higher initial carbon prices can increase long-term sequestration. Consider,

for example, scenarios 3 and 5. Carbon prices in 2100 in scenario 3 are \$143 per t C and in scenario 5 they are \$100 per t C. Scenario 5, with lower prices in 2100, sequesters more C (74 Pg) than scenario 3 (59 Pg) because the higher prices earlier increase the land devoted to forestry, which increases long-term sequestration. The results confirm the finding in Sohngen and Mendelsohn (2003) that it takes some time to sequester carbon, and that attempts to obtain carbon more quickly could be expensive.

Regionally, most carbon by 2100 is stored in tropical regions (South America, SE Asia, and Africa) due to high rates of deforestation and the costs of maintaining that land in forests is lower compared to other regions (Table 2). North America sequesters substantial carbon due to the relatively large area of existing agricultural land that can be converted to forests. Russia has a large land area, and many forests, but sequesters less carbon than North America because there is less agricultural land there suitable for forests, and forest growth rates are slower.

The rapid price increases in scenarios 1–4 suggest little near-term carbon sequestration in all regions. In some tropical regions, rapidly increasing carbon prices can lead to additional emissions by 2020 because additional forestland is converted to agriculture (Table 3). Landowners can get the benefits of agriculture now, and the benefits of carbon sequestration in the future by reforestation at high carbon prices, so they increase deforestation in early periods if carbon prices are rising rapidly as in scenarios 1 and 2.⁵ Temperate regions represent a larger proportion of total global storage in 2020 than in the long-run, with North America and Russia having the most near-term potential, followed by Europe, China, and Oceania. Temperate regions take advantage of the current heavy use of forests for industrial forestry activities, and focus on extending timber rotations initially. For example, by 2020 in North America, there is positive sequestration (Table 2) due to rotation extensions (Table 3). Higher initial prices, as in scenarios 4 and 5, lead to an even heavier emphasis on increasing rotations and increasing forest management in order to sequester carbon.

To see the relative contributions of land versus management for sequestration in forestry, Table 4 presents the percentage of carbon storage in 2100 derived from land use change, with the remainder of the carbon coming from increased management. In temperate regions, 35–46% of the carbon is stored as a result of land use change, and 55–65% of the carbon is stored as a result of changes in management. The balance between management and land use change depends in part upon the price path. Rising prices over time (Scenarios 1–4) imply that more than 40% of carbon is likely to result from land-use change in temperate regions. Stable, but higher prices (scenarios 5 and 6), place more emphasis on adjustments in management, and in particular on extending rotation ages. The tropical regions behave differently, with 73–88% of the carbon resulting from land use change.

5. The model assumes rational expectations. Alternative models that do not allow for expectations would likely show more sequestration in early periods for the same carbon price paths.

Table 3. Additional Forestland Area Above Baseline in Each Region of the Model for the Years 2020 and 2100

Original Land Use Change Assumptions						
Scenario →	1	2	3	4	5	6
Additional Area (Million Hectares) in 2020						
<i>Temperate</i>						
North America	-7.3	-1.8	6.2	10.0	63.1	66.9
Europe	8.2	0.9	8.2	12.8	34.8	31.9
FSU	5.6	17.5	12.7	30.5	94.5	73.1
China	0.8	1.0	4.7	6.0	27.7	31.1
Oceania	1.2	-1.7	1.3	1.7	7.3	9.2
<i>Tropical</i>						
South America	-0.9	1.9	5.2	9.3	47.5	56.2
India	0.0	0.1	0.1	0.1	5.0	6.1
SE Asia	-1.9	2.0	5.1	11.2	49.5	49.6
Africa	0.3	0.3	3.8	7.4	36.6	47.7
Total	6.0	20.0	47.3	89.0	366.0	371.9
Additional Area (Million Hectares) in 2100						
<i>Temperate</i>						
North America	167.2	225.0	87.8	146.1	56.8	133.1
Europe	105.2	164.8	44.0	77.3	33.1	71.1
FSU	185.5	230.2	115.5	152.3	96.1	126.0
China	88.9	138.5	43.3	71.7	31.1	61.7
Oceania	38.6	49.9	9.0	21.7	4.2	17.4
<i>Tropical</i>						
South America	251.4	275.6	209.2	242.9	155.3	228.9
India	20.9	24.8	9.5	19.9	7.7	19.8
SE Asia	160.8	165.8	88.0	151.6	71.1	150.2
Africa	215.1	252.8	188.4	204.7	132.6	204.9
Total	1233.6	1527.3	794.7	1088.2	588.0	1013.1

3.3 Sensitivity Analysis on Land Use Change in Tropics

The results above suggest the relative importance of reducing deforestation the tropics as an option for mitigating climate change. Central and South America, Africa, and Southeast Asia account for more than 65% of global potential sequestration over the century. The model emphasizes reducing deforestation during early periods, followed by afforestation in later periods. There is widespread uncertainty about the level of deforestation that will occur in the tropics over the next century in the baseline, however. This section describes the results of an analysis of the same six scenarios with an alternative baseline that allows greater deforestation in early periods in tropical regions.

The alternative baseline is developed to mimic the levels of deforestation exogenously imposed in many energy models used for the IPCC Special Report on

Table 4. Percent of Cumulative Carbon Sequestration in Each Region Accomplished by Changes in Land Use in 2100

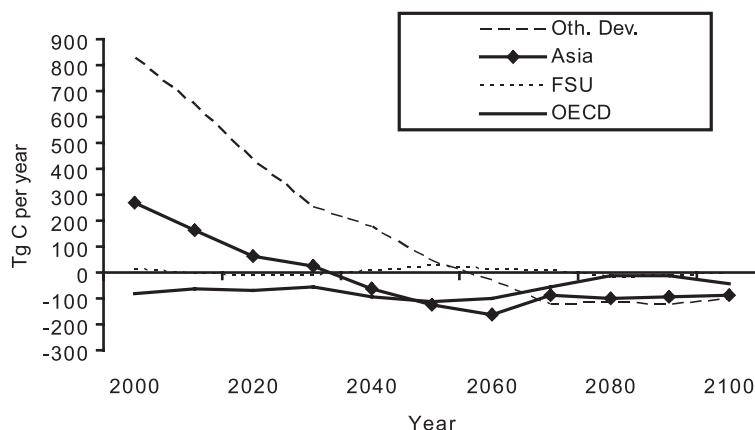
Scenario →	Percentage C from Land Use Change in 2100 ¹					
	1	2	3	4	5	6
<i>Temperate</i>						
North America	42	40	43	35	25	27
Europe	42	38	31	37	38	42
FSU	50	49	56	50	46	56
China	47	46	51	47	31	34
Oceania	54	43	46	44	24	24
Temperate Total	45	43	46	41	33	37
<i>Tropical</i>						
South America	85	75	88	87	88	84
India	67	62	61	45	51	46
SE Asia	74	70	81	76	73	50
Africa	87	79	95	90	95	83
Tropical Total	82	75	88	84	85	73
Global Total	71	65	75	70	69	62

1. The role of management and market storage can be determined by calculating $100\% - \text{Land Use Change } \%$.

Emission Scenarios (SRES; IPCC, 2000). This alternative baseline is generated by adjusting the parameters of the rental function in equation (10) above for forests in Central and South America, Africa, and Southeast Asia only. The parameters for the alternative baseline are chosen to obtain more deforestation initially, less future deforestation, and more cumulative deforestation than the original baseline. Deforestation rates in tropical regions, including South and Central America, Africa, and Southeast Asia, have been estimated at around 12.2 million hectares of net forest loss per year for the period 1991–2000 (Houghton, 2003). Annual deforestation in these same regions projected for the period 2000–2010 is 7.2 million hectares per year in the original baseline, and 12.7 million hectares per year in the alternative baseline. Overall deforestation during the century in the original baseline is 431 million hectares, while in the alternative baseline it is 525 million hectares. The baseline carbon emission from land use change and forestry generated by the alternative baseline is shown in Figure 4, which can be compared directly to Figure 2. Total emissions from deforestation are initially greater in the alternative baseline scenario, although they decline over time. By 2100, all regions in the model are sequestering net carbon in the alternative baseline.

The alternative baseline suggests a range of total potential carbon sequestration over the century of 48 to 133 Pg C. This amounts to about 16% less carbon sequestration than projected under the original baseline (Table 5). The differences are largest in the tropical regions because the rental functions were adjusted in these regions only. Timber prices do not change substantially, and the temperate regions sequester nearly as much carbon as in the baseline case.

Figure 4. Alternative Baseline Scenario Carbon Emission Path. (OECD = North America, Europe, and Oceania; FSU = Russia and Central Asia; Asia = China, India, SE Asia; Oth. Dev. = South America and Africa)



Even though the assumption of increased deforestation rates suggests that more land is available for reducing deforestation or ultimately for afforestation, costs are higher. Economic forces that lead to more deforestation in the tropics include higher demand for agricultural land. This higher demand for agricultural land raises rental rates, and increases the costs of keeping land in forests. This in turn raises the costs of carbon sequestration in regions where land use is particularly important, such as the tropics.

4. CONCLUSION

This paper presents the results of a scenario analysis exploring how alternative greenhouse gas abatement prices and price paths could potentially affect the timing and quantity of carbon sequestration in forests. In addition, the paper explores the sensitivity of carbon sequestration costs to alternative assumptions about deforestation rates in the tropics. The carbon price scenarios are developed as part of the EMF-21 process to be consistent with other models exploring carbon sequestration, and to be consistent with prices generally observed in energy models analyzing the efficiency of climate policy.

Overall, the results indicate that 48–147 Pg C could be stored in forests through land use and forestry activities in the next century if carbon prices rise to \$100 to more than \$800 per t C. About 65% of the sequestration projected by this model occurs in tropical regions, with over 65% of that resulting from

Table 5. Cumulative Carbon Sequestration Above the Alternative Baseline in each Region of the Model for the Years 2020 and 2100. The Alternative Baseline Scenario Projects More Initial and Total Land Use Change in Tropical Regions than the Baseline

Accelerated Deforestation Baseline						
Scenario →	1	2	3	4	5	6
Pg C Cumulative Sequestration in 2020						
<i>Temperate</i>						
North America	0.3	0.0	0.5	0.8	4.2	2.9
Europe	0.0	-0.1	0.0	0.2	0.5	0.8
FSU	0.1	0.3	0.3	0.7	3.2	3.2
China	0.1	0.0	0.1	0.2	1.0	0.8
Oceania	0.0	0.0	0.0	0.1	0.3	0.3
<i>Tropical</i>						
South America	-0.1	-0.3	0.8	1.3	4.9	4.1
India	0.0	0.0	0.0	0.0	0.1	0.1
SE Asia	0.1	0.4	0.3	0.7	5.3	2.5
Africa	0.0	0.0	0.3	0.5	3.5	2.7
Total	0.4	0.4	2.4	4.4	23.1	17.4
Pg C Cumulative Sequestration in 2100						
<i>Temperate</i>						
North America	13.7	22.8	6.8	15.7	8.7	18.6
Europe	3.8	9.2	1.8	3.9	3.6	5.8
FSU	6.9	11.9	4.8	8.0	8.7	11.8
China	4.1	8.8	2.1	4.4	1.7	9.9
Oceania	2.3	5.2	0.7	1.7	0.5	1.5
<i>Tropical</i>						
South America	21.1	30.9	14.2	22.7	16.5	26.0
India	0.6	1.1	0.2	0.6	0.3	0.8
SE Asia	15.9	22.1	9.8	17.2	11.3	19.6
Africa	13.3	20.9	7.9	14.3	8.8	19.0
Total	81.8	132.9	48.2	88.3	60.2	112.9

changes in land use (either reducing deforestation or inducing afforestation). The temperate zones sequester less carbon overall, but sequester more of it (54–67%) by changing management of forests to increase growing stock.

Sensitivity analysis on an alternative baseline case with more extensive deforestation in tropical regions suggests that assuming more deforestation in the baseline can increase the costs of sequestration. Higher deforestation rates are generated in the model by changing parameters in the land rental functions for tropical regions. Higher rental rates induce more deforestation. While the area of land deforested increases when comparing the alternative baseline case to the original baseline case, the cost of reforesting land or maintaining it in forests, is

higher as well. Thus, higher land prices reduce the potential role for tropical regions for the same prices. The rental rates were changed only for the tropical regions, so while there are some slight adjustments in potential carbon sequestration in the temperate zone, the results are fairly consistent for the temperate forests under both sets of baseline assumptions.

The results highlight several key issues that will arise when considering how carbon sequestration in forests should efficiently enter the set of policy prescriptions that could be used to reduce climate change damages. First, the rate of growth of carbon prices can influence the timing of sequestration. The results of this study indicate that if carbon prices are rising more than 3% per year, then most carbon sequestration occurs in later periods. Higher rates of growth in carbon prices give landowners an incentive to hold-off on investing in forest carbon sequestration until later periods when carbon sequestration is most valuable. Second, the rate of growth of carbon prices influences the regional distribution of sequestration, in particular early during the century. More rapid price increases enhance the relative contribution of sequestration from temperate regions. South America and Asia-Pacific emit additional carbon during early periods if carbon prices are rising rapidly because additional deforestation occurs in early periods when carbon prices are low. This confirms the finding in earlier research by Sedjo et al. (2001) who also found that rising prices could limit the role of sequestration in carbon policy during the early part of the century.

Third, including other options reduces the costs of greenhouse gas abatement over the long run, i.e. methane abatement, then carbon prices will be lower and forestry will be a smaller part of the puzzle. We find that a 50% increase in carbon prices over the century increases projected carbon sequestration by 32%–42%. Of course, to fully understand the effects of alternative options for greenhouse gas mitigation on prices and forest sequestration, one would need to integrate forestry directly into energy models that include a full range of options for greenhouse gas abatement. Finally, more rapid carbon sequestration is possible, although it could be very costly. The two scenarios that had high initial carbon prices, scenarios 5 and 6, sequester substantial carbon initially and in the long run. These scenarios are most consistent with policies that set strict emissions targets in particular commitment periods, or that attempt to limit the rate of change of temperatures over time. More stringent earlier targets for carbon sequestration therefore, likely should rely on forestry options for meeting these targets.

Overall, the results in this study imply that forestry is less of a stop-gap measure for a long-term policy, but instead, an important long-term source of carbon abatement. Large forest sequestration programs early in the century are efficient only if policy focuses on stringent targets early in the century that result in high and fairly stable carbon prices. These results differ from the role typically suggested for forests as a short term measure that can buy time for other technologies to emerge (Watson et al., 2000; Metz et al., 2001).

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Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry

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Traditionally, economic analyses of greenhouse gas (GHG) mitigation focused on carbon dioxide (CO₂) emissions from energy sources, while non-CO₂ GHGs were not incorporated into the studies, due to the lack of data on abatement costs of non-CO₂ GHGs. In recent years, however, increasing attention has been dedicated to the benefits of reducing emissions of non-CO₂ GHGs such as methane and nitrous oxide. Increased attention to the potential role of these gases in a GHG reduction policy increased the need for better data on the costs of non-CO₂ GHG abatement for countries and regions outside of the US and the European Union (EU). Using a net present value calculation, this analysis develops regionally adjusted costs per mitigation option and marginal abatement cost curves by region for use in economic models. The result is worldwide cost estimates for methane and nitrous oxide from waste, energy and the industrial sectors. This paper also demonstrates the ability to significantly reduce greenhouse gases from these sectors with current technologies and the low cost of methane and nitrous oxide relative to CO₂ reductions.

1. INTRODUCTION

Information on the range of options for and costs of abating non-CO₂ greenhouse gases (GHGs) from anthropogenic sources is of primary importance

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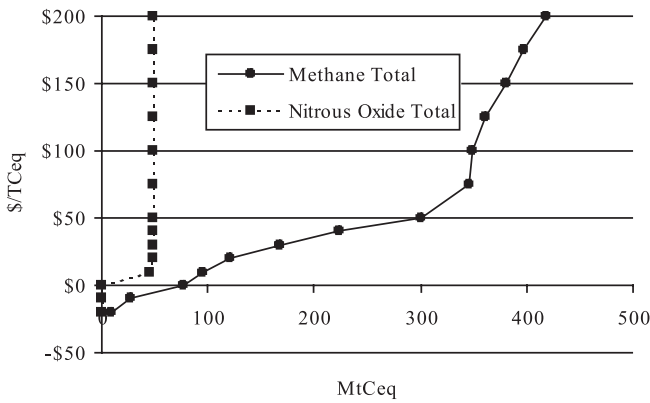
for decision-makers to optimize the allocation of resources in support of climate change policies. The objective of this analysis is to provide economic modeling teams with engineering and cost information for non-CO₂ GHG abatement options to incorporate into established climate analysis models. In this paper, the focus is on methane and nitrous oxide mitigation from the waste, industry and energy sectors. However, the methodology presented can be adapted to estimate mitigation costs of other gases from both industrial and agricultural sectors (DeAngelo et al., 2006, Ottinger et al., 2006). Methane sources analyzed in this report include: coal mining; natural gas systems; oil production; and solid waste management. Nitrous oxide sources analyzed in this report include adipic and nitric acid production only.

To facilitate its use, the data is presented in both the form of marginal abatement curves (MACs) and in a more disaggregated technology-specific reporting format that provides specific reductions and costs associated with particular technologies. For models able to generate a marginal abatement analysis endogenously using mitigation option data, information in the form of abatement potential and mitigation costs is provided in a database format for each technology. Each methane and nitrous oxide abatement option included in this analysis is characterized by an abatement potential expressed as a percent reduction from baseline emissions and by the associated costs and benefits of achieving a reduction expressed in constant 2000 US dollars per ton of carbon equivalent (\$/TCeq). The construction of this data is based on existing engineering-economic studies for the US (USEPA, 2001a, 2001c, 1999) and the EU (EC, 2001, IEAGHG, 2000. If not, then this source is not listed under resources) that apply available abatement options (technologies and management practices) to major sources of methane and nitrous oxide from the waste, industry and energy sectors. These studies together with available country or region-specific emissions and economic data are the basis for this new international cost analysis of non-CO₂ GHG abatement. The technology-specific data was then used to build the MAC curves.

MACs are straightforward, informative tools in policy analyses for evaluating economic impacts of GHG mitigation. A MAC illustrates the amount of reductions possible at various values for a unit reduction of GHG emissions and is derived by rank ordering individual opportunities by cost per unit of emission reduction. Any point along a MAC represents the marginal cost of abating an additional amount of a GHG. The total cost of meeting an absolute emission reduction target can be estimated by taking the integral of a MAC curve from the origin to the target.

For both the MACs and the more technology-specific data set, sets of sector-specific options are applied to each region and the costs and benefits of the options are adjusted for the regional differences in energy and labor costs, and a regional abatement potential. The results vary by region and by source, and by discount rate, tax rate and energy price. The MACs and technology information is presented in full in the complete data set available on the Stanford Energy Modeling Forum web site at <http://www.stanford.edu/group/EMF/home/index.htm>, see EMF21 Data.

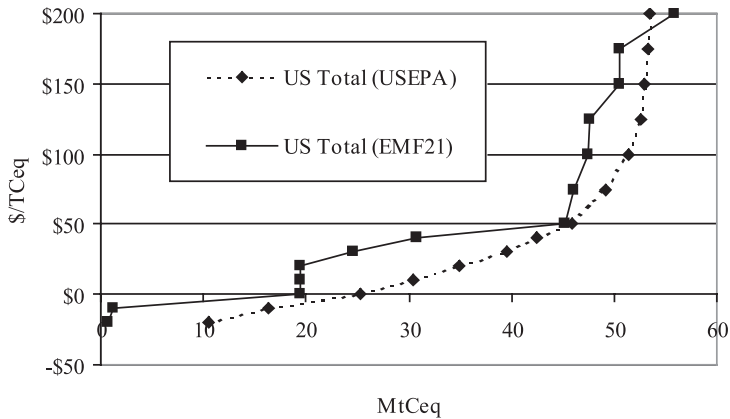
Figure 1. Summary Results for 2020 Global Reductions
(Using a 20% Discount Rate and 40% Corporate Tax Rate)



2. COST ANALYSIS METHODOLOGY

The international estimates of methane and nitrous oxide abatement in this analysis are based on previous studies by the US Environmental Protection Agency (USEPA), the International Energy Agency Greenhouse Gas R&D Programme (IEAGHG), and the European Commission (EC). The USEPA published several studies detailing the reduction potential and costs of mitigation technologies, including estimates for sector-specific marginal abatement costs for methane (USEPA, 2001a, 1999) and nitrous oxide (USEPA, 2001c). An analysis conducted by the IEAGHG evaluated technologies and costs of methane and nitrous oxide reductions for the major developed regions (IEAGHG, 2000) and one study by the EC evaluated technologies and costs for non-CO₂ GHGs in the EU-15 countries (EC, 2001). The US, IEAGHG and EU studies provide estimates of potential non-CO₂ GHG emission reductions from major emitting sectors and the technical characteristics of the mitigation options used in the analysis, and quantifies the costs and benefits of these mitigation options.

The EC and IEAGHG analyses primarily are based on evaluating the abatement potential options and associated costs at representative facilities or point sources of emissions, e.g., waste digesters, and then extrapolating the results to a country or region. USEPA's US analysis (USEPA 1999, 2001a, 2001c) also uses representative facility estimates but applies them to a highly disaggregated and detailed set of emissions sources for all major sectors and sub-sectors. This approach is possible primarily due to the availability of more detailed data in the US. This more detailed approach also results in a marginal abatement cost curve with more data points for the US, i.e., additional abatement cost calculations per sector. For example, the US analysis of the natural gas sector is based on emission factors for over 100 sources for that industry, including gas well equipment, pipeline compressors and equipment, and system upsets.

Figure 2. Comparison of the U.S. Analysis (USEPA) and the Current Average Methodology for 2020 Methane Mitigation

The EC analysis provides a sector-average cost for individual abatement options at the country or EU-15 regional level, which can be applied to published sector-level emissions data. The US cost information is firm specific and can not be applied to most countries because of limited data availability. The US cost information is therefore aggregated to the sector level in order to apply the information to sub-sector or sector level emissions data. For this international analysis, the average approach was adopted. The use of average costs and benefits facilitates the use of national, aggregated emissions estimates, since data on detailed source-specific emissions is limited. This allows for a consistent methodology throughout the analysis for all regions. The average EU and US abatement costs and benefits for a variety of abatement options are then combined to build a set of options. This new combined set of abatement options is applied to all defined regions in the study, including the US and the EU, as well as for regions where data and detailed analyses are not available. It should be noted that mitigation estimates from this “average” approach are more conservative than those reported in the more detailed US reports, both in terms of costs and potential reductions, shifting the curve upward due to higher costs and towards the left due to less abatement potential (See Figure 2). However, due to the addition of technologies not considered in the original US reports, at higher cost levels, the curve shifts to the right compared to the more detailed methodology due to higher prices to the inclusion of more mitigation options.

2.1 Abatement Options

The analysis starts by establishing a list of abatement options for each gas by source category (e.g. coal mining, natural gas) from previous engineering and economic studies (USEPA 1999, 2001a, 2001c; IEAGHG, 2000; EC, 2001). Abatement options for methane and nitrous oxide emissions from energy, waste and

industry are well established. Because methane is the major component of natural gas, many natural gas technologies apply to the major, non-agriculture-related emissions of methane. Nitrous oxide reductions can be reduced from industry by technologies related to NO_x emission reductions developed due to clean air regulations. Each abatement technology is applied to a region's emission projection baseline based on expert analysis of whether a specific option is appropriate for that region's infrastructure and economic conditions. The selective omission of options represents a 'static' view of the region's socio-economic conditions. Ideally, more detailed information on country-specific conditions, technologies and experiences will be available in the future, which will enable more rigorous analyses of abatement potential in other regions.

If a technology is considered appropriate for a specific region in the given time frame, the option is applied to the baseline emissions of the appropriate sector (e.g. natural gas sector) or subsector (e.g. transmission and distribution of natural gas, processing of natural gas). Reductions are based on the reduction efficiency of the mitigation technology and the applicability of the technology to the sector or sub-sector specific emissions.

Methane abatement options generally capture methane and use it as energy, flare the methane or avoid methane releases. Nitrous oxide abatement technologies for industry reduce the nitrous oxide to nitrogen and oxygen. Specific abatement options vary by sector. For a complete list and short description of each technology, please see the technology tables listed on the EMF website at <http://www.stanford.edu/group/EMF/home/index.htm>.

2.1.1 Methane Abatement Options for Solid Waste Emissions

Landfill gas contains about 50 percent methane and can be collected by vertical wells and horizontal trenches after the section or cell of the landfill has been closed. Once the landfill methane is collected it can be used in a number of ways, including on-site electricity generation (sold to the electric grid), direct gas use (e.g. used near by industrial boilers) or flared. Methane can also be prevented from escaping from the landfill through improved landfill caps (clay or other cover soils). Waste streams can also be diverted from landfills and composted or utilized in a bio-reactor to create energy.

2.1.2 Methane Abatement Options for Natural Gas Sector Emissions

Reductions in the natural gas sector come from reducing leakage in the system. There are over a hundred documented techniques to reduce leakage during each stage. In this analysis, these options are grouped into 33 equipment or management practices. Management practices involve increased maintenance and inspection at various points in the natural gas system. Equipment options include installing more efficient pipes and seals in the system, and installing low-bleed pneumatic devices, installing more efficient compressors and chemical injection

pumps, installing catalytic converters which more efficiently combust methane, reducing circulation rates in glycol dehydrators, and reduced venting.

2.1.3 Methane Abatement Options for Coal Mining Emissions

Coal mines already employ a range of technologies for draining methane from coal seams. These methods have been developed primarily for safety reasons, as a supplement to ventilation systems. However, degasification systems are generally used to vent methane emissions into the atmosphere. Additional measures are needed to capture and use methane liberated from the coal seam. Methane abatement options can be applied to either methane recovered from degasification systems, which can be used in natural gas pipeline injection or as onsite electricity generation, or applied to methane captured in the ventilation system which can be catalytically oxidized and used to generate onsite electricity.

2.1.4 Methane Abatement Options for Oil Extraction Emissions

In oil extraction, methane is released from the oil well during drilling. The methane released can be flared, captured and used for electricity or turned into liquefied natural gas. The costs of the options vary widely depending on whether or not the drilling is onshore or offshore.

2.1.5 Nitrous Oxide Abatement Options for Adipic Acid Production Emissions

The only adipic acid production option considered in this analysis is thermal destruction. Thermal destruction eliminates 96 percent of the nitrous oxide from the process by destroying the off-gases released from the boiler in flame burners.

2.1.6 Nitrous Oxide Abatement Options for Nitric Acid Production Emissions

Nitrous oxide from nitric acid production can be destroyed through either high temperature or low temperature catalytic reduction methods or a non-selective catalytic reduction method. Each method, seven in all, uses different catalysts to reduce nitrous oxide to nitrogen and oxygen. On average, these methods reduce nitrous oxide emissions by 89 percent.

2.2 Application of Mitigation Options to Emission Stream

Current and projected methane and nitrous oxide emission estimates to 2020 in this report are obtained primarily from referenced documents (Scheehle and Kruger, 2006) and represent the business-as-usual or no climate policy baseline. Baselines for methane and nitrous oxide are sector specific and in some cases sub-sector specific depending on the portion of the emission stream that corresponds to the abatement technology. For example, coal mine degasification

systems can only be applied to underground mines; therefore, the coal sector emissions are divided into underground and surface mining emissions.

Although the methane and nitrous oxide emissions data are from published sources, little or no data are available on options that are currently implemented. For the purpose of this analysis, due to the lack of more specific information on market potential, the majority of options were given an equal market potential across all options. Overlapping projects and non-overlapping projects are treated differently in the analysis. Overlapping options are defined as options where only one option could be applied to the same source of emissions. For example, it is assumed that a landfill will choose either a direct gas use project or an electricity project, but could not implement both. Each of the *n* overlapping options is applicable to $1/n$ of the total emissions, which assumes a uniform distribution of options competing to reduce emissions, notwithstanding their net costs or other factors. This assumption reflects the lack of region-specific data for determining the relative level of diffusion of overlapping options, which can be used as alternatives to abate the same emission stream.

The applicability of *non-overlapping* options is assumed to be equal to 100 percent. An example of two non-overlapping options in the natural gas system are (1) inspection and maintenance of compressors, and (2) replacement of distribution pipes. These options are applied independently to different parts of the sector and do not “compete” for the same emission stream. This estimate represents the market potential each option has in a given region. In summary, the market potential is $1/n$ for overlapping options or 100 percent for non-overlapping options.

Once the emission stream available for reduction is disaggregated into subsector estimates and divided among overlapping or non-overlapping technologies, the reductions calculated are based on the reduction efficiency of the technology. For example, if eight landfill mitigation technologies are applicable to a region and can be applied to the entire landfill sector emission stream, each of the eight technologies is given a market potential of 12.5 percent. The reduction efficiency of a technology is the ability of the technology itself to reduce methane or nitrous oxide from the source. To continue with the landfill example, a direct gas use project can reduce on average the emissions from a landfill by 75 percent. Therefore, the emission reductions is estimated by multiplying the landfill sector baseline emissions by 12.5 percent representing the market potential of each of the eight competing options, and then by 75 percent representing the actual reductions from a direct gas use project. This calculation yields the emissions reduced in a given country by direct gas use projects in the marginal abatement analysis.

2.2.1 Indirect Greenhouse Gas Emission Reductions

For methane and nitrous oxide, this analysis does not account for indirect emission reductions, which can result from either the substitution of electricity from

the grid with electricity produced on-site from recovered methane or the substitution of natural gas in pipelines with recovered methane. Calculation of such indirect reductions requires additional assumptions about the carbon intensity of electricity in different regions. In the US landfill sector, indirect reductions generally augment emission reductions by about 15 percent. For nitrous oxide, reductions do not include potential benefits in NO_x reductions from the abatement technologies.

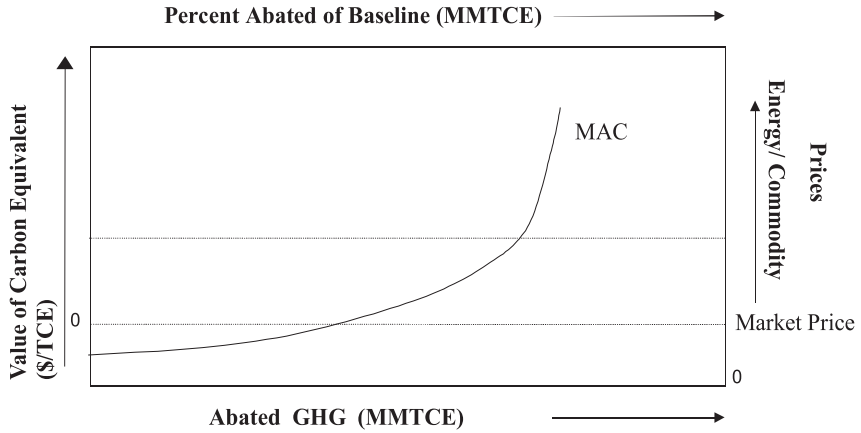
2.3 Economic Characteristics of Abatement Options

Each abatement option is characterized in terms of its costs and benefits per an abated ton of methane or nitrous oxide, then converted into metric ton of carbon equivalent (MtCeq) and carbon dioxide equivalent (MtCO₂eq). To convert from N₂O and CH₄ to MtCO₂eq, the 100-year Global Warming Potentials (GWPs) from the 1996 IPCC Second Assessment Report are used. According to the report, the GWP for N₂O and CH₄ is 310 and 21, respectively. To convert to MtCeq the data is then converted from MtCO₂eq by multiplying by (12/44). The GWPs from the IPCC Third Assessment Report (2001) are not used because international GHG reporting guidelines are still based on the Second Assessment Report.

All costs and revenues are reported in 2000 USD. Costs include capital or one-time costs (κ) and operation and maintenance costs (μ). Furthermore, some one-time costs (where data are available) are subdivided into labor and equipment components. Benefits or revenues from employing an abatement option include: (1) the value of methane either as natural gas or electricity/heat; and (2) the value of abating a GHG in terms of \$/TCeq or \$/metric ton of GHG. In most cases, two price signals exist for the abatement of methane: one based on their market value as energy or an industrial gas and one based on their value as a GHG.

In Figure 3, the commodity/energy market price is aligned to \$0/TCeq since this price represents the point at which where no additional price signals exist from GHG credits to motivate emission reductions; all emission reductions are due to increased energy efficiencies, conservation of production materials, or both. As a value is placed on GHG reductions in terms of \$/TCeq, these values are added to the commodity/energy market prices and allow for additional emissions reductions to clear the market. The “below-the-line” amounts, with respect to \$/TCeq, illustrate this dual price-signal market.

The equipment component of fixed costs is the same for all the regions. However, costs of abatement options are adjusted based on regional labor costs. Since labor costs compose the majority of operation and maintenance (O&M) costs, they are used as a proxy to adjust O&M costs across regions as well as the labor component of the capital cost for some sectors. Specifically, O&M costs for each region are estimated based on a ratio between the average regional labor cost in manufacturing in that region and in the United States or European Union for US-based options or EU-based options, respectively. Regional labor costs in manufacturing are taken from World Bank data (2000). Benefits expressed

Figure 3. Illustrative Non-CO₂ Marginal Abatement Curve

as energy cost savings are adjusted based on regional energy costs (EIA, 2002). For methane, revenues are scaled based on the ratio between average prices of natural gas (when methane is abated and sold as natural gas) or of electricity (when methane is used to generate electricity or heat) in a given region and either the US or the EU.

2.3.1 Present Value Calculation

A present value analysis of each option is used to determine break-even abatement cost of an option in a given region. The analysis solves for ρ in the following equation:

PV (Benefits) = PV (Costs) or more specifically,

$$\sum_{t=1}^T \left[\frac{(\rho)(\epsilon)(1-\chi) + \psi(1-\chi) + \beta}{(1+\gamma)^t} \right] = \kappa + \sum_{t=1}^T \left[\frac{(\mu)(1-\chi)}{(1+\gamma)^t} \right]$$

where: ρ is the break even price of the option in \$/TCEq or \$/metric ton of GHG; ϵ is the emissions reduction achieved by the technology; ψ is the revenue generated from energy production (scaled based on regional energy prices) or sales of by-products of abatement (e.g., compost); T is the option lifetime; γ is the selected discount rate; κ is the capital cost of the option; μ is the recurring (O&M) cost of the option (scaled based on regional labor costs); β is the tax break equal to $\kappa/T * \chi$; and χ is the tax rate. All costs and benefits are expressed in constant 2000 USD. The conversion of EU costs, which were initially expressed in 1990 Euros (in the EC report), is conducted using appropriate inflation and exchange rates.

Table 1. Example Technology Data: Catalytic Oxidation of Ventilation Air Methane at Coal Mines (production of electricity)

	Capital Costs (\$/TCeq)	O&M Costs (\$/TCeq) adjusted by regional labor rate	Energy Revenue or Revenue from Gas Savings (\$/TCeq)	Abatement Potential (% of Baseline)	Break Even Price discount rate=4%; tax rate =0%	Break Even Price discount rate=20%; tax rate =40%
U.S.	\$166.90	\$10.80	\$15.20	19%	\$10.00	\$47.50
China	\$166.90	\$ 0.30	\$ 9.60	49%	\$ 5.00	\$42.50
Russia	\$166.90	\$ 0.60	\$11.00	11%	\$ 3.90	\$41.50

3. RESULTS

The main objective of this analysis is to evaluate the international potential and costs of non-CO₂ greenhouse gas abatement. The results cover the major emitting regions and the major sources of non-agricultural related sources of methane and nitrous oxide. The figures below illustrate the results. The full data set is available on the Stanford Energy Modeling Forum web site at <http://www.stanford.edu/group/EMF/home/index.htm>, see EMF21 Data.

Table 1 above is an example of the data available by technology by region. For each technology, the capital costs, O&M costs, energy revenue, reduction potential and the break even prices by discount rate and tax rate are presented in a tabular form for use in technology-rich models. In addition, each table has a short description of the technology and is categorized by sector and subsector.

Building on the above data shown in Table 1, the MAC curves are calculated and presented in tabular form by region, year and discount and tax rate combinations. Below are the global potential reductions at \$200/TCeq in 2020 at a 20 percent discount rate and a 40 percent tax rate. At \$200/TCeq, using current technologies, global emissions of methane from natural gas, oil, coal and solid waste can be reduced by 50 percent on average.

Adipic and nitric acid production only occurs in a few of the countries analyzed. However, in the countries where it occurs, current technology can reduce nitrous oxide emissions by 96 percent in the adipic acid production sector and by 89 percent in the nitric acid production sector. This analysis, however, does not reflect changes (either increases or decreases) in NO_x emissions associated with the adoption of these technologies.

3.1 Regional Results by Sector

The countries or regions with the highest emission rates generally have the highest reduction potentials as few countries have implemented mandatory reduction measures outside of the solid waste sector. The cost of reducing

Table 2. Marginal Abatement Curves for Methane Emitting Sectors in 2020 at \$200/TCeq (20% discount rate; 40% tax rate)

MtCeq	Solid Waste		Natural Gas		Coal		Oil		Total*	
	Absolute reduction	%	absolute reduction	%	absolute reduction	%	absolute reduction	%	absolute reduction	%
Africa	13.3	53%	4.7	44%	2.2	86%	0.2	37%	20.4	52%
ANZ	3.3	37%	1.8	38%	6.5	83%	0.0	14%	11.6	54%
Brazil	2.8	53%	2.3	37%	0.0	0%	0.0	27%	5.2	43%
Canada	2.4	37%	2.1	30%	0.0	0%	1.2	27%	5.6	31%
China	28.2	53%	1.2	44%	63.9	84%	0.4	38%	93.7	71%
CIS	2.8	53%	11.6	36%	1.6	58%	0.0	33%	16.0	40%
Eastern Europe	5.9	53%	4.1	34%	5.4	73%	0.0	13%	15.5	50%
EU15	7.5	37%	2.6	29%	2.1	41%	0.0	12%	12.2	35%
India	2.2	53%	10.1	43%	8.4	84%	0.0	18%	20.8	55%
Japan	0.3	47%	0.2	35%	0.3	98%	0.0	0%	0.8	52%
Latin America	9.8	53%	20.8	44%	0.0	0%	0.7	32%	31.3	44%
Mexico	2.9	53%	3.0	44%	0.8	86%	1.3	35%	8.0	47%
Middle East	9.0	53%	24.3	37%	0.0	86%	1.7	39%	35.1	40%
Non-EU Europe	1.1	86%	0.1	37%	0.0	50%	0.0	38%	1.2	79%
Russia	5.4	53%	28.3	35%	6.0	84%	0.1	31%	39.9	41%
South and SE Asia	9.3	53%	9.9	44%	9.8	84%	0.1	24%	29.1	56%
South Korea	0.5	37%	1.3	43%	0.0	0%	0.0	2%	1.9	38%
Turkey	1.4	37%	0.8	43%	0.3	24%	0.0	11%	2.5	37%
Ukraine	4.4	53%	2.7	38%	4.3	85%	0.0	16%	11.4	56%
United States	25.3	53%	12.2	31%	17.2	86%	1.0	18%	55.8	49%
Total	138.1	51%	144.2	38%	128.7	80%	6.8	29%	417.8	50%

*Note that data above does not include manure management or any other agricultural sectors.

emissions varies by sector and by region based on available mitigation options, cost of labor, and revenue potential of recovered energy.

3.1.1 Natural Gas Sector

The natural gas sector has the highest potential reductions in 2020 of any of the sectors analyzed in this analysis, with the top five emitting countries making

Table 3. Marginal Abatement Curves for Nitrous Oxide Emitting Sectors in 2020 at \$200/TCEq (20% discount rate; 40% tax rate)

MtCeq	Adipic Acid Production		Nitric Acid Production		Total	
	Absolute reduction	%	absolute reduction	%	absolute reduction	%
Africa	0.0	0%	0.0	0%	0.0	0%
ANZ	0.0	96%	0.1	89%	0.2	91%
Brazil	2.1	96%	0.2	89%	2.2	95%
Canada	0.2	96%	0.5	89%	0.8	91%
China	4.3	96%	5.0	89%	9.3	92%
CIS	0.0	0%	0.0	0%	0.0	0%
Eastern Europe	0.6	96%	1.3	89%	1.9	91%
EU15	4.1	96%	9.5	89%	13.6	91%
India	0.0	0%	5.0	89%	5.0	89%
Japan	0.9	96%	2.0	89%	2.9	91%
Latin America	0.0	0%	0.0	0%	0.0	0%
Mexico	0.0	0%	0.5	89%	0.5	89%
Middle East	0.0	0%	0.0	0%	0.0	0%
Non-EU Europe	0.2	96%	0.3	89%	0.5	91%
Russia	0.0	0%	0.0	0%	0.0	0%
South and SE Asia	0.2	96%	0.0	0%	0.2	96%
South Korea	2.1	96%	0.0	0%	2.1	96%
Turkey	0.0	0%	0.0	0%	0.0	0%
Ukraine	0.0	0%	0.0	0%	0.0	0%
United States	3.5	96%	5.8	89%	9.4	91%
Total	18.3	96%	30.2	89%	48.5	91%

up approximately 67% of the potential reductions. Of the 206 MtCeq of potential reductions from natural gas, Russia has the largest portion of those reductions at 39 MtCeq. The Middle East region, which includes the major OPEC countries, has the second largest reduction potential with a potential of 38 MtCeq in 2020. The Latin America region, which includes Venezuela, is third with 28 MtCeq. The US is ranked fourth and Commonwealth of Independent States (CIS) is ranked fifth with 22 MtCeq and 12 MtCeq of potential reductions, respectively.

Many low-cost or “no-regrets” options exist in the natural gas sector. For example, reducing glycol circulation rates in compressors in order to reduce the methane absorbed by the glycol and vented or cleaning compressors while turbines are still running instead of shutting them down and venting the gas. Changes in maintenance practices are cost effective ways of reducing methane, making the total cost of reductions in this sector low.

Table 4. Highest Potential for Methane Emission Reductions in the Natural Gas Sector

MtCeq	Russia	Middle East	Latin America	United States	CIS
\$(10)	0.0	1.6	0.6	0.7	0.0
\$(20)	0.0	2.4	3.1	1.2	0.0
\$0	3.0	7.2	3.1	4.8	1.1
\$10	3.0	7.2	5.2	4.8	3.5
\$20	12.5	7.2	10.4	4.8	5.7
\$30	15.9	10.9	10.5	6.5	6.8
\$40	21.3	10.9	13.2	7.6	8.9
\$50	21.4	13.4	13.5	7.7	8.9
\$75	21.7	16.3	13.6	7.7	9.0
\$100	21.7	16.4	13.6	9.1	9.0
\$125	24.2	17.2	17.0	9.2	9.9
\$150	28.1	20.4	17.5	12.1	11.5
\$175	28.1	20.4	17.6	12.1	11.5
\$200	28.3	24.3	20.8	12.2	11.6
Maximum Reduction	39.1	37.5	28.0	21.9	15.3

3.1.2 Solid Waste Sector

Emission projections from the solid waste sector are generally tied to population and population growth. Not surprisingly, the region with the largest potential reductions in the solid waste sector is China with the potential to reduce emissions by 28 MtCeq in 2020. The US has the second largest reduction potential, with 25 MtCeq in potential reductions, followed by Africa with 13 MtCeq in potential reductions. EU15 region is ranked seventh in the list because of the regions efforts in reducing waste placed in landfills.

The lowest cost options for the solid waste sector are those options that sell electricity or landfill gas rather than techniques such as composting or flaring. The revenue from selling the energy considerably reduces the cost of the mitigation project.

3.1.3 Coal Sector

Approximately 60 percent of projected 2020 methane emissions from underground coal mining are from China and the US. Because of this, the majority of potential reductions also comes from these two countries. Total potential reductions from the coal sector are 129 MtCeq. Potential reductions from the Chinese and US coal sector are estimated to be 64 MtCeq in 2020 and 17 MtCeq, respectively.

Table 5. Highest Potential for Methane Emission Reductions in the Solid Waste Sector

MtCeq	China	US	Africa
\$(10)	0.00	0.00	0.00
\$0	5.34	4.79	2.52
\$10	5.34	4.79	2.52
\$20	5.34	4.79	5.22
\$30	11.06	4.79	7.91
\$40	22.50	9.92	10.61
\$50	22.50	20.17	10.61
\$100	22.50	20.17	10.61
\$150	22.50	20.17	10.61
\$200	28.22	25.30	13.31
Greater than \$200	46.61	41.80	21.99

Table 6. Highest Potential for Methane Emission Reductions in the Coal Sector

MtCeq	China	US
\$(10)	0.00	0.00
\$0	0.00	9.85
\$10	0.61	9.85
\$20	0.61	9.85
\$30	0.61	13.31
\$40	0.61	13.31
\$50	37.58	17.20
\$75	63.91	17.20
\$100	63.91	17.20
\$200 and above	63.91	17.20

The majority of reductions in China are assumed to come from the catalytic oxidation of ventilation air methane. In the US, reductions are spread among degasifacation before mining and catalytic oxidation of methane in the ventilation air.

3.1.4 Oil Sector

The oil sector is the smallest source of methane emissions analyzed in this study, with only 8 MtCeq of potential reductions from the sector. The Middle East, Mexico, Canada, and the US are the regions with the most potential

Table 7. Highest Potential for Methane Emission Reductions in the Oil Sector

MtCeq	Middle East	Mexico	Canada	United States
\$0	0.00	0.00	0.00	0.00
\$20	0.00	0.00	0.00	0.00
\$40	0.00	0.15	0.00	0.00
\$50	0.20	0.15	0.14	0.12
\$75	1.68	1.29	0.76	1.04
\$100	1.68	1.29	1.15	1.04
\$200	1.68	1.29	1.15	1.04
Maximum Reduction	2.08	1.59	1.42	1.28

Table 8. Highest Potential for Nitrous Oxide Emission Reductions in the Adipic and Nitric Acid Production Sectors

MtCeq	EU15	US	China
\$0	0.0	0.0	0.0
\$10	12.2	8.5	9.3
\$20	13.6	9.4	9.3
\$50	13.6	9.4	9.3
\$100	13.6	9.4	9.3
\$200 and above	13.6	9.4	9.3

reductions as well as the strongest oil industries. No options for reducing methane emissions from the oil sector exist for under \$40/TCE.

3.1.5 Adipic and Nitric Acid Production

Few countries have significant emissions of nitrous oxide from adipic and nitric acid production. There are 48 MtCeq in potential reductions world wide, with approximately 30 MtCeq coming from the nitric acid production sector. The largest emissions come from EU15, US, and China. At approximately \$5/TCE, the majority of nitrous oxide mitigation options for these two sectors become profitable.

3.2 Sensitivities and Time Factor

The marginal abatement cost curves shift outwards between 2010 and 2020. This is due to the increase in the emissions baseline over time and not due to technical change. The analysis does not account for the technological change in such characteristics as the availability, reduction efficiency, applicability, and costs of reduction options. For example, the same sets of options are applied in

2010 and 2020 and an option's parameters are not changed over its lifetime. This current limitation likely underestimates abatement potential in later years because technologies generally improve over time and costs decrease. The introduction of a dynamic approach to assessing regional abatement potentials requires additional assumptions about rates of technological progress and the degree of implementation of options in the baseline projections. Recently, Gallaher and Delhotal (2005) used this analysis as a basis for estimating technical change in the coal, natural gas, and landfill gas sectors. This approach addresses some of the limitations outlined here.

3.3 Results of Discounting and Tax Rate Options

The analysis is conducted for the following combinations of discount and tax rates, respectively: from a social perspective – 4 and 0 percent; 5 and 0 percent; 10 and 0 percent; and from various industry perspectives – 10 and 40 percent, 15 and 40 percent, and 20 and 40 percent. These scenarios allow modeling teams to choose the appropriate discount and tax rate for their policy analysis. As expected, the MACs shift to the left as the discount rate and tax rate increases (See Figure 4).

3.4 Results of Energy Price Changes

Because of the high sensitivity to energy prices, this analysis tests the methane MACs sensitivity to changes in base energy price (from –50% to +200%), both for electricity and natural gas. A detailed list of country-specific energy prices is included in the complete data set.

As is shown in Figure 5, the marginal abatement curves are more sensitive to the energy price when energy revenues are relatively high compared to the cost of the mitigation option. As the cost of the option increases, energy prices are less relevant.

4. CONCLUSIONS

Traditionally, economic analyses of GHG mitigation focused on CO₂ emissions from energy sources for two reasons: first, they are the largest single source of GHG emissions; and second, reliable global data on the costs and abatement potential of the non-CO₂ greenhouse gases did not exist. This analysis builds on the US and EU specific analyses to develop a framework to estimate costs and abatement potential for non-CO₂ greenhouse gases by gas, by emitting sector, and by country or region.

The analytical framework used in this study is flexible enough to incorporate the latest baseline estimates, changes in costs and abatement potential over time, introduction of new technologies, addition of new sectors, and regional differences in all the characteristics of abatement options. Currently, the framework is being adapted to incorporate estimates of technical change, both

Figure 4. Comparison of Discount and Tax Rates for Methane and Nitrous Oxide in 2020

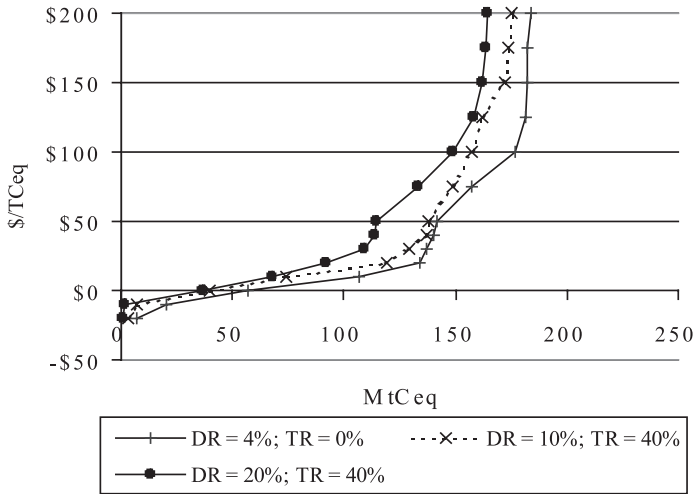
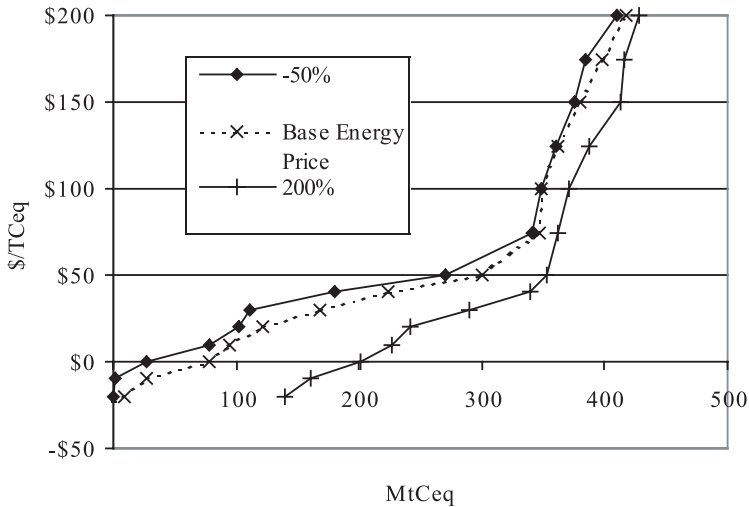


Figure 5. Methane Gas Price Sensitivities in 2020



in terms of increased engineering efficiency and reduced costs over time. As more information becomes available, this information can be easily incorporated into the framework creating more refined estimates. A much greater use of data originating from local experts and organizations is recommended for the follow-up research of non-CO₂ GHG abatement in countries outside the US and EU.

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Estimating Future Emissions and Potential Reductions of HFCs, PFCs, and SF₆

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Atmospheric concentrations of HFCs, PFCs, and SF₆ have been growing rapidly over the last 100 years, and they have the potential to continue growing rapidly, given the high growth rates of some emitting industries and the role of HFCs and PFCs as replacements for ozone-depleting substances. This analysis estimates global emissions of HFCs, PFCs, and SF₆ from twelve source categories for the years 1990, 1995, 2000, 2010, and 2020, and provides guidance for projecting emissions beyond 2020. It also presents 2010 and 2020 marginal abatement cost curves (MACs) for the same source categories. To address issues unique to the fluorinated gases, the analysis accounts for the impact of international industry agreements to voluntarily reduce emission rates, and it aggregates emissions and MACs by gas lifetime as well as economic sector. Results indicate the availability of large, low-cost reductions, especially in developing countries, and the importance of better characterizing these reductions in future analysis.

1. INTRODUCTION

Unlike carbon dioxide, methane, and nitrous oxide, the fluorinated gases, including hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and

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sulfur hexafluoride (SF_6), are almost exclusively anthropogenic in origin.¹ These gases are emitted from a number of processes and products, ranging from aluminum smelting (beginning in the late 1800s) to air conditioning and refrigeration equipment (beginning in the 1990s with the phaseout of ozone-depleting substances or ODSs). Over the past 100 years, atmospheric concentrations of most of these gases have risen from zero to the parts-per-trillion level. Although the gases make up a very small fraction of greenhouse gas emissions by mass, they are responsible for a more significant amount of climate forcing because of their high global warming potentials (GWPs), which range from approximately 120 to 22,200 (the 100-year GWPs of HFC-152a and SF_6 , respectively) (IPCC, 2001). In addition, in the absence of voluntary or regulatory action to reduce emission rates, emissions of HFCs, PFCs, and SF_6 would be expected to rise quickly due to (1) the rapid growth rate of some emitting industries (e.g., semiconductor manufacture and magnesium production and processing), and (2) the replacement of ODSs with HFCs (and other chemicals) in a wide range of applications. Finally, the PFCs and SF_6 have very long atmospheric lifetimes, ranging from 3,200 years for SF_6 to 50,000 years for CF_4 . Thus, emissions of PFCs and SF_6 today will have a radiative effect for millennia.

At the same time, HFCs, PFCs, and SF_6 are currently critical to a number of environmentally important industries. HFCs are used as substitutes for ODSs in a range of applications, facilitating worldwide efforts to protect stratospheric ozone. PFCs and SF_6 are emitted from the production of aluminum and magnesium, respectively, which are both used to decrease vehicle weight and thereby increase fuel efficiency. All three types of gases are emitted during the manufacture of semiconductors, which are used in “smart” devices that reduce energy consumption.

Fortunately, technologies exist that can reduce emissions of these gases without compromising these environmentally important industries. In fact, the high GWPs that amplify the impact of these gases on the climate can make them relatively inexpensive to abate per unit of carbon equivalent. Including high-GWP gases in an emission control regime can therefore reduce the price of carbon and the overall costs of the regime (see Reilly et al., 2003).

This analysis estimates international emissions of HFCs, PFCs, and SF_6 from twelve source categories for the years 1990, 1995, 2000, 2010, and 2020. It also presents 2010 and 2020 marginal abatement cost curves (MACs) for the same source categories. The source categories and chemicals emitted from each are presented in Table 1, below.

1. CF_4 and SF_6 have a small natural source; they are emitted from granite. Although their emission rates are quite low, the lifetime of CF_4 is so long (50,000 years) that a substantial fraction of the current atmospheric burden of this gas is estimated to be from this source (Harnisch and Eisenhauer, 1998).

Table 1. Chemicals Emitted by Source Category

SOURCE CATEGORY	EMITTED CHEMICAL(S)	REASON EMITTED
ODS Substitutes		
Air conditioning and refrigeration	HFC-32, HFC-125, HFC-134a, HFC-143a, HFC-152a, HFC-236fa	Refrigerant emitted from system leaks and during system service and disposal.
Foams	HFC-134a, HFC-152a, HFC-245fa, HFC-365mfc	Blowing agent released during foam manufacture, use, and disposal.
Solvents	HFC-4310mee, various PFCs and PFPEs (perfluoropolyethers)	Solvent leaks from cleaning equipment and evaporates from open-air uses.
Metered-Dose Inhalers (MDIs)	HFC-134a, HFC-227ea	Propellant released to deliver medicine to lungs.
Aerosols (non-MDI)	HFC-134a, HFC-152a	Propellant released to deliver product.
Fire suppression	CF ₄ , HFC-23, HFC-227ea, HFC-236fa	Suppression agent emitted from system leaks and to extinguish fires.
Industrial		
HCFC-22 production	HFC-23	Byproduct resulting from incidental overfluorination of HCFC-22.
Aluminum production	CF ₄ , C ₂ F ₆	Byproducts formed during transient process disturbances.
Semiconductor manufacture	CF ₄ , C ₂ F ₆ , C ₃ F ₈ , C ₄ F ₈ , SF ₆ , HFC-23, NF ₃	Fluorine sources for etching circuits, cleaning chambers. Incompletely reacted.
Magnesium production and casting	SF ₆	Cover gas to prevent oxidation of magnesium. Incompletely reacted; leaks from blending/distribution system.
Electrical equip. manuf.	SF ₆	Insulating gas for equipment.
Electrical equipment use	SF ₆	Insulating gas emitted from equipment leaks and during equipment service and disposal.

2. METHODS FOR ESTIMATING PAST AND FUTURE EMISSIONS

At present, few countries have published estimates of their past, present, or future HFC, PFC, and SF₆ emissions. Where countries have published emission projections (e.g., in their UNFCCC National Communications), they have generally done so only in aggregate form, combining the results for many industries. This information is not sufficient for the development of marginal abatement curves because technologies to reduce emissions are applied on an industry-specific basis.

In the absence of country-reported estimates, two previous analyses have quantified global (or semi-global) emissions of high-GWP gases on an industry-specific basis. In 2001, Ecofys developed emission projections and MACs for the IEA GHG R&D Programme for four world regions: (1) North America, (2) Western Europe, (3) Japan, and (4) Rest of World (Harnisch et al., 2001; Harnisch et al., 2002). Also in 2001, USEPA published projections of HFC, PFC, and SF₆ emissions for 38 developed countries (USEPA, 2001a). This analysis builds on both of these previous analyses to develop country-by-country and industry-by-industry projections of emissions using projections of activity data, emission factors, or other data related to emissions. For the industrial sources, activity data were multiplied by emission factors to obtain emission projections. For the substitutes for ozone-depleting substances, a combination of approaches was used, as described below.

Activity data and activity growth projections were obtained from a variety of sources, including international industry trade organizations and databases, U.S. government agencies, and international organizations. For all industries, country-specific estimates of activity (or a factor related to activity) were available. Information on emission rates was generally less precise, but was often available on a regional if not country-specific basis.

One issue that was critical in the projection of emissions was how to reflect current and expected trends toward decreased emission rates per unit of activity. These decreases, which affect several sources of HFCs, PFCs, and SF₆, have been caused by both economic factors and environmental concerns. The latter, and accompanying concerns regarding potential regulation, are amplified by the high GWPs and long lifetimes of many fluorinated gases, and by the high growth rates of several emitting industries. These concerns have prompted many industries not only to reduce their current emission rate, but also to commit to reducing that rate further in the future, frequently by substantial percentages. For example, the World Semiconductor Council (WSC), which represents approximately 92% of GWP-weighted fluorinated gas emissions from the semiconductor industry, has committed to reduce 2010 emissions to 90% of 1995 emissions (Burton, 2004). Given the high growth rate of this industry, this represents approximately a 70% reduction relative to “without measures” or “business-as-usual” (BAU) emissions. Table 2 provides a summary of quantitative global emission reduction commitments that have been made by industries that emit fluorinated gases.

In view of these commitments and of continuing declines in the emission rates of other industries, this analysis assumes that emission rates will fall in several industries. Table 3 summarizes these assumptions.

Following are brief descriptions of how emission projections were developed for each industry.

Table 2. Global Emission Reduction Commitments

Industry	Industry Association	Percent of World Production	Goal
Semiconductor manufacturing	World Semiconductor Council	92%	Reduce fluorinated emissions to 90% of 1995 level by 2010
Magnesium production	International Magnesium Association	70% (about 90% of sector's SF6 emissions)	Phase out SF6 use by 2011
Aluminum production	International Aluminum Institute	70% (but goal applies to entire industry)	Reduce PFCs/ton Al by 80% relative to 1990 levels by 2010

Table 3. Assumed Declines in Emission Factors

Industry	Assumed Decline in Emission Factor
Semiconductor	Global achievement of World Semiconductor Council Goal
Magnesium	80% phaseout of SF6 use by 2015*
Aluminum	60% reduction in global emission factor between 1990 and 2010*
HCFC-22 production	Developed countries: All install thermal abatement by 2020 Developing countries: Reduce emission factor from 3% to 2% by 2020
Electric Power Systems	80% use of SF6 recycling and leak detection and repair by 2010.
Air Conditioning and Refrigeration	Reduced emission factors, varying by particular end-use.

*Projections were developed before industry goals were finalized.

3. SUBSTITUTES FOR OZONE-DEPLETING SUBSTANCES

Limited information was available to track and project use and emissions of HFCs and PFCs used as ODS substitutes in different countries. Due to the lack of consistent and reliable information, two different methodologies were used to develop baseline emissions. The results were then compared and averaged to obtain the baselines used in the study. The first methodology analyzed consumption of ODSs in various end-uses and countries, how substitutes have replaced the ODSs in those end-uses, and how chemicals are emitted from those end-uses. The second methodology estimated stock of ODSs and substitute chemicals in various sectors, end-uses, and countries, and then applied variable emission factors to determine emissions.

Both methodologies determined the emissions of both ODSs and ODS substitutes. Although it was recognized that ODSs exhibit radiative forcing properties, only the emissions of the HFC and PFC substitutes were included in the baseline, consistent with UNFCCC reporting.

3.1 Consumption Methodology

Under the consumption methodology, the U.S. Environmental Protection Agency (EPA) used a detailed model of equipment and processes that have historically consumed ODSs to project the use and emissions of various ODS substitutes (including HFCs and PFCs) for the United States. This model—EPA's Vintaging Model—estimates ODS and ODS substitute use and emissions using a bottom-up approach, based on estimates of the quantity of equipment sold each year containing these chemicals, and the amount of the chemical required to make or maintain equipment and products over time (Godwin et al., 2003.). Emission estimates for the U.S. are specific to each end-use within each of the six sectors or source categories (i.e., refrigeration and air conditioning, solvents, foams, MDIs, non-MDI aerosols, and fire suppression). For example, within the air conditioning and refrigeration sector, emissions are estimated for 24 end-uses, ranging from motor vehicle air conditioners to medium-temperature retail food refrigeration. Emissions are estimated by applying annual leak rates and release profiles. In total, the model aggregates data for more than 40 end-uses, keeping track of equipment vintages to estimate annual use and emissions of each compound. The Vintaging Model tracks direct emissions only; it does not account for either the emissions associated with the production of energy to power the equipment or processes, or the energy used to produce the chemicals themselves. Although the Vintaging Model accounts for the reductions in emission rates that are widely agreed to have occurred (and to continue to occur) during the transition from ODSs to their substitutes, it does not project significant additional reductions in any end-uses, except one. The exception is the motor vehicle air conditioning end-use, where emission rates are projected to decline as a result of a voluntary global emission reduction effort. The model may therefore underestimate emissions from this end-use if the projected reductions are not realized. Alternatively, it may overestimate emissions where industries undertake additional voluntary efforts to reduce emissions.

Emission baselines for non-U.S. countries were derived using country-specific data when available. For countries where detailed sector-level information was available, data were incorporated into country-specific versions of the Vintaging Model to develop emission estimates. Such customized models were generated for the fire suppression sector and for the motor vehicle air conditioning end-use of the refrigeration and air conditioning sector. In instances where specific country-level data were not available, preliminary estimates were calculated by analyzing the consumption of ODSs in the country prior to the introduction of ODS substitutes, and then assuming that the transition from ODSs to HFCs and other substitutes follows the same general substitution patterns as observed in the United States and calculated in detail using the Vintaging Model. From this preliminary assumption, emission estimates were then tailored to individual countries or regions by applying adjustment factors to U.S. substitution scenarios, based on relative differences (i.e., ratios) including (1) the distribution

of ODS use across end-use sectors in each region or country; (2) historical and future economic growth; (3) timing, rates and patterns of ODS phaseout; and (4) substitution preferences in each region or country (e.g., adoption of non-fluorinated alternatives vs. HFCs).

3.2 Stock and Emission Factor Methodology

Under the stock and emission factor methodology, an inventory of equipment or chemical use for each sector (and in some cases, end-uses or sub-sectors within a sector) was developed for different world regions. Regional influences were considered to determine how that inventory may grow in the future. The distribution of various chemicals, including ODSs and substitutes such as HFCs, was determined for the inventory for the required years. This yielded a time-dependent technological activity, which was multiplied by an emission factor (which could also vary over time) to determine chemical emissions for the required years.

The specific emission model which was used for this assessment exercise is an improved version of the one developed by Ecofys for the IEA GHG R&D Programme (Harnisch et al., 2001). It covers 22 different sub-sectors that contribute to emissions, including 14 ODS Substitute sub-sectors. The regions used (North America, Europe, Japan and “Rest of the World”) are the same as in most of the recent United Nations Environmental Programme (UNEP) Technical Options Reports. The model derives emission estimates for three years (base year, 2010 and 2020) covering a period of roughly 25 years. The year 1996 was selected as the base year because it is the year for which data coverage by the UNEP Technical Options Reports is most complete for almost all processes in which ODSs have been used in the past. (For this study, it was assumed that no HFC or PFC emissions occurred in 1990, and linear interpolations were used to determine 1995 and 2000 emissions.) The reference scenario that is calculated for the years 2010 and 2020 is based on conservative assumptions about technological progress; that is, it avoids reliance on large autonomous emission reductions without a corresponding regulatory framework. In regions in which companies, through their actions, already anticipate future regulation on greenhouse gas emissions, this might lead to an overestimate of future emissions. The choice of present and future emission factors is based on studies such as Öko-Recherche (1999), March (1998), and Harnisch and Hendriks (2000).

3.3 Baselines

The results of these two methodologies were then evaluated. For some sectors and regions, both methodologies yielded relatively consistent results. In some instances, however, the results were significantly different. Although the consumption methodology predicted higher emissions for the total of all ODS substitute sectors, there were some sectors and regions in which the stock and

emission factor methodology predicted higher emissions. The largest differences appeared to result from different assumptions regarding (1) base year activity levels (e.g., ODS consumption or ODS bank in equipment stock, which led to divergent results for developing countries), and (2) future activity growth rates (which led to divergent results for North America). The closest matches in the results were seen in those areas where the most reliable data were available and where neither model predicted strong activity growth, specifically Western Europe and Japan.

Given the complexity in modeling the ODS substitute sectors, the plethora of information needed to accurately determine emissions, and the general lack of reliable data for many countries, we decided to average the results of both methodologies to obtain baseline emissions. While this gave a result that was not completely consistent with either methodology, it did yield a single estimate with reasonable accuracy with which abatement options and costs were then studied.

3.3.1 Industrial Sector Methodologies

Table 4 outlines the data and assumptions used to generate the emission projections for the industrial sectors. As noted above, the projections were developed by multiplying activity data by appropriate emission factors.

4. AGGREGATION BY ECONOMIC SECTOR AND GAS LIFETIME

Climate change models currently model the fluorinated gases at many different levels of detail, ranging from a single set of aggregate emissions to industry-by-industry and gas-by-gas emissions. To permit modelers to incorporate our results into their models at a level of detail appropriate for them, we presented the projections and MACs for the fluorinated gases at four levels of aggregation. From highest to lowest, the levels of aggregation were:

- (1) All high-GWP fluorinated gases from all source categories, which were reported in MtCeq.
- (2) Short-lived HFCs (ODS substitutes) and long-lived fluorinated gases (emissions from industrial sources). The former were reported in kilograms of HFC-134a-equivalents and MtCeq; the latter were reported as SF₆-equivalents and MtCeq.
- (3) Short-lived HFCs (ODS substitutes), HFC-23 (emissions from HCFC-22 manufacture), SF₆ (emissions from the production and processing of magnesium and from the manufacture and use of electrical equipment), and PFCs (emissions from aluminum and semiconductor manufacture). These were reported in terms of equivalents of HFC-134a, HFC-23, SF₆, and CF₄, respectively, as well as in MtCeq.
- (4) Sector-by-sector, reported in terms of the gases listed in (3) and MtCeq.

Table 4. Assumptions Behind Emissions Projections for Industrial Sources

Base Year Activity (Metric Tons)	Activity Growth Rate (Percent/Year)	Base Year Emission Factor	Emission Factor Changes
HFC-23 Emissions from HCFC-22 Production			
1999: 485,000 Metric Tons of HCFC-22 produced.	Developed Countries: Production of HCFC-22 for use as refrigerant declines to 0 by 2015 or 2020, depending on country. Production for feedstock grows at 2.5%.	Metric tons of HFC-23/metric ton of HCFC-22 produced :	Developed Countries: Market penetration by thermal oxidation grows to 100% for all by 2020.
Current split of production: 25% feedstock; 75% refrigerant.		Developed Countries: 0.02, with following market penetrations by thermal oxidation: 100% in France, Germany, Italy, and Netherlands; 75% in UK; 33% in US; 0 in Japan, Spain and Greece.	Developing Countries and Russia: Emission factor falls from 0.03 to 0.02 by 2020.
Sources: HCFC production: UNEP (2001) HCFC-22 share: AFEAS (2001) Country-specific capacities: CEH (2001) Feedstock to refrigerant ratio: Midgley and Fisher (1993) U.S. data: USEPA (2002)	Developing Countries: Production for use as refrigerant grows at GDP growth rate until 2015, then declines linearly to 2040. Production for feedstock grows with GDP. Sources: EIA (2001), World Bank (2001)	Developing Countries and Russia: 0.03 Sources: Harnisch et al. (2001), USEPA (2002), IPCC (2000)	
SF₆ from Magnesium Production and Casting			
2000: Metric tons of magnesium Primary 380,900 Casting 127,600 Recycling 22,500	Primary Production: 2001-2010 = 8% (1.5% in U.S.) 2011-2015 = 4% (0.5% in U.S.) Casting and Recycling: 2001-2010 = 13% 2011-2020 = 6.5%	Kg SF₆/metric ton Mg: Primary Production: 0.75 Casting: 1.0 (0.5 in Europe) Recycling: 1.0	For all countries except China, 80% phaseout of SF ₆ use by 2015. For China, market penetration by SF ₆ will grow to 30% by 2010, and then remain constant through 2020.
Sources: Primary and secondary: USGS (2001) and USEPA (2003a) Casting estimated based on U.S. casting from USGS and ratio of country auto production to U.S. auto production as provided in Wards (2001)	Sources: Global: Aroule (2001) US: USEPA (2003a)	Sources: Communications with U.S., Canadian, and European producers and casters	

Table 4. Assumptions Behind Emissions Projections for Industrial Sources (continued)

Base Year Activity (Metric Tons)	Activity Growth Rate (Percent/Year)	Base Year Emission Factor	Emission Factor Changes
SF ₆ from EPS			
1995: Metric tons SF6 banked:	North America: no growth	North America: 13%	North America: no change
North America: 4600 (in 2000)	Western Europe: no growth	Western Europe: 2.5%	Western Europe: no change
Western Europe: 4500	Japan: no growth	Japan: 2.5%	Japan: no change
Japan: 6200	Rest of World: 3% per year	Rest of World: 5%	Rest of World: decline to 2.5% in 2010.
Rest of World: 1190	In developed countries, decline in average SF6 charge size is assumed to balance slow growth in grids.	Sources: All regions but North America: Harnisch et al. (2001)	Sources: All regions but North America: Harnisch et al. (2001)
Sources: All regions but North America: Harnisch et al. (2001)		North America: USEPA (2002)	
North America: USEPA (2003b)			
SF ₆ from Manufacture of Electrical Equipment			
1995: Metric tons SF6 charged into equipment:	North America: no growth	North America: 12.5%	No changes.
North America: 230 (in 2000)	Western Europe and Japan: no growth or change, except 25% of manufacturing moves to Rest of World (China) between 2000 and 2010.	Western Europe: 12.5%	
Western Europe: 1250		Japan: 12.5%	
Japan: 1406		Rest of World: 25%	
Rest of World: 313	Rest of World: 3% per year; in addition, receives 25% of European and Japanese manufacturing between 2000 and 2010.	Sources: All regions but North America: Harnisch et al. (2001)	
Sources: All regions but North America: Harnisch et al. (2001)		North America: O'Connell et al. (2002)	
North America: USEPA (2002)	Sources: Harnisch et al. (2001)		

Table 4. Assumptions Behind Emissions Projections for Industrial Sources (continued)

Base Year Activity (Metric Tons)	Activity Growth Rate (Percent/Year)	Base Year Emission Factor	Emission Factor Changes
PFCs from Aluminum Production			
2000: 21,783,000 metric tons of aluminum produced, divided among five primary production technologies: VSS (Vertical Stud Soderberg): 5,984,000 HSS (Horizontal Stud Soderberg): 901,000 PB-SW (Prebaked Side-Worked): 2,621,000 PB-CW (Prebaked Center-Worked): 4,319,000 PB-PF (Prebaked Point-Feed): 7,958,000 Sources: Europe and the former Soviet Union; European Aluminum Association (Nordheim, 1999) All other countries: International Aluminum Institute (IAI) surveys (IPAL, 1998; IAI, 2002)	Regional-level, technology-specific production projections through 2020 as reported in Greenhouse Gas Emissions from the Aluminum Industry (IEA, 2000). Average aluminum production annual growth rate = 2000-2010: 4.2% 2010-2020: 1.6% 2000-2020: 2.9% (growth rate accounts for anticipated global smelter openings, closings and changes in aluminum demand) Source: IEA (2000)	PFC emission factors estimated using IPCC Tier 2 methodology and IAI anode effect minutes. (IPCC slope factor * tons of Al produced * anode effect minutes) CF4 (kg CF4/tonne Al) VSS = 0.44 HSS = 0.52 PB-SW = 1.4 PB-CW = 0.20 PB-PF = 0.15 Weighted avg. = 0.41 C2F6 (kg C2F6/tonne Al) VSS = 0.018 HSS = 0.052 PB-SW = 0.14 PB-CW = 0.025 PB-PF = 0.019 Weighted avg. = 0.036 Sources: IPCC (2000); IAI (1999)	2000-2010 annual CF4 EF growth = -3.2% annual C2F6 EF growth = -2.8% 2010-2020 annual CF4 EF growth = -4.7% annual C2F6 EF growth = -4.2% The emission rate declines because (1) anode effect frequency and duration are assumed to decline for all cell technologies as major and minor retrofits are implemented in the baseline, and (2) industry is assumed to move from more to less emissive cell technologies as new capacity is built (e.g., from PB-SW to PB-PF).
PFCs from Semiconductors			
Emissions vary with the product of silicon area and layers per device. Layers increase as chip complexity grows. 1999 global emissions were estimated based on the estimated manufacture of 14,116 millions of square inch-layers of silicon (MSI-layers) world wide. Sources: PFC Emissions Vintage Model (PEVM), v. 100r5b5, based on information in VLSI (2001), ITRS (2000), and IFD (2001).	Average Annual Growth Rate: 1999-2010: 19% 2010-2020: 8%. Sources: PEVM (1999-2010)	691.6 TCe/MSI-layer Sources: PEVM, based on emissions reported under the USEPA PFC Emission Reduction Partnership for Semiconductor Industry.	Emission reduction technologies are assumed to be deployed sufficiently to meet the World Semiconductor Council goal of reducing emissions to 90% of the 1995 level by 2010.

Modelers who plan to evaluate short-term scenarios and therefore to model fluorinated gases using MtCeq and a single set of economic drivers will probably find the highest level of aggregation (1) sufficient. Modelers who plan to model fluorinated gases using the gases themselves (with their associated radiative efficiencies and atmospheric lifetimes) and/or two or more sets of economic drivers will probably find the second (2) or third (3) levels of aggregation more useful. Modelers who prefer sector-by-sector information can use (4), the most disaggregated set.

In developing the groupings (except for the most aggregated one), our goal was to ensure that the components of each aggregate projection and MAC had similar economic and atmospheric behavior. That is, we wanted to group together (1) source categories that had similar trends and drivers, and (2) gases that had similar atmospheric lifetimes. Similarity in atmospheric lifetimes is important because many models have atmospheric modules that model gas concentrations over time as a function of emissions and decay rates. In addition, some modeling teams have shown that levels and rates of temperature change are sensitive to gas lifetime (Manne and Richels, 2001; Sygna et al., 2002). To avoid losing information on atmospheric behavior, we report emissions not only in MtCeq but also in gigagrams of one representative gas per group, where each representative gas is selected because its lifetime is near the weighted average lifetime of the gases in its group.

Table 5 provides the atmospheric lifetimes and GWPs² for selected gases over 20-, 100-, and 500-year time horizons. The lifetime and first three columns of the GWPs are from the Third Assessment Report (TAR), which is the most recent IPCC publication regarding lifetimes and GWPs (IPCC, 2001). The fourth column of GWPs shows the 100-year GWPs from the Second Assessment Report (SAR) (IPCC, 1996). International greenhouse gas reporting guidelines continue to require the use of the SAR GWPs, and these GWPs, when available, were therefore used in this study. The table shows two interesting phenomena. First, the differences between the 100-year GWPs established by the SAR and the TAR show that GWPs continue to be re-evaluated; uncertainties in the GWPs of the fluorinated gases are estimated to be $\pm 35\%$ (IPCC, 2001). Second, as atmospheric lifetime increases, the relationship between the 20-, 100-, and 500-year GWPs changes. The GWPs of shorter lived gases decline as the time horizon increases, but the GWPs of longer lived gases increase as the time horizon increases. This demonstrates the importance of grouping gases by lifetime in order to accurately represent their behavior over time.

Both emission trends and atmospheric lifetimes suggest distinguishing between ODS substitutes and industrial sources. As discussed below, emissions of ODS substitutes are likely to continue rising rapidly until 2030 or 2040 as

2. The GWP or Global Warming Potential of a gas is defined as the ratio between (1) the radiative forcing that results from the instantaneous release of one kg of that gas, integrated over a given time horizon, and (2) the radiative forcing that results from the instantaneous release of one kg of CO₂, integrated over the same time horizon.

Table 5. Atmospheric Lifetimes and GWPs of Selected Fluorinated Gases

Gas	Lifetime (Years)	TAR GWPs			SAR GWPs 100-year
		20-year	100-year	500-year	
HFC-152a	1.4	410	120	37	140
HFC-32	5.0	1,800	550	170	650
HFC-245fa*	7.2	3,000	950	300	Not reported
HFC-365mfc*	9.9	2,600	890	280	Not reported
HFC-134a	13.8	3,300	1,300	400	1,300
HFC-4310mee	15	3,700	1,500	470	1,300
HFC-125	29	5,900	3,400	1,100	2,800
HFC-227ea	33	5,600	3,500	1,100	2,900
HFC-143a	52	5,500	4,300	1,600	3,800
HFC-236fa	220	7,500	9,400	7,100	6,300
HFC-23	260	9,400	12,000	10,000	11,700
NF ₃ *	740	7,700	10,800	13,100	Not reported
C ₃ F ₈	2,600	5,900	8,600	12,400	7,000
C ₄ F ₈	3,200	6,800	10,000	14,500	8,700
SF ₆	3,200	15,100	22,200	32,400	23,900
C ₂ F ₆	10,000	8,000	11,900	18,000	9,200
CF ₄	50,000	3,900	5,700	8,900	6,500

*Because no GWPs were listed for these gases in the SAR, this analysis uses the 100-year GWPs provided in the TAR.

HFCs and other substitutes replace CFCs, HCFCs and other ODSs in a number of applications. In contrast, emissions from the industrial sources are expected to actually decrease (overall) over the next 20 years as industries continue to reduce emission rates per unit of activity to meet voluntary global commitments. While the vast majority of greenhouse gases that are emitted as ODS substitutes are relatively short-lived HFCs, with lifetimes ranging from 1.5 years to 52 years (for HFC-152a and HFC-143a respectively), the gases that are emitted from industrial processes have lifetimes ranging from 260 years to 50,000 years (for HFC-23 and CF₄ respectively).

The distinctions among the long-lived gases are also suggested by both industry differences and atmospheric lifetimes. Over the 50- to 100-year span covered by most models, the long-lived gases behave fairly similarly, but not identically. One hundred years after the release of a pulse of each chemical, approximately 70% of the HFC-23, 97% of the SF₆, and 100 percent of the PFCs will remain. Distinguishing between HFC-23 and the other long-lived gases therefore increases the precision of the modeling.

One area where it might be useful to further disaggregate the data is within emissions of short-lived HFCs that are ODS substitutes. As noted above, the lifetimes of these gases range from 1.5 to 52 years, implying a wide range of atmospheric behaviors over the short term. In this study, these gases are represented by HFC-134a, which has an atmospheric lifetime of 14 years and which is expected to dominate ODS substitute emissions through 2010. However, the share of ODS substitute emissions comprised of longer-lived HFCs (with lifetimes of 29 to 52 years) is expected to grow significantly (to about 60% in the U.S.) by 2020. Thus, to increase the precision of modeling in 2020 and beyond, it may be illuminating to separate the longer-lived from the shorter-lived ODS substitutes in future studies, using two or more representative gases rather than one.

5. ESTIMATED EMISSIONS

5.1 Emissions Through 2020

Figure 1 summarizes emission estimates for the ODS substitutes and for industrial sources.

As Figure 1 shows, global emissions from ODS substitutes are expected to increase by nearly a factor of five over the next 15 years as developing countries join developed countries in replacing CFCs, HCFCs, and halons with HFCs and (to a much smaller extent) PFCs. Emissions from industrial sources, on the other hand, are expected to decrease by 20% over the same period as emitting industries sharply reduce their emission rates per unit of activity to meet voluntary emission reduction commitments.

Figures 2 and 3 break down ODS substitute and industrial source emissions by sector.

Refrigeration and air conditioning emissions clearly dominate ODS substitute emissions in all years, with foams also contributing substantial emissions by 2020. The share of emissions represented by these two sectors rises over time because it takes decades for HFCs and PFCs to fully penetrate the stock of existing refrigeration and air conditioning equipment and foams and then to be emitted from those sources. In contrast, emissions from aerosols and solvents, which are much shorter-lived products, reach their maximum share quickly.

The industrial sectors compete not in emissions growth but in emissions decline, because the largest emitting industries are projected to meet voluntary global emission reduction commitments. Only one sector, electric GIS manufacture, shows strong emissions growth (47%) between 2000 and 2020. Two other sectors, electric transmission and distribution and magnesium production and processing, show modest emissions growth (less than 10%) during this period, and in these cases emissions grow despite reductions in emission rates, simply because of the strong growth of the emitting activities. Emissions decline significantly (by over 20%) in the HCFC-22 production, aluminum production, and semiconductor

Figure 1. Global Emissions of Fluorinated Gases

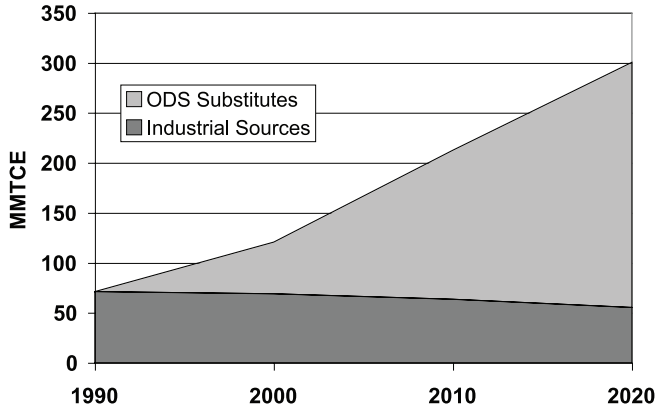


Figure 2. Global Emissions of ODS Substitutes by Source Category

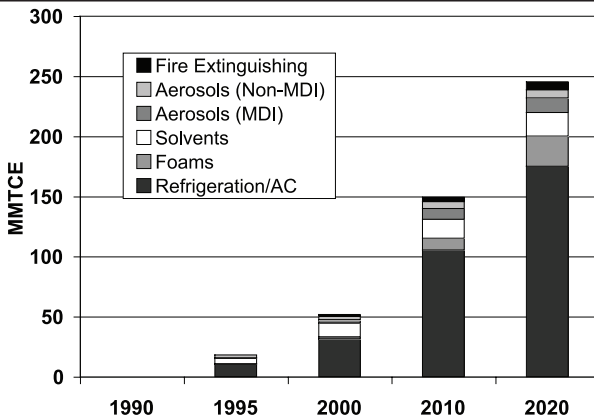
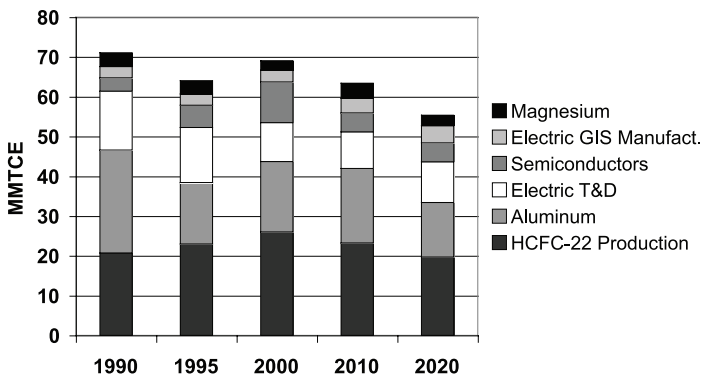


Figure 3. Global Industrial High-GWP Emissions by Source Category



production sectors, as all three of these sectors reduce their emission rates. In 2020, emissions of HFC-23 from HCFC-22 production, PFCs from aluminum production, and SF₆ from electrical transmission and distribution comprise 79% of industrial emissions, almost exactly the same fraction as in 2000.

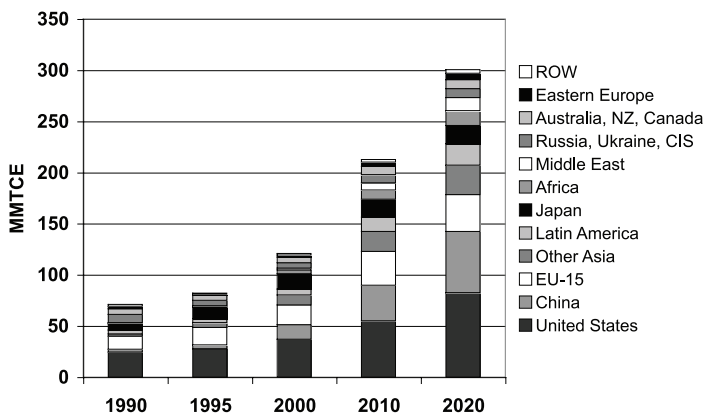
Figure 4 shows total fluorinated gas emissions by region. Although the U.S. is the largest emitter throughout the time series, the share of emissions represented by the U.S. drops from 35% to 27% between 1990 and 2020. The share of emissions represented by China, on the other hand, rises from 4% in 1990 to 20% in 2020. (China's 2020 emissions from industrial sources actually exceed those of the U.S.) These patterns are followed by most developed and developing countries, respectively. This occurs because (1) developed countries are assumed to have a lower rate of economic growth than developing countries, and (2) developed countries are assumed to take more actions to reduce emission rates than developing countries.

5.2 Long-Term Outlook (2020-2100)

Most climate change models project results to 2050 or 2100, necessitating the development of emission projections beyond 2020. Because fluorinated gas emissions have industry-specific drivers that are not always well known and that change in importance over time, we developed a table of key long-term drivers as well as guidance for applying the drivers and projecting long-term emission rates. The table of drivers is available on the EMF web site at <http://www.stanford.edu/group/EMF/resources/index.htm>. Drivers were provided both for top-down economic models with 50- to 100-year (or longer) time horizons and for technology-rich, bottom-up models.

In developing the guidance, we considered both the relatively rapid pace of technological change and adoption in these sectors and the changing relationship

Figure 4. Fluorinated Gas Emissions by Region, 1990–2020



between emissions and drivers as per-capita incomes rise (particularly for ODS substitutes, whose emissions are dominated by air conditioning and refrigeration). Although it is quite conceivable that some sectors will actually reduce emissions to zero by 2100,³ we took the relatively conservative approach of recommending modest rates of decline for emission factors, between 1 and 2 percent per year. In addition, to model likely limits on growth, we recommended capping emissions from both ODS substitutes and industrial sources at specified levels.

5.2.1 ODS Substitutes

We identified the following factors and trends behind the expected regional growth in estimated emissions from ODS substitutes between 1990 and 2020.

- (1) Replacement of ODSs, such as CFCs and HCFCs (emissions of which are not counted or included in the data), with HFCs and other substitutes, a process which is expected to be largely complete in 2030 in developed countries and in 2040 in developing countries,
- (2) Different preferences among regions (e.g., for more or less air conditioning or for HFCs vs. substitutes),
- (3) Population growth,
- (4) Income growth,
- (5) Autonomous technology improvements to reduce emissions, and
- (6) Innovative technological change and adoption, including significant lowering of emission factors.

After considering how these trends would affect emissions in the future, we developed the following recommendations for projecting emissions from ODS substitutes over the long-term:

- (1) Grow 1990-2020 baselines linearly until 2030 (developed countries) or 2040 (developing countries).
- (2) Grow/Decline emissions from 2030 or 2040 to 2100 linearly with GDP per capita and population, but:
 - (a) Assume no growth in per-capita annual emissions once GDP per capita reaches that of France in 2000
 - (b) Assume no growth in per-capita annual emissions once they reach 2030 level seen in United States (for North America), France (for Europe and Russia) or Japan (for rest of world).
- (3) Assume 1 to 2% per annum decline in emission factors from 2030 or 2040.

3. For example, widespread adoption of inert anodes in aluminum smelting would eliminate PFC emissions from this sector, and moving to a non-silicon substrate in semiconductor manufacture could eliminate PFC use and emissions from this source as well.

5.2.2. *Industrial Sources*

Similarly, we identified the following trends behind the growth in estimated emissions from the industrial sectors between 1990 and 2020.

- (1) Industry-specific activity growth rates, the highest of which are likely to decline over time,
- (2) Autonomous technology improvements that reduce emissions, and
- (3) Innovative technological change and adoption, including significant lowering of emission factors.

After considering how these trends would affect emissions in the future, we developed the following recommendations for projecting emissions from industrial sources over the long-term:

- (1) Grow emissions linearly with industrial output or with the sector-specific drivers listed in the Economic Drivers table,
- (2) Assume 1% per annum decline in emission factors from 2020 in developed countries,
- (3) Assume that emission factors in developing countries converge with those of developed countries by 2100, and
- (4) Cap total global emissions from industrial sectors at 275 million metric tons of carbon equivalent per year (MtCeq/year).

5.2.3. *All Sources Combined*

Finally, we developed the following guidance for modelers who model all fluorinated gases in aggregate:

Follow the guidance for modeling the ODS substitutes, with the following adjustments:

- (1) Include industrial emissions in the 1990-2020 baseline when developing the linear projections to 2030 and 2040, and
- (2) Increase the per-capita annual emissions caps by the industrial emissions cap (275 MtCeq) divided by 2100 world population.

6. MARGINAL ABATEMENT COST ANALYSIS

6.1 Methodology

This cost analysis expands upon two previous regional analyses of the costs of mitigating fluorinated gases: (1) *U.S. High GWP Gas Emissions 1990-2010: Inventories, Projections and Opportunities for Reductions* (USEPA, 2001a), which presented 2010 MACs for 10 source categories in the U.S., and (2) Harnisch et al., 2001, described above.

The MACs for the fluorinated gases were constructed using the same methodology as those constructed for methane and nitrous oxide, except as described below. For a detailed description of the methodology used to construct the MACs for methane and nitrous oxide, see Delhotal et al. in this issue.

The method used to construct the MACs for the fluorinated gases differs from the method used to construct the MACs for methane and nitrous oxide by (1) explicitly modeling the application of certain mitigation technologies in the baseline in order to meet industry reduction targets, and (2) using expert judgement to assign different market penetration rates (in both the baseline and policy scenarios) to technologies competing for the same set of emissions. To model the implementation of global industry commitments to reduce emissions of fluorinated gases, we assume that industries adopt abatement technologies in the baseline. When an option is adopted in the baseline, the emissions stream to which that option is applied in the MAC is correspondingly decreased, so that options that are fully implemented in the baseline are not present in the MAC at all.

While technologies competing for the same set of methane emissions are assumed to claim equal shares of their market, technologies competing for the same set of fluorinated gas emissions are sometimes assumed to claim different shares. Estimates of market penetrations by different options are based on expert judgement, considering each option's cost and desirability (e.g., the preferences of consumers or plant operators in different regions).

The development of the semiconductor MAC illustrates both of these approaches. In semiconductor manufacture, several technologies were assumed to be deployed in the baseline to meet the World Semiconductor Council goal. NF_3 Remote Clean technology was assumed to be fully implemented in the baseline (applied to all emissions to which it is technically applicable) because it is believed to significantly reduce the time required to clean chambers, permitting more throughput per chamber. A more expensive abatement technology, catalytic abatement, was assumed to be only partially implemented in the baseline (applied to only a fraction of the emissions to which it is technically applicable). Catalytic abatement therefore remains in the MAC (albeit with a reduced emission stream), while NF_3 Remote Clean does not.

6.2 Emission Reduction Technologies

The MACs for the fluorinated gases were constructed using cost and emission reduction information on 43 emission reduction technologies.^{4,5} These technologies were judged to be technically and economically feasible either now

4. Five additional reduction technologies were considered but do not appear in the MACs because they were assumed to be fully implemented in the baseline. These included NF_3 Remote Clean (discussed above), plasma abatement, substitution of C_3F_8 for C_4F_8 , and PFC capture and recovery in semiconductor manufacturing, and good housekeeping in magnesium production and processing.

5. Detailed, country-by-country information on each of the technologies is available on the EMF website at <http://www.stanford.edu/group/EMF/home/index.htm>.

or in the immediate future; longer-term technologies such as inert anodes for aluminum were not included in the MACs. The technologies fall into six general types, provided in Table 6. Each technology type can be applied to multiple source categories. In general, all six types can be applied to source categories in which the HFC, PFC, or SF₆ is used to address a technical need (i.e., ODS substitutes, manufacture of semiconductors, magnesium, and electrical equipment, and use of electrical equipment) while the last two may also be applied to source categories from which the HFC or PFC is emitted as a byproduct during the manufacture of another product (i.e., production of aluminum and HCFC-22). Many technical options involve more than one type; for instance, a product can be modified to reduce emissions in a number of ways, including improving containment.

Table 6. Emission Reduction Approaches

Approach	Description	Cost Parameters	Examples
Substitution	- Substituting low- or 0-GWP chemical for HFC, PFC or SF₆ - Not-in-kind technology	- Relative prices and amounts of original and substitute gases or equipment - Product or process changes that accompany transition	- Ammonia for HFCs in refrigeration - Aqueous cleaning for fluorocarbon solvents - SO₂ for SF₆ in magnesium production
Improved Containment	- Building or retrofitting equipment to leak less - Improved maintenance, including leak detection and repair (LDAR)	- Extent of product or process changes - Extent of leak reduction - Labor costs	- Retrofit of solvent equipment - LDAR in refrigeration and electrical equipment.
Recovery and Recycling	Recovering the HFC, PFC, or SF ₆ and reusing it in same or another product or process	- Price and quantity of the recovered chemical - Recovery equipment capital costs and frequency of use - Labor costs	Recycling of gas in air conditioning and electrical equipment.
Modified product design	Changing design of current product to lower emissions	- Extent of product or process changes - Extent of reduction	Replacing conventional HFC commercial refrigeration systems with HFC distributed or HFC secondary loop systems
Process optimization	Monitoring and/or adjusting process parameters to reduce emissions	- Extent of product or process changes - Extent of reduction	Computer control of aluminum production (minor retrofit)
Destruction	Chemically transforming emissions into 0-GWP materials	- Quantity destroyed - Energy requirements of destruction technology	Thermal destruction of HFC-23 emissions from HCFC-22 production

The “Cost Parameters” column of Table 6 lists the emission reduction and cost parameters that affect the cost per TCE of the various abatement options. These include capital and operating costs, gas savings, and emission reductions, as well as some indirect (i.e., energy-related) costs and benefits. For example, the replacement of a conventional HFC refrigeration system with a new technology or a different, low-GWP refrigerant could change the energy efficiency of the system. This would, in turn, change the CO₂ emissions related to the production of energy to power the system, as well as the annual electricity costs. To the extent that reliable data and estimates were available, we accounted for these effects by adjusting the emissions abated by the technical option to account for the avoided or additional CO₂ emissions, and by adjusting the O&M costs to reflect the increase or decrease in electricity costs.

7. RESULTS

Figure 5 displays the global 2010 sector-by-sector MACs for the sectors with the largest reductions, using a 4% discount rate and a 0% tax rate. Refrigeration and air-conditioning yields the largest reductions (30 MtCeq), reflecting that sector’s large contribution to emissions. HCFC-22 production follows with 22 MtCeq of reductions. Although 2010 HFC-23 emissions from HCFC-22 production are considerably smaller than HFC refrigerant emissions (23 vs. 105 MtCeq, respectively), thermal abatement is expected to be able to eliminate 93% of HFC-23 emissions in 2010, while the combined abatement technologies for refrigeration are expected to be able to reduce at most 30% of refrigerant emissions in that year.

Table 7 displays the technologies yielding the largest low-cost (<\$50/TCEq) reductions in 2010.

Figure 6 displays the 2010 MAC curves for four regions and the world, using a 4% discount rate and 0% tax rate. Although U.S. emissions are 60% greater than Chinese emissions in 2010, the reductions available for under \$50/TCE in the

Table 7. Emission Reduction Technologies Yielding Largest Low-cost Reductions (2010)

Technology	Gas	Cost (\$/TCEq)	Reduction (MtCeq)	Share of Baseline (Percent)
Thermal Oxidation (HCFC-22 production)	HFC-23	0.80	22	10
Refrigerant Recovery	Short-lived HFCs	5.40	14	7
Distributed Refrigeration (commercial ref.)	Short-lived HFCs	(21)	5.5	3
Major retrofit (aluminum)	PFCs	(14)	4.8	2
A/C&R leak repair	Short-lived HFCs	4.40	3.6	2

Figure 5. 2010 MACs by Source Category

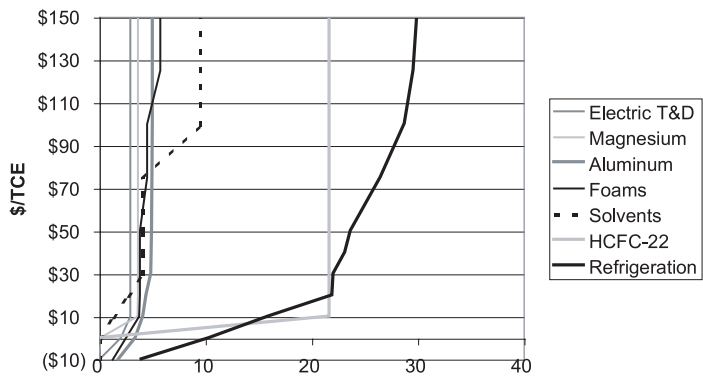


Figure 6. 2010 MACs by Region

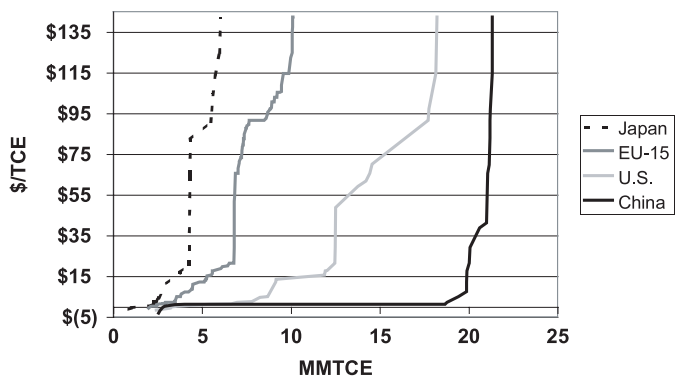
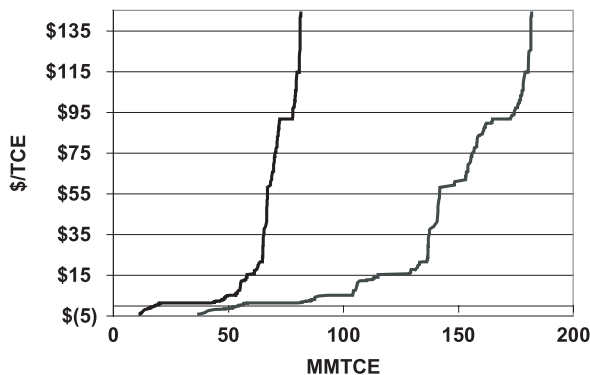


Figure 7. 2010 and 2020 Global MACs



U.S. are 38% smaller than the reductions available for the same price in China. This reflects the implementation of abatement options in the baseline in the U.S., particularly the implementation of thermal abatement of HFC-23 emissions from HCFC-22 production. While just two additional MtCeq of reductions from this source are expected to be available in the U.S. in 2010, 15 MtCeq of reductions from this source are expected to be available in China in 2010. This pattern holds for other developed and developing countries as well.

Figure 7 displays the 2010 and 2020 global MAC curves for all sources of fluorinated gases, using a 4% discount rate and 0% tax rate. The 2020 MAC is larger than the 2010 MAC for two reasons. First, emissions are larger in 2020 than in 2010 due to the continuing growth of ODS substitutes. Second, the percentage of emissions abated is higher in 2020 than in 2010 because many of the abatement options for air conditioning and refrigeration take time to penetrate the stock of equipment. Thus, only a relatively small percentage of the market can be penetrated by 2010, but a larger percentage of the market can be penetrated by 2020.

8. CONCLUSIONS

The work carried out under EMF-21 on fluorinated gases has identified several reasonably robust emission trends and reduction options, a number of important uncertainties and sensitivities, and some critical areas for further research. Although all projections for these quickly evolving source categories are subject to uncertainty, the researchers agree that some broad outcomes are fairly likely. Specifically, emissions of ODS substitutes will probably continue their rapid increase until about 2030 in developed countries and 2040 in developing countries. After those dates, emissions of ODS substitutes are expected to grow more slowly, ultimately closely matching population growth. Fluorinated emissions from industrial sources are expected to grow considerably more slowly over the next 15 years than emissions of ODS substitutes; in fact, if emitting industries meet their emission reduction commitments (as is assumed here), global emissions from these sources are likely to decline between 2000 and 2020. Developing countries will contribute a growing share of global fluorinated emissions over the next 15 years, largely as a result of their expected strong economic growth. Consequently, developing countries will also provide some of the largest abatement opportunities for fluorinated gases. Globally, large, low-cost reductions are likely to be available from the thermal oxidation of HFC-23 from HCFC-22 production, refrigerant recovery, distributed refrigeration, major retrofits of aluminum smelters, and refrigerant leak detection and repair.

Beyond these general trends and patterns, the study has illuminated some important uncertainties and sensitivities. The ODS consumption data and the ODS stock data yielded widely divergent base year ODS substitute emissions estimates for developing countries, indicating that research is necessary to better quantify emissions from these regions. Projected emissions from all sources are very sensitive to the growth rates of both emitting activities and emission factors, and

these are uncertain, particularly more than 10 years into the future. This analysis assumes that industries that have announced emission reduction commitments actually fulfill them; emissions will be significantly higher if they do not.

For abatement technologies, areas of uncertainty include the costs and reductions associated with technologies that have not yet been widely implemented or that are used for relatively small sources (such as the manufacture of electrical equipment). It is worth noting that the technical and economic feasibility of similar abatement options (e.g., substitution of hydrocarbons for HFCs) can vary significantly across applications (e.g., domestic refrigeration vs. stationary air conditioning). To some extent, the same is true across regions, but region-specific technical and cost data was not always available, particularly for developing countries. For example, energy-related costs and emissions, which can have a significant impact on the costs and benefits of some options, are related to the annual operating hours for equipment. However, country-specific information on this parameter was not readily available for incorporation into this study. Finally, large uncertainties are introduced by the fact that bottom-up analyses of this type are not capable of capturing the effect of radical technology shifts on either future emissions or future abatement costs. Given the rapid pace of technological advancement in these sectors, such shifts are quite possible in the next 15 years, and they grow increasingly likely beyond that.

Future analyses can address many of these uncertainties and sensitivities, both by further researching poorly understood areas and by generating multiple scenarios to understand the range of possible futures. Among the most important questions to address are those involving the emissions and abatement costs of developing countries, because these are expected to account for a large fraction of global emissions and abatement opportunities by 2020. Other important areas of research include better quantifying (1) the regional variability of energy-related emissions and (2) the costs and reductions associated with alternative end-of-life options, such as the recovery or destruction of the HFC blowing agent during the disposal of rigid foams.

Overall, this analysis illustrates the importance of assessing the costs and reductions associated with abatement options at a detailed level (i.e., by source category, gas-type, and country), even if these results are ultimately aggregated for modeling. Based on a detailed sectoral and regional understanding, and with proper caveats, bottom-up analyses like this one can serve as a valuable guide to policy development.

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GHG Mitigation Potential, Costs and Benefits in Global Forests: A Dynamic Partial Equilibrium Approach

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This paper reports on the global potential for carbon sequestration in forest plantations, and the reduction of carbon emissions from deforestation, in response to six carbon price scenarios from 2000 to 2100. These carbon price scenarios cover a range typically seen in global integrated assessment models. The world forest sector was disaggregated into ten regions, four largely temperate, developed regions: the European Union, Oceania, Russia, and the United States; and six developing, mostly tropical, regions: Africa, Central America, China, India, Rest of Asia, and South America. Three mitigation options—long- and short-rotation forestry, and the reduction of deforestation—were analyzed using a global dynamic partial equilibrium model (GCOMAP). Key findings of this work are that cumulative carbon gain ranges from 50.9 to 113.2 Gt C by 2100, higher carbon prices early lead to earlier carbon gain and vice versa, and avoided deforestation accounts for 51 to 78% of modeled carbon gains by 2100. The estimated present value of cumulative welfare change in the sector ranges from a decline of \$158 billion to a gain of \$81 billion by 2100. The decline is associated with a decrease in deforestation.

1. INTRODUCTION

Forests play an important role in the global carbon cycle. An estimated 1,146 Gt C are stored within the 4.17 billion hectares of tropical, temperate and boreal forest areas. A third of this carbon is stored in forest vegetation, and the rest in forest soils (Watson et al. 2000). Another 634 Gt C is stored in tropical

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savannas and temperate grasslands. Watson et al. (2000) estimate a net terrestrial carbon uptake of 0.7 ± 1.0 Gt C/year. Carbon dioxide annual average emissions from land use change, mostly from deforestation, are estimated to be 1.6 ± 0.8 Gt C/year for 1989-95. Other estimates suggest a range between 1.2 to 1.9 Gt C/year for the early 1990s (Foley and Ramankutty, 2004).

The IPCC Second Assessment Report (SAR) noted that the technical potential for carbon sequestration through forestry activities over a 50-year period ranged from 55-76 Gt C, without considering carbon price incentives (Brown et al. 1996). A more recent assessment of the technical potential for afforestation and reforestation options for storing carbon suggests a total potential in the range of 197-584 Mt C/year in 2010, and a potential for reducing emissions from deforestation of 1788 Mt C by 2010 (Watson and the Core Writing Team, 2001). This potential is about one-sixth of the net annual anthropogenic emissions, estimated at 6.3 ± 0.6 Gt C/year between 1989-1998 by Watson and the Core Writing Team (2001), and at 6.6 Gt C/year for 2001 by the US Department of Energy (2003).

The mitigation potential in forestry varies across countries, and over time. Significant factors that influence this potential include the availability and suitability of land for forestation, its carbon sequestration potential; current and future land use activities, including deforestation trends; and changes in the efficiency and use of forest products, including biomass dedicated for fuel.

A number of studies have analyzed mitigation activities in forestry and estimated the associated costs per t C in different countries (Watson et al. 2000). These studies use different assumptions and methodologies with respect to carbon pools and cost elements included in the estimation. Watson et al. (2000) report costs ranging from \$0.1 to \$15/t C. Sathaye et al. (2001) summarized the potential and cost for seven tropical and subtropical countries—Brazil, China, India, Indonesia, Mexico, the Philippines and Tanzania—by applying a common bottom-up model, COMAP (Sathaye et al. 1995). They report a forest sector total carbon sequestration and emissions avoidance potential of about 6 Gt C by 2030 half of which is at negative cost after accounting for the market value of the associated forest products.

Other models have addressed these questions using partial and general equilibrium frameworks. The Global Timber Model (GTM), a partial equilibrium model, has been used to examine the effects of carbon prices on afforestation and forest management options for 53 forest ecosystems in nine regions in an integrated framework of global demand and supply of timber (Sedjo and Sohngen, 2000; and Sohngen and Sedjo, 2006). The Mini Climate Assessment Model (MiniCam) is a long-run integrated assessment framework (Edmonds et al., 1996) that generates a commercial biomass price and a carbon price and passes these to another partial equilibrium model, AgLU, which generates a biomass crop supply, and GHG emissions from land use. Competition for land occurs in the AgLU in estimating the commercial biomass supply. These models have been used to assess the demand for agricultural products over time, by region, and competition between agricultural and forest lands for production of crops, biofuels, and tree planting. At an aggregate level, MiniCam ensures that demand for agricultural and forest

products is met over the model time horizon to 2100. The Integrated Model to Assess the Global Environment (IMAGE 2.2) provides similar analysis using a heuristic, decision-rule approach to the allocation of global lands by region for agriculture, biofuels, and afforestation (Graveland et al., 2002). Manne and Richels (2006) applied the general equilibrium model (MERGE) to evaluate the role of non-CO₂ GHG and carbon sinks in mitigating global climate.

In this paper, we use a dynamic partial equilibrium model (Generalized Comprehensive Mitigation Assessment Process, GCOMAP) built to simulate the response of the forestry sector to changes in future carbon prices. The general equilibrium models reported above mostly rely on a few global data sets. A major goal of GCOMAP is to make use of detailed country-specific activity, demand, and cost data available to the authors on mitigation options and land use change by region (see Appendix A, and Sathaye et al., (2001) for tropical country data). The model permits explicit analysis of the carbon benefits of reducing deforestation in tropical countries. However, it does not consider the impact of increasing carbon dioxide concentration (i.e., CO₂ fertilization) on changes in the carbon cycle, and its effect on biomass growth.

This paper seeks to: (1) report results in a format readily usable by climate change general equilibrium modelers, and (2) facilitate comparisons of land use change and carbon benefits across developed and developing regions by mitigation options over time. For example, the MERGE model incorporates GCOMAP model results to estimate the potential for carbon benefits from the forest sector given alternative carbon price paths.

The paper is organized as follows. Section 2 reports on the model structure and the approach adopted for the accounting of carbon and monetary flows, and for the determination of land area that is planted in response to an exogenous carbon price scenario. Section 3 discusses the data and sources, and Section 4 the reference case land use change and carbon price scenarios. Section 5 discusses the impacts of these scenarios on the increase in planted land area and its carbon consequences, and the sensitivity of results to changes in the reference case land use scenario. Finally, Section 6 concludes with observations about the key findings of this study.

2. STRUCTURE OF THE MODEL

The GCOMAP model establishes a reference case level of land use, absent carbon prices, for 2000 to 2100. It then simulates the response of forest land users (farmers) to changes in prices of forest land and products, and prices emerging in carbon markets. The objective is to estimate the land area that land users would plant above the reference case level, or prevent from being deforested, in response to carbon prices. The model then estimates the net changes in carbon stocks while meeting the annual demand for timber and non-timber products. Table 1 provides a list of the key features of the model. The ten world regions covered by the model and as utilized in the EMF 21 modeling process are listed in Table 2. More detailed

description of the model structure, approaches, and data are presented in the model description paper (Sathaye et al., 2005), including regional land use and carbon stock data, equations for the carbon accounting and financial modules, and other details.

Earlier studies have grouped forestry mitigation activities into three categories (Brown et al. 1996, and Watson et al. 2000). One category, carbon sequestration, includes activities that store carbon, for example through afforestation, reforestation and agroforestry. A second one, conservation, includes activities that avoid the release of emissions from carbon stock, such as forest conservation and protection, and a third category, substitution, involves the substitution of carbon-intensive products and fossil fuels with sustainably harvested wood products and wood fuel. Activities and products in these categories may be interlinked.

We analyze three mitigation options: 1) short-rotation forestry, i.e., new or replanted tree crops or forests managed on a rotation of growth and harvest between 6-60 years; varying by region and forest type; 2) long-rotation forestry, i.e., planting and management for rotations between 20-100 years; and 3) avoided deforestation, i.e., land use management that extends rotations and prevents deforestation. The first two options conform to the first IPCC category, carbon sequestration, and the third conforms to the conservation category. These options currently are practiced in many countries in a wide range of biophysical and socioeconomic conditions, and often co-exist on similar lands, especially in the tropics. (The model also is capable of analyzing biofuels mitigation, a substitution option, but that is not reported here.) Afforestation and reforestation are difficult to define and track separately, especially in the tropics, so they are combined into two forestation options analyzed for each of the ten regions. The option to avoid deforestation is analyzed for four developing regions where deforestation is significant – Africa, Central America, Rest of Asia, and South America. We did not analyze the forest management option in the model and hence vintages of carbon stocks were not tracked for managed or unmanaged forests.

The model is composed of three modules.¹ The carbon stock module tracks annual changes in carbon stocks in ten carbon pools (Table 2): above- and below-ground biomass, soils, litter, post-harvest residues, and wood products – domestic and international timber, non-timber products (fuelwood, resin, honey, and fruits), mill waste, and biofuels (though not reported in this analysis). Product decay and deforestation releases carbon and other greenhouse gas emissions and causes carbon stocks to decline. The same carbon stock dynamics apply to each parcel of forest or planted land in a region over the model time horizon. Vintages of future carbon stock are tracked on planted land. Data for each option represent the characteristics of a representative species for a given region.

The financial module tracks the annual monetary flows associated with the implementation of each of the three mitigation options. The costs of forestation activity include the value of inputs used during establishment (or

1. Equations that describe the carbon stored in each pool, monetary costs and benefits, and the amount of land area planted in response to a carbon price scenario are described in Sathaye, Makundi, Dale, Chan, and Andrasko (2005).

Table 1. GCOMAP Model Features

Feature	GCOMAP
Temporal coverage	2000 to 2100; changes tracked annually.
Land-use change scenarios	Reference scenario—Historical trends, modified government plans. Mitigation scenarios—Driven by land use response to six future carbon price scenarios
Timber and non-timber forest product output and prices	Use supply and demand elasticities to estimate timber price and quantity changes. Five timber and non-timber products. Separate domestic and international markets.
Discount rates	Rate of return (ROR) remains unchanged between reference and mitigation scenarios. Reference case ROR is derived from input costs, product price, and output levels.
Model mechanics	Region-specific for 10 regions. Perfect foresight; based on investment theory. Permits sensitivity and alternative scenario analyses. Software: Excel, Visual Basic.
Macro-economic implications	Estimates total outlays and changes in consumer and producer surpluses and net social pay-off (welfare)

Table 2. Mitigation Options, Regions, and Carbon Pools in GCOMAP

Mitigation Option	GCOMAP Reporting Regions	Carbon Pools (All Regions)
Forestation • Short rotation • Long rotation • Biofuels (not reported in this paper)	• China • India • Rest of Asia • Africa • South America • Central America • USA • EU (Incl. E Europe and Baltic States) • Russia • Oceania (Australia/NZ/Japan/PNG)	Above/below ground biomass Soil organic carbon Litter Post-harvest residues Products: - Domestic timber products - International timber products - Fuelwood products Biofuels (mill-waste) – used as a substitute for coal in power plants
Avoided deforestation	• Rest of Asia • Africa • South America • Central America (Minimal or no deforestation assumed for other regions)	

during deforestation), usually in the first three years or so (e.g., opportunity cost of land, machinery, labor and materiel), as well as expenditures on periodic operations thereafter (e.g., thinning, harvest, and annual overheads like management, maintenance, and monitoring). Costs of deforestation include the cost of harvesting trees and transporting timber from the deforested site, and the opportunity cost, which is estimated as the value of economic activity on deforested land. The benefits from forestation include the revenues derived from the sale of

domestic and international timber, non-timber products and fuelwood that have no associated carbon storage, and other mill-waste products. The benefits from deforestation include the above components, except non-timber products.

The land use change module tracks the annual changes in land use in the forestry sector for each of the three mitigation options. Based on the price elasticity values for land supply and demand, the model computes the price of land and the area to be planted or not deforested annually in response to a carbon price. The module ensures that the cumulative planted land area does not exceed the estimated maximum available area suitable for that option in a region.

2.1 Approach

Each mitigation option is analyzed separately for each region in the model. The analysis begins with the specification of a land use change scenario for the reference case. Using input data on biophysical characteristics of the region—biomass yield, carbon content of the biomass and soils, product shares, etc.,—the first module computes the annual changes in carbon stock over the model time horizon. It tracks both the accumulation of carbon and its release due to the decay of vegetation and products separately on lands planted each year. Simultaneously, using input data on fixed and variable costs, and product prices, the second module computes the financial viability of the forestry option. While the model is capable of computing several financial parameters, we are mainly interested in the estimate of the rate of return. Since the carbon dynamics are the same on land planted each year, as are costs and product prices, the rate of return remains unchanged on lands planted in subsequent years.

The third module of the model then estimates the changes in land use that result from a carbon price scenario. The rate of return is maintained the same as in the reference case scenario, which decides the additional land area to be planted in the mitigation case each year. The first module is then rerun to compute the annual changes in carbon stock brought about by the change in mitigation land use. Finally, the model computes the difference in carbon stocks in the mitigation and reference cases and reports the carbon and land area gain for each decade between 2000 and 2100. This module also estimates the change in social welfare in the forestry sector.

Various land uses (short, and long rotation forestry, agriculture, human habitats, etc.) coexist in competition with one another in each region. Our estimated historical rates of return for forestation options reflect the prevailing returns at which land markets are in equilibrium. In the reference case, we project future planting using the historical planting rate, and assume that the current equilibrium conditions will hold over the model time horizon.

2.1.1 Rates of Return

Two approaches to discounting—prescriptive and descriptive—may be used in climate change modeling (IPCC, 1996). The former approach leads to

lower, and the latter to higher, rates of discount. The descriptive approach is based on the private or social rates of discount that, savers and investors actually apply in their daily decisions. Private rates of discount typically range between 10% and 25%, and social rates of discount between 4% and 12% (Markandya and Halsnaes, 2001). The rates are lower for developed countries and higher for developing ones. We estimate private rates of discount from data on cost and revenue profiles in forestry land use activities, and use these in our analysis of the three mitigation options. Cost and revenue profiles are derived from data shown in Appendix A1.

The estimated rates of return (ROR) for land use activities may also depend on the capital markets from which a land user may borrow funds for investment in forestry projects. The estimation of changes in capital markets between the reference and mitigation cases and their influence on interest rates is outside the scope of a partial equilibrium framework. Instead, we assume a conservative rule that the land user would demand at least the same rate of return in a mitigation case as the ROR in the reference case otherwise the user would have no monetary incentive to plant additional land area or reduce the area being deforested.

Within a region, the model may compute different rates of return for short- and long-rotation forestation options, each of which satisfies demand for different wood products. The differences among land users in their access to financing, timing of revenue streams, biophysical conditions of their lands, etc., results in the coexistence of both options in each region. The model allows both forestry options to persist in the future, consistent with historical and current land use trends. Forestry options also co-exist with other land uses, with comparable implicit effective rates of return after taking into account specific factors like taxes, subsidies and risk. A carbon price allows the land-owner to increase the land under forestry by enabling him/her to plant on higher marginal cost lands. The higher costs of this incremental planting are offset by the carbon price subsidy such that the rate of return from the new areas is maintained at its reference case value.

The rates of return vary across regions but are held constant over time. For short rotation forestry, the rates range from 6% to 12% for the three OECD regions and Russia, between 12% and 19% for Africa and Latin America, and between 26% and 30% for the Asian countries. These rates are derived from sources specific to these regions, and are higher than societal discount rates². The rates for long-rotation forestry are uniformly lower, between 3% to 7% for the three OECD regions and Russia, from 6% to 11% for Africa and Latin America, and from 9% to 13% for the Asian countries. The higher rates of return in Asia

2. These rates of return are higher than the societal discount rates that are used in national and global models of climate change. LBNL's review of 23 forestry projects in the tropics shows societal discount rates to range from 1% to 12%, with the median value at 10% and the average at 7% (Dale, 2003). Other studies have used a 10% rate for short-rotation forestry and arrived at a high positive net present value of benefits. For example, Xu *et al* (2001) using a discount rate of 10% report NPV estimates for China of \$540 - \$740 and \$410 - \$610 per hectare for short- and long-rotation forestry respectively. Likewise, Masera *et al.* (2001) reported NPV of \$497 and \$5780 per ha for short- and long-rotation respectively, using a 10% real discount rate.

also correspond to significantly higher planting rates in those countries (Figure 2). In each region, the rates of return for long rotation are lower than those for short rotation due to the temporal distribution of costs and revenues, with costs occurring in the beginning in both options but revenues coming in much later for long rotation. The price differential (with long rotation species generally having higher product prices), is not sufficient to defray the temporal effect.

2.1.2 Timber Market: Supply and Demand

The model represents international (timber products) and domestic markets (three types of products—timber, fuelwood, and non-timber products) with separate demand curves and product prices by region, using International Tropical Timber Organization (ITTO) and other data (see Appendix A, Table A1). There is no single global timber clearing price, but rather a separate demand curve for each product in each region. Demand is exogenous, and supply of products meets it by region.

Consistent with historical data, this analysis assumes that real timber price remains unchanged in the reference case, mostly due to technological improvements and substitution effects. Future timber demand increases over time as population and economies continue to expand, but timber supply continues to increase to meet this demand. Data from the last 40 years suggest that real prices of forest products have remained static over this period (FAO, 2000; FAO, 1992; FAO 1985), with the exception of tropical logs, whose real prices have been slowly increasing. Prices for wood-based panels, paper, and paperboard had been declining since the early 1960s, but have remained constant since the 1980s (FAO, 1992). This may be because substitution of other materials for wood products and technological improvements have reduced the quantity of wood demanded per unit of GDP over time.

In the past 50 years, production of industrial roundwood has grown at about 1 percent per year, with the share of plantations rising from negligible to the current 25% of global industrial roundwood and 5% of wood fuel production (FAO, 2000). This shift to a managed, faster growing, higher timber density source of wood and fiber represents part of the technological change that has kept real product prices unchanged, and is assumed to persist in the reference case analyzed in GCOMAP, which allows recent rates of forestation observed in each region to be maintained in the reference case. Productivity change is computed within the model, and is defined broadly to include not only productivity improvements, but also changes in species mix and distribution of timber production within a region. Other authors have used a narrower definition, for example, in the AgLU model Sands and Leimbach (2003) simulate increases in crop yields in a range of 0.0% to 1.5% per year.

2.1.3 Social Welfare Change in the Forest Sector

While we use the land user's perspective in estimating the increased land area that will be planted, it is also useful to estimate the implied increase in social welfare as estimated by the increase in consumer and producer surplus

(Varian, 1992). This welfare gain (net social payoff) is an estimate for the forestry sector only. In order to be comprehensive, one ought to use a general equilibrium approach and adjust the welfare gain in this sector by the change in net social payoff (NSP) in all the other related sectors whose demand and supply may have been affected by this sector, especially the carbon credit buyers. Since this is outside the scope of our paper, we estimate only the regional and global welfare gain for the forestry sector. The assumption of constant marginal utility for money among timber producers and consumers applies to the estimate of the social welfare gain. However, this is partly mitigated by the use of region-specific implicit discount rates.

3. DATA AND SOURCES

Data on land use change, biomass stocks and growth, carbon pools, forestation and deforestation activity, emission factors, and costs and benefits of forestation and avoiding deforestation were gathered for each region. The data and sources are shown in the Appendix Table A1. By their very nature, data from various sources may use similar but not identical definitions. For the tropical countries, country-specific data were gathered over a period of years by the F7 network on tropical forestry. Definitions of various activities and data differences were reconciled by network researchers through workshops and meetings beginning in the early 1990s (Makundi and Sathaye, 1992; Makundi et al, 1995; Sathaye et al, 1995).

Data on land use change, (forestation and deforestation) for the tropical and temperate/boreal countries were gathered largely from the FAO 2002 Forest Resource Assessment (FAO, 2003a) and FAO 1990 FRA - Tropical Countries (FAO, 1993). The regional data on forestland cover, biomass volume, planting and deforestation rates, and industrial roundwood production were based on FAO and ITTO statistics. The FAO and ITTO data collection and publishing process involves some standardization, thus enhancing comparability across regions.

The afforestation and reforestation costs/benefits data as well as carbon sequestration data for the tropical countries are drawn from earlier studies for the COMAP model (summarized in Sathaye et al., 2001), and supplemented with country- or region-specific sources (RSMD, 2001; Potter and Lee, 1998; Sist et al., 1997; Kaimowitz, 1996; Nambiar et al., 1998; Nair, 2000; Nambiar et al., 1999; Barraclough and Ghimire, 2000; and Pandey, 1983). When data were not available for other countries in a region, these sources were applied to represent tropical regions in geographic proximity. The yield data were adjusted to ensure that all biomes are appropriately covered. Country-specific labor costs are used where available or adjusted by wage index for a given region, as detailed in Table A1 in the Appendix. Domestic prices of timber and non-timber products were scaled using regional average values weighted by volume for these parameters. The regionalization approach provides coverage of tropical countries in Asia, Africa, and Latin America.

Some of the data for the industrialized regions were obtained from common international sources (FAO, 1992; FAO 2001, FAO, 2002). However, the bulk of the data were gathered from sources unique to each region (see Appendix 1) (Moulton et al., 1995; Moulton et al., 1996; EPA, 2002; Cairns et al., 1995; Parks and Hardie, 1997; King, 1993; Peterson, 1993; Izrael and Avdjushin, 1997; ECE/FAO, 1992; Hutjes et al., 2001; Nilsson et al., 1992; Kirshbaum et al., 2000; Lyons, 1997; Petrov, 2001). Country-specific data were scaled to regional values using ratios of regional averages to country-specific values for the industrialized regions—the EU countries, Russia, and Oceania. These were supplemented with additional country-specific data for the US. Although Canada has a large forested area, it is not included in this analysis since we do not analyze the forest management option, and we assume that there is no net deforestation in non-tropical regions. Furthermore, we do not analyze Canada's forestation potential since there is negligible area under industrial plantations, a key element in initializing the forestation module in the model.

Data on price elasticity of timber demand and supply were obtained from the literature; these are relatively sparse and dated and were applied to each region. This lack of differentiation by region, and constancy over time, of the elasticities is conceptually sub-optimal, but the few data available seem inadequate to justify a range of values by region. A very elastic demand for exported timber, -33.3 was used (Makundi, 1990), while price elasticity of -1.0 was used for domestic timber demand (McKillop, 1967; Robinson, 1974; Adams, 1985). The supply of timber was assumed to be much more inelastic, +0.5 (Adams, et al, 1986; Adams and Haynes, 1980). In this analysis we used the US forestland supply price elasticity, 0.25, and applied it to all regions over the 100-year horizon, since few studies of such elasticities exist. This value is also the average price elasticity of forestland reported in Sohngen and Mendelsohn (2002) for eight of the ten regions in GCOMAP.³ Cost and price data were adjusted to 2000 US dollars.

The supply of woodfuel was determined as a residual from the harvested biomass after extracting timber and an estimate of a proportion of onsite post-harvest wood waste. This estimate varies across regions depending on the level of woodfuel use in the country, with developing regions having a much higher proportion than the developed regions. As mentioned above, the proportion of firewood from industrial plantations is about 5%, but in some regions e.g., Africa and Asia, some plantations are dedicated for firewood. The demand for woodfuel and mill-waste for fuel in the reference case is modeled as a residual in the combined multiple-product demand function (international timber, domestic timber and woodfuel).

3. Sohngen and Mendelsohn (2002) report elasticities for North America, Former Soviet Union, and China that are lower than the average we use; and higher elasticities for Western Europe, India, and Oceania. The relatively high elasticity of 1 reported for India and Oceania was considered uncharacteristically high and was excluded from the average.

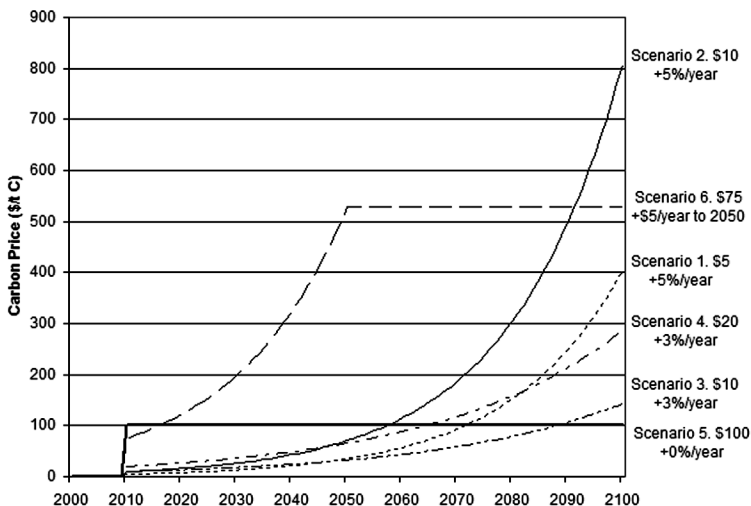
4. SCENARIOS

We analyze the incremental effect of six carbon price mitigation scenarios on changes in land use and carbon gain between 2000 and 2100 in comparison to a single reference scenario. The reference scenario has no carbon market and hence there is no price for carbon. The six mitigation scenarios were developed for use in the EMF-21 forest and agriculture sequestration analyses, and have different initial carbon prices and follow varying carbon price paths. The six carbon price scenarios are illustrated in Figure 1. Scenario 1 has the lowest initial carbon price of \$5/t C rising at 5% per year. Scenario 2 has a higher initial price of \$10/t C, but rises at 5% per year, while Scenario 3 also starts at \$10/t C but has a lower growth rate of 3% per year and reaches the second-lowest price in 2100 of \$143 per t C. Scenario 4 starts at a higher initial price of \$20/t C, and rises at 3% per year. Scenario 5 represents a different trend where the carbon price is held constant at \$100/tC through 2100. In Scenario 6, the carbon price starts at \$75/tC, rises at 5% per year until 2050, and is then held constant to 2100. Because of their unusual price paths, the timing of carbon gains, and the relative contributions of forestation and avoided deforestation in these two scenarios, is quite different from that for the first four scenarios. All scenarios are below or at \$100/tC by 2050, except for Scenario 6, but they range from \$100 to over \$800/tC in 2100.

4.1 Reference Scenario – Land Use Change

The amount of carbon sequestered through forestation and that released through deforestation depends critically on future reference case scenarios of land

Figure 1. Carbon Price Mitigation Scenarios



use change. Below, we describe the historical land use change patterns, and our estimated availability of lands that may be suitable for tree planting in each region.

Forestation: The reference case for short- and long-rotation forestry assumes that historical forest planting rates in each of the ten regions continue out to 2100. The historical data range from 1975 to 2000, and are largely based on FAO statistics on land area planted. In the case of the US, EU, and Oceania, however, the data are derived from national statistics (see Table A1). For some regions, like US and China, we collected data by sub-regions, nine for the US and four for China and used these to estimate aggregate totals or weighted average values for the relevant model parameters. By using historical planting rates that vary by region, we reflect differential regional infrastructure, response to economic incentives, and institutional settings. As noted in Section 3 above, the price of land increases at a supply price elasticity of 0.25. The unit cost of planting, however, remains constant due to productivity improvements over the period of analysis in the reference case.

The above land data show that the average total land area planted annually amounted to about 6.1 Mha/year, of which about 3.3 Mha/year was used for long-rotation planting. Figure 2 shows the land area planted annually under short- and long-rotation plantations, based on available historical data (for varying years during the period 1975 to 2000). The assumption that historical planting rates continue through 2100 in the reference case importantly drives the availability of land suitable for planting in mitigation scenarios. In some regions and time periods this assumption limits the quantity of planting that occurs. Other reasonable assumptions of afforestation, both lower and higher than historical rates, may be used and these would impact the mitigation potential and timing for afforestation. We report on the results of a sensitivity analysis, which tests the model's response to alternative forestation assumptions, in Section 5.4.

Figure 2. Average Annual Planting Rate Per Region Using Available Data from Varying Periods During 1975-2000

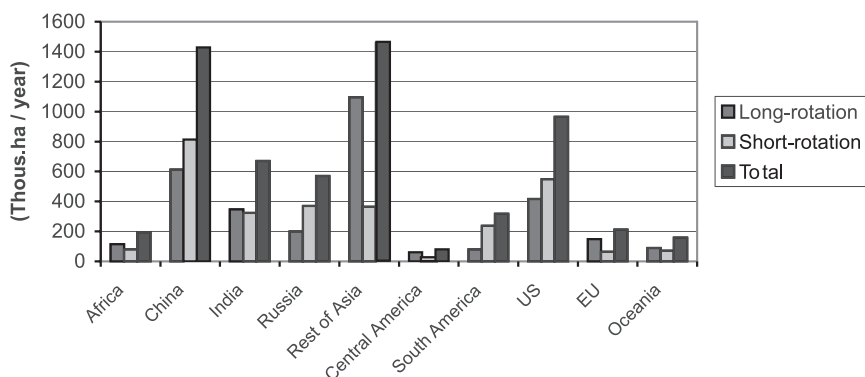


Table 3. Maximum land area suitable for tree planting

Regions	Short- rotation forestation (Mha)	Long- rotation forestation (Mha)	Comments
Africa	80.0	120.0	50% of the deforested land (4 Mha/yr 1970-2020), the rest from grasslands, woodlands, and abandoned agricultural lands. (FAO 2000, FAO, 1993, Barraclough and Ghimire, 2000)
China	35.9	27.1	Based on China's short, medium, and long-term expansion plans for timber and non-timber forests by 117 Mha by 2050. (MOF, 2000)
India	10.2	11.5	National Forest Action Plan to increase India's forest area by 33% by 2020 (FSI, 1999)
Russia	37.5	20.2	50% of the 115 Mha of the Unforested land under FFS, part of which is currently used for Reforestation (NEAP, 1995 In National Implementation of Agenda 21)
Rest of Asia	50.0	150.0	Degraded forestland and wasteland. (FAO, 2001 (FRA 2000), FAO, 1993 (TFRA 1990), CIFOR, 2000)
Central America	6.5	15.0	Degraded forestland and wasteland. (FAO, 2001 (FRA 2000), FAO, 1993 (TFRA 1990), Cairns et al., 1995, Kaimowitz, 1996)
South America	50.0	150.0	Degraded forests, deforested lands and cerrados. (FAO, 1993; 2001 (FRA, 2000; TFRA, 1990), Fearnside, 2001; Cairns et al., 1995.)
United States	50.1	65.9	Dry and wet soil pastureland and cropland and non-grazing forest from 10 US regions. (US Forest Service, 2001; Moulton et al., 1990; 1996, Lubowski et al., 2001)
European Union	40.0	50.0	Abandoned crop and pasturelands and sparse woodlands. (ECE/FAO, 1990, FAO 2000 (GFPOS) FAO, 2001 (FRA 2000), Nilsson et al., 1992)
Oceania	28.0	42.0	Australia wastelands and cropland, NZ FAO 2050 scenario, and Japan sparsely wooded lands, and PNG degraded and deforested land. (ECE/FAO, 1990, FAO, 1993 (TFRA 1990), UNFCCC National Communications, Kirschbaum 2000)
TOTAL	388.3	651.7	

The maximum amount of land area that could be planted is quite large in each region (Table 3). Regions such as Africa, South America, and Rest of Asia have vast amounts of marginally utilized land and/or wastelands that could be available for tree planting. In other regions like the US, EU, and perhaps Russia, croplands could become suitable areas for tree planting as increased agricultural

productivity reduces land requirements for farming, releasing some lands currently under agriculture for forestry.

Finally, in China and India notably, but to some extent in Russia, the total land area is large but only a small fraction is suitable for planting. Table 3 shows the land area (including previously deforested land) that is deemed suitable for planting in each region. The comments column explains the approach and references used to estimate the land types and areas suitable for short- and long-rotation plantations.

A consequence of the limited area of land suitable for planting in each region, and of current high rates of planting, is that the amount of land area suitable for planting is exhausted in the reference case by 2030 and 2050 in India and China respectively (Figure 3). As will be shown below, mitigation planting accelerates the planting rate and exhausts the land area sooner than in the reference case.

Deforestation: The rate and spatial distribution of deforestation remains uncertain. The FAO estimated that global tropical deforestation in Africa, Central and South America, and in the Rest of Asia region exceeded 17 Mha annually in the 1980s (FAO, 2001), and was 12.2 Mha annually in the 1990's (FAO, 2003a). Deforestation reportedly has been virtually halted in two of the study regions, India and China (Ravindranath et al., 2001, and Xu et al., 2001, respectively). More recent analysis by Houghton (2003) has revised downward to 700 Mt C/year the previous estimate of 1400 Mt C/year carbon flux from tropical deforestation. Deforestation is assumed to be net zero for developed regions.

In the past two decades, Central and South America, and Rest of Asia showed a decline in the annual rate of deforestation (FAO, 2001). Annual remote sensing data in the last few years from Brazil, however, indicate that the decline shown for South America may have reversed. Africa's rate of deforestation is still rising in step with its rural population's continued dependence on agriculture and primary resources.

Figure 3. Reference Case Land Area Planted (Cumulative) Short- and Long-Rotation

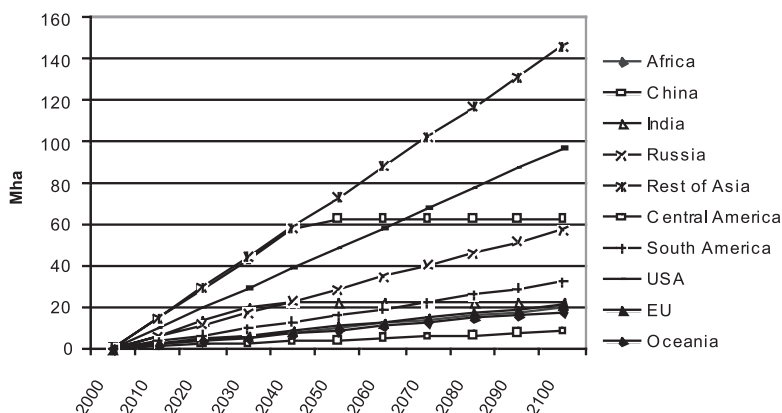


Table 4 shows the annual percent change in deforestation rates for 1990 and 2000, and our projection of the deforestation trend to 2100 for each of the four tropical regions. The deforestation rate during the last decade increased in Africa at 0.026% per year, while it declined in the other three study regions. Consistent with IPCC scenarios, we project the rate in Africa to rise through 2020 before beginning to decline largely due to the depletion of its forests and a high rural-urban migration rate (Nakicenovic, 2000). Meanwhile deforestation continues to decline in the other regions due to economic development, urbanization, and increased agricultural productivity, which reduce the pressure on forest land. Figure 4 shows the projected quantity of deforested land for each of the four tropical regions. The implications of the deforestation rate projection over time are significant for avoided deforestation as a mitigation option in several scenarios, and for the timeframe of any such mitigation. We test the sensitivity of carbon gains to land use change due to deforestation and report this in Section 5.4.

Assumptions of global forest area change over the next century vary significantly across several studies, by model structure, and factors driving land use e.g., population changes, changes in diet and demand for calories in response to changes in GDP over time, and substitution of biomass fuels for fossil fuels. Like other sectoral models, we do not explicitly model these assumptions. Instead we simply and transparently assume that recent historical deforestation rates increase (in the case of Africa), or decline over the near- and long-term time horizons, by region. The carbon consequences of our reference scenario are reported in Section 5.1 and shown in Figure 7 in comparison to those reported for IPCC scenarios.

The changes in forest cover reported in the IPCC scenarios may be compared with the combined forestation and deforestation land use change in our reference case (Nakicenovic, 2000). Similar to some of the IPCC non-marker

Table 4. Historical and Projected Deforestation Rates Used in GCOMAP

Region	Deforestation Rates ^(a) (%/year)				
	2000 ^b	2020	2040	2050	2100
Africa	0.80(+0.026)	1.29(-0.026)	0.78(-0.013)	0.65(-0.006)	0.26
Rest of Asia	1.03(-0.005)	0.82(-0.008)	0.60(-0.008)	0.52(-0.008)	0.12
Central America	1.19(-0.011)	0.97(-0.011)	0.75(-0.011)	0.65(-0.011)	0.37
South America	0.40(-0.013)	0.26(-0.001)	0.21(-0.001)	0.20(-0.001)	0.13

Notes: (a) The values are percent of the land area deforested in the year shown. For example, Africa will lose 0.8 percent of its forests in 2000, while South America will lose 0.4 percent. (b) The value in parenthesis is the rate at which the deforestation rate is changing each year, with a (+) sign indicating the rate is increasing. The initial rate of change is estimated from the land use change between 1990 and 2000. For example, Africa is losing 0.8% of its existing forest in year 2000, and this rate is increasing by 0.026% per year, as such by 2020 it will lose 1.29% of the then existing forest. The decline in deforestation rates are region-specific, with the rates estimated to cause a smooth decline ensuring that by the end of the period the rate will still be adequate to support necessary forest conversion to settlements, development and communications infrastructure.

**Figure 4. Reference Case: Land Area Deforested by Region
(Cumulative to year reported)**

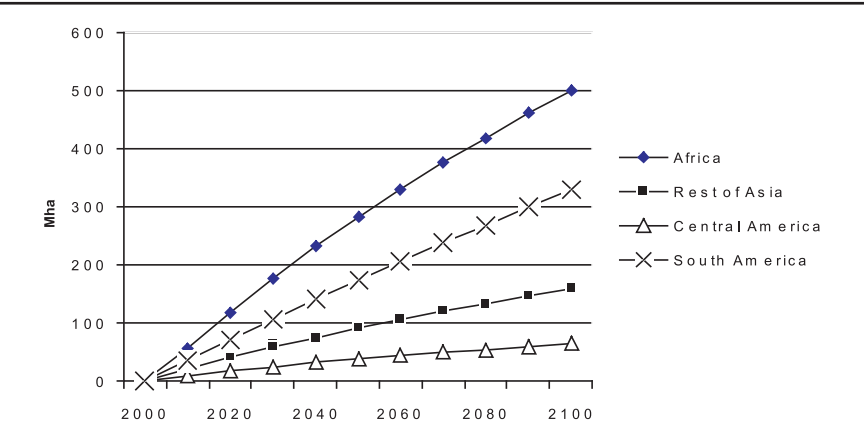
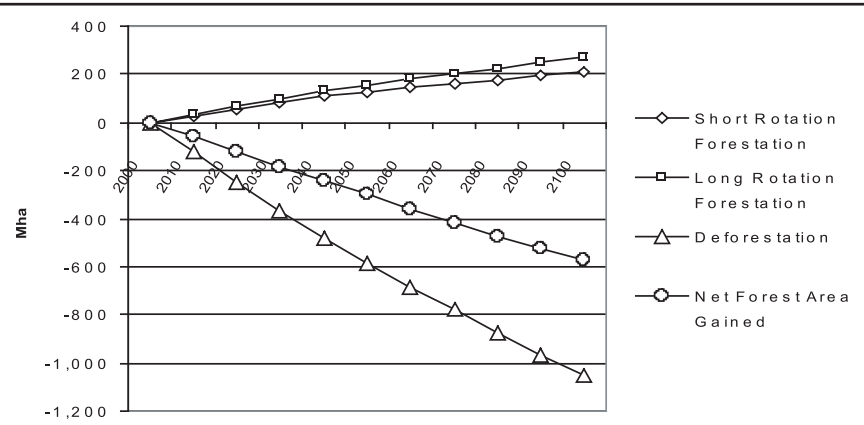


**Figure 5. Reference Case: Land Use Change by Activity for All Regions
(Cumulative to year reported)**



scenarios, world forest land in our reference case declines continually starting in 2000 with a cumulative loss of 570 Mha by 2100 (Figure 5). Forest cover increases in Asia and decreases in the Africa and Latin America regions continually up to 2100. In all other model regions, forest cover increases between 2000 and 2100.

5. RESULTS

We analyze six mitigation carbon price scenarios using the GCOMAP model, and compare land use change and carbon sequestration between each scenario and the common reference scenario. For each scenario, we estimate

the increase in land use and carbon stock over time for ten global regions for the short- and long-term forestation options. We also estimate the effect of the avoided deforestation option for four tropical regions (Africa, Asia, Central and South America), which when compared to a reference scenario slows the rate of deforestation in each region.

5.1 Reference Case

The decline in forest land area by 570 Mha between 2000 and 2100 in the reference case is caused by continued deforestation, which results in a net loss of forest land in each of the four tropical regions. This loss is partly offset by an increase in forest land in the six other model regions of the world. Break down of regional land use and carbon stock data are presented in the model description report (Sathaye et al., 2005).

Figure 6 shows the changes in carbon stock in the reference case. Carbon stock declines initially until 2030 and then increases up to 2100. The decline in the earlier years is caused by the higher deforestation rates in the earlier decades. In the latter decades, deforestation rates decline and carbon stocks from forestation, particularly from long-rotation planting, increase enough to offset the loss in carbon stock due to deforestation. The net result is that despite the large loss in forest land area, carbon stock is slightly higher in 2100 than in 2000. Two regions, Rest of Asia and the US, account for the bulk of the increase in carbon stock in the reference case. Rest of Asia contributes 34 Gt C stock and the US 15 Gt C stock in 2100 out of a total stock of 82 Gt C in short- and long- rotation forestry. Because the net carbon gain is small compared to either the forestation or the deforestation carbon gain, small changes in reference case assumptions about land use change for either of the two types of activities have a significant impact on the net carbon gained estimated by the model. In order to explore this issue further, we analyze the sensitivity of the model results to changes in the reference case land use scenario in Section 5.4.

Our results are within the range of results reported for the IPCC scenarios by Nakicenovic (2000). Figure 7 shows that in the IPCC scenarios, emissions from deforestation have a wide range by 2100, from about 2.8 Gt C/year in the A1B Maria scenario to -1.7 Gt C/year in the B1 MiniCAM scenario. While the IPCC made an effort to produce comparable results, some inconsistencies in accounting for gross and net deforestation remained, and these may account for the wide variation in the 2100 emissions even within the same scenario family (see for example the difference between B2 MARIA and B2 MESSAGE scenarios). We also show GCOMAP emissions from gross and net deforestation in Figure 7. Net deforestation figures are calculated by subtracting the sequestration due to forestation from the emissions due to gross deforestation. Our gross deforestation scenario shows a small peak in 2030 due to the increase in deforestation in Africa. It is similar in magnitude and path to the B2 MARIA scenario, and our net

Figure 6. Reference Case: Carbon Stock Change (Cumulative to Year Reported)

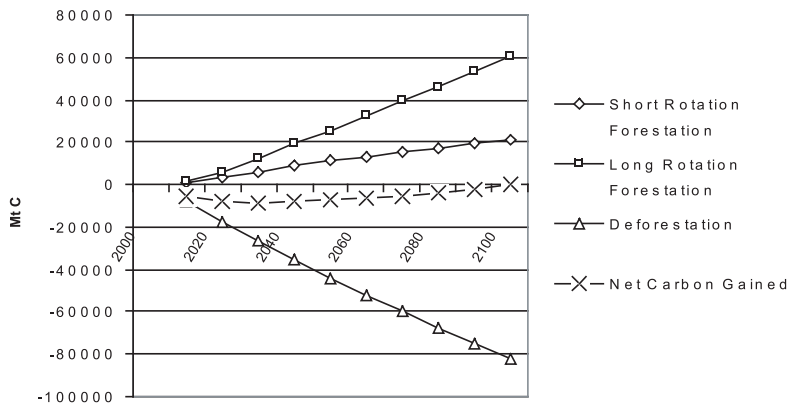
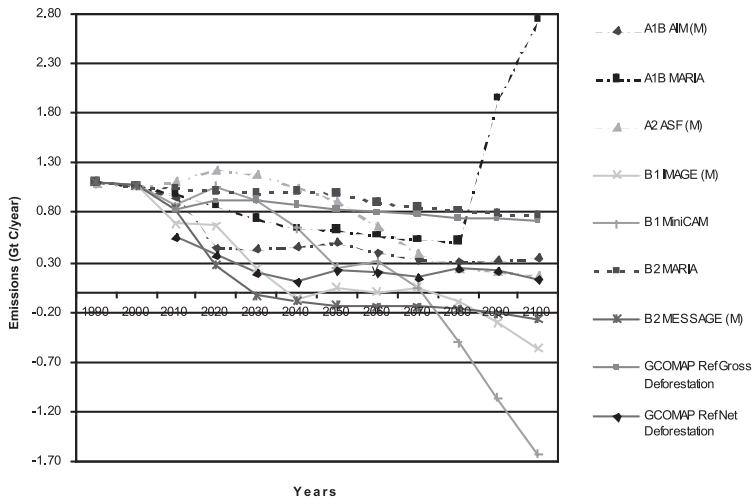


Figure 7. Carbon Emissions from Deforestation: GCOMAP Reference Case (Gross and Net) and IPCC SRES Scenarios (Africa, Asia, Latin America and the Middle East)



deforestation scenario is similar in path but lower in magnitude to the A1B AIM marker scenario.

5.2 Mitigation Cases

Table 5 shows the results for carbon sequestration and emissions avoided across the six carbon price scenarios for 2050 and 2100. Scenarios that

explicitly model the effect of reference case drivers like population and economic growth on changes in forested and deforested areas are feasible, but we have not attempted these as yet. Two sensitivity analyses on reference case deforestation and forestation rates, however, are reported below.

The land area and carbon benefits gained in the price scenarios are consistent with the trends in carbon prices. Scenario 1 (\$5 initial carbon price in 2010, rising at 5%/year to 2100) and Scenario 3 (\$10 initial carbon price in 2010, rising at 3%/year to 2100) have the lowest amount of land area and carbon benefits gained by 2050. This result is consistent with the lowest prices (\$35 and \$33, respectively) reached by 2050 among the six scenarios.

Generally, the higher the carbon price, the higher the land area planted and the carbon benefits gained by that date. However, the model uses perfect foresight, where land users “know” today the price path of C in future periods and use that knowledge to make land use decisions. Thus the model tends to report lower C change for a date in scenarios where prices continue to rise after that date (compared to constant prices). For example, Scenarios 1 and 3 have similar 2050 carbon prices of \$35 and \$33 respectively, but the increase in forest area through forestation relative to the reference case is disproportionately higher in Scenario 1. The land user in the model anticipates the higher prices beyond 2050 in Scenario 1, and hence increases the planting rate for long rotation forestry before 2050. Since forest growth takes time, this anticipatory behavior results in carbon benefits later in the century, but they reach a higher level relative to Scenario 3 by 2100. Similarly in Scenario 5 (\$100 + 0%/year) a high carbon price early results in a large carbon gain relative to Scenario 4 (\$20 + 3%/year) by 2050, but by 2100, both scenarios have the same carbon gains.

The carbon price reaches \$807 by 2100 in Scenario 2 (\$10+5%/year), which leads to continued high rates of planting throughout the 100-year period, and the large carbon gain of 96.5 Gt C by 2100. Because the carbon price rises quickly in Scenario 6 (\$75+\$5/year to 2050 and constant thereafter) to \$275 and stays at this relatively high level until 2100, this scenario results in the largest carbon gain of 113.2 Gt C by 2100.

In Scenarios 5 and 6, the land area gained (relative to the reference scenario) declines after 2050. The high initial price results in a large increase in land area planted relative to the reference case up to 2050, but this declines in subsequent years as the land cap limit is approached in many regions.

Table 5 also shows the contribution of forestation and avoided deforestation to the total amount of carbon benefits and forest land area. Avoided deforestation—although not widely reported as a mitigation option in other analyses—contributes substantially, and accounts for more than half of the carbon benefits gained in each scenario by 2050. By 2100, the percentage of carbon benefits gained from avoided deforestation is lower or the same in the first four scenarios, but it increases in Scenarios 5 and 6. In Scenario 2 (\$10+5%/year), for instance, it declines to 51%, but in Scenario 5 it increases to 78% by 2100. A slowly increasing or constant price (as in Scenarios 3 and 5, respectively)

Table 5. Land Area And Carbon Benefits Gained^a Across Scenarios, Relative to Reference Case

Scenario ^b	Carbon Price (\$/t C)		Land Area Gained (Mha)		Carbon Benefits Gained (Mt C)	
2010 C Price + Annual Increase	2050	2100	2050	2100	2050	2100
1. \$5 + 5%	35	404	190	662	13,570	70,145
Forestation			68	163	5,554	33,162
Avoided deforestation			122	499	8,034	37,105
2. \$10 + 5%	70	807	327	880	24,917	96,496
Forestation			108	231	10,123	47,849
Avoided deforestation			219	649	14,796	48,835
3. \$10 + 3%	33	143	212	555	15,628	50,905
Forestation			52	77	4,934	16,358
Avoided deforestation			160	478	10,694	34,547
4. \$20 + 3%	65	286	363	819	28,582	79,559
Forestation			75	135	8,917	28,575
Avoided deforestation			288	684	19,665	50,985
5. \$100 + 0%	100	100	537	866	47,252	78,970
Forestation			83	56	13,587	17,245
Avoided deforestation			454	810	33,665	61,725
6. \$75 + \$5	275	275	664	1081	63,300	113,208
Forestation			192	146	25,675	38,422
Avoided deforestation			501	959	37,625	74,786

Notes: a) Gained amount refers to the cumulative difference between a mitigation scenario and the reference case scenario by 2050 and 2100

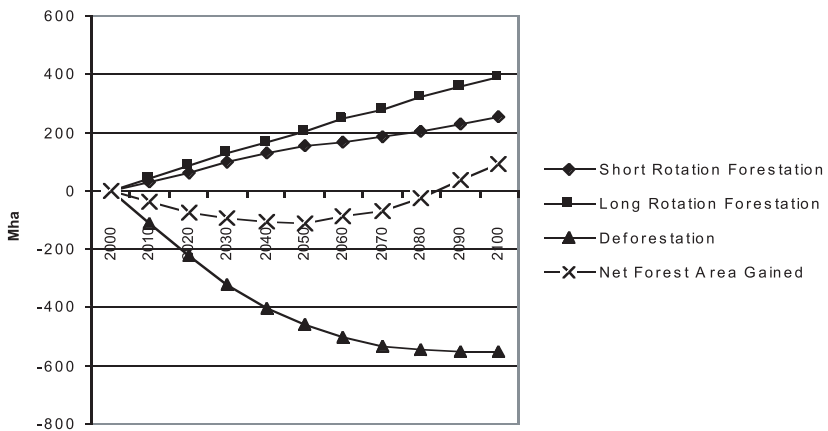
b) All carbon prices are zero until 2009, and begin with the stated value in 2010.

provides less incentive for increased planting in the later decades. Hence much of the carbon benefits gain from forestation occurs prior to 2050 under these price paths. Gains from avoided deforestation, however, continue past 2050.

In the reference scenario, short- and long-rotation forestry increase the area of forested land over the timeframe analyzed, but are overshadowed by deforestation practices that remove forest cover from land (Figure 5). The mitigation scenarios reverse this process by planting more land in trees and reducing the rate of deforestation. In each mitigation scenario, global forest area declines in the earlier decades, but the decline is halted and net forest area begins to increase before 2100. The decade in which the decline is halted is earlier for higher carbon price scenarios than for lower price ones. This transition is realized by 2090 for Scenario 1, for example (Figure 8).

The regional distribution of carbon gains varies across scenarios. The total amount of land available for planting is limited in each region. For instance in India and China, due to the high planting rates in the reference case, the land cap is reached in 2040 and 2050 respectively. The mitigation scenario accelerates the date by which the cap is reached depending on the magnitude, and rate of

Figure 8. Scenario 1 (\$5 + 5% /year) — Land Use Change by Activity for All Regions (Cumulative to year reported)



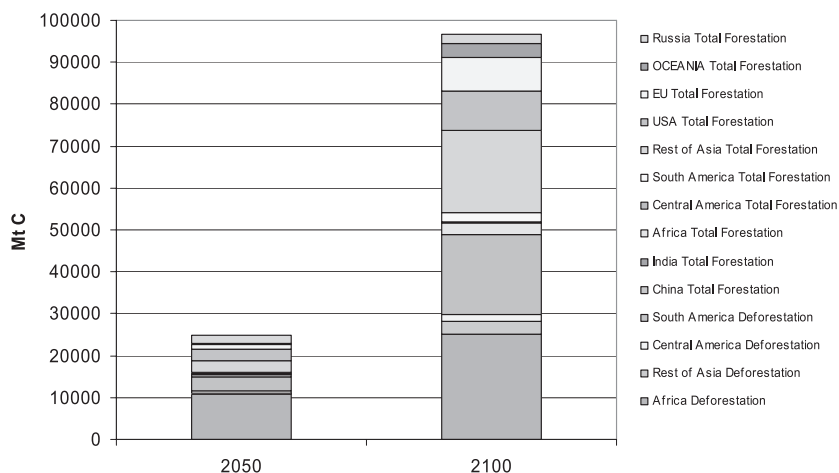
increase, of the carbon price. A similar cap is reached for long-rotation planting in Russia in the reference case by 2100. Elsewhere land availability is not a constraint to tree planting.

The contribution to carbon gain varies by region over time (Figure 9). Rest of Asia, US and Russia account for the more significant carbon gains through forestation in 2050, and the first two along with the EU are the largest contributors to carbon gains in 2100. While the different rates of return and carbon dynamics have some influence, the high rates of planting in the reference case and the large availability of suitable land areas (no cap) are the main reasons for these results.

Figure 9 also shows the carbon gain from avoided deforestation by model regions. Africa and South America are the predominant contributors to this carbon gain. Africa contributes more emissions avoided earlier than the other regions. Two factors play a role. One is the absolute magnitude of deforestation in the reference case, which is high in both Africa and South America. The second factor is the opportunity cost of avoiding deforestation, which is lowest among the four regions in Africa.

5.2.1 Reducing Deforestation

Reducing emissions due to deforestation has the potential to be an important mitigation option particularly in Africa, South and Central America and the Rest of Asia region. Population growth, extraction of timber, road network expansion, shifting cultivation for subsistence agriculture, higher agricultural prices, national debt and other macroeconomic factors, and weak forest management and protection institutions, are major contributors to deforestation (Bhattarai and Hammig, 2001). The contribution of these factors to deforestation

Figure 9. Scenario 2 (\$10+5%/year): Regional Contribution to Carbon Gain in 2050 and 2100

varies across the regions. Timber extraction is more dominant in the Rest of Asia region, subsistence agriculture in Africa, and road building, cattle ranching and land speculation in the Americas.

Reducing deforestation would thus require that deforesters be compensated for the loss of revenue or welfare derived from these activities. It also may require that a complex web of social, economic, institutional, and land tenure barriers or conditions be assessed and addressed in any practices or policies to slow deforestation. Land in the model on which deforestation is avoided due to the imposition of a price incentive is assumed to be mature forest with the average biomass and carbon density of the dominant merchantable timber species or forest type reported in timber trade from the region. These lands continue under the reference case assumptions of timber growth and land use and land use change, except in the event that they are deforested in the future.

The results show that slowing deforestation in Rest of Asia would require higher compensation than in the other regions, since export-quality timber commands a much higher price than other products. The global carbon price at which deforestation theoretically could be halted in Africa is lower than for other regions, due to Africa's low opportunity costs and low rate of export of wood products into international markets. The price is higher in the other tropical regions. Based on region-specific data and GCOMAP analysis, we estimate a global carbon price of \$39/t C in Africa, \$127/t C in Central America, \$147/t C in South America, and \$281/t C in the Rest of the Asia region would be sufficient to theoretically halt deforestation.⁴

4. The corresponding net revenue amounts to \$4836, \$21,590, \$30,723 and \$41,026 per ha respectively for Africa, Central America, South America, and Rest of Asia.

Depending on the carbon price, deforestation is virtually halted in each of the four regions by 2100. A carbon price path that begins low and rises slowly means that deforestation is not halted until later in this century, and vice versa. Since the revenue derived per ha from deforestation is low in Africa, a \$100 per t C price (Scenario 5) is sufficient to halt deforestation in that region, while significantly reducing it in other regions. In the highest carbon price scenario (Scenario 2), deforestation is halted by 2040 in Africa, 2060 in Central America, 2070 in South America, and by 2080 in Rest of Asia.

Slowing deforestation is a feasible, though difficult public policy and climate mitigation strategy. Altering land use patterns and incentives requires a strong government commitment and clear policies, strict enforcement, and incentives for adoption of alternative land management practices. India, for example, passed a Forest Conservation Act in 1980, which has been reasonably well-enforced, thus slowing deforestation to a negligible fraction of its historical rate (Ravindranath et al., 1994). Elsewhere, a carbon price is likely to provide the monetary incentive to slow or even halt deforestation, but it will need to be accompanied by: (1) mechanisms to translate this price incentive into effective monetary stimuli, and (2) well-enforced policies and measures that encourage institutional change in order to provide strong disincentives to deforesters.

5.3 Welfare Gain

The GCOMAP model also allows the computation of the gross change in welfare in the forestry sector in each region due to the higher carbon price. This would be offset by the loss in welfare in other sectors in these regions. Forestation leads to an increase and avoided deforestation to a loss in social welfare. The magnitude of the change in social welfare depends on the carbon price trajectory and level, and the proportion of carbon benefit that is derived from forestation compared to that from avoided deforestation. The largest increases in social welfare per tonne of carbon are achieved in Scenarios 1 and 2 (US \$ 0.9 and 0.8/t C respectively), which have a lower proportion of carbon gains from avoided deforestation. The lowest value is for Scenario 5 (\$ -2.0/t C) in which avoided deforestation accounts for 78% of the carbon benefit gains. The carbon gain per dollar of subsidy is proportional to the total carbon benefits gained. Higher carbon benefits require a higher subsidy to achieve those gains ranging from \$4.0 per t C for Scenario 3 (51 Gt C gain by 2100) to a high of \$20.4 per t C for Scenario 6 (113 Gt C gain by 2100). The estimated present value of cumulative welfare change ranges from a decline of \$158 billion in Scenario 5 to a gain of \$81 billion in Scenario 1 by 2100. The decline is associated with a decrease in deforestation.

5.4 Sensitivity Analysis

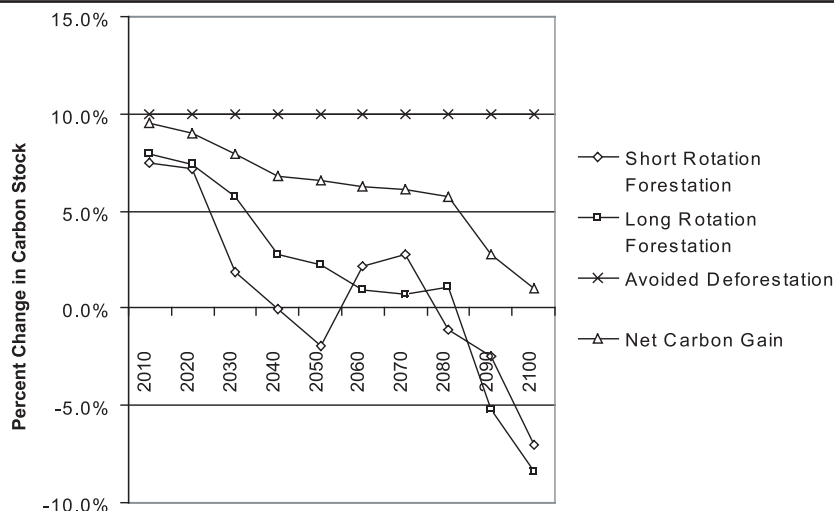
We tested the sensitivity of the results of the GCOMAP model to changes in the reference case land use scenario, which forms the basis for the

estimation of mitigation carbon benefits. We change the reference case land use by 10% uniformly between 2000 and 2100, and estimate the resulting change in the carbon gain for one of the carbon price scenarios (Scenario 2).

A 10% increase in deforestation rate applied to the reference case for each of the four regions, and over the time horizon of the model, caused a 10% decline in carbon gain by 2050 and 2100, and a 10% reduction caused a 10% increase in carbon gain in both years. This sensitivity run demonstrates inverse perfect correlation between deforestation rate and carbon gain. Other deforestation rate assumptions would be useful to evaluate (such as the range represented in the IPCC SRES scenarios), as would alternate land availability caps, but have not been analyzed here.

Whereas, a 10% increase in forestation in the reference case applied to each model region causes a 2% increase in carbon gain by 2050, but an 8.8% *decrease* in carbon gain by 2100 (Figure 10). The lower increase in carbon gain by 2050 is due to the higher marginal cost of land, and the cap on land area causes the reversal. For instance, in Africa, where the land cap is not reached in the model, 10% more forestation increases the carbon gain by 5.1% by 2100. However, in China and India, carbon gain turns negative by 2040 and 2030 respectively, which contributes to a sharp decline in the forestation carbon gain in those years in Figure 10. For short-rotation forestation, carbon gain turns positive in 2060 and 2070, since trees planted in earlier years accumulate carbon during those years only to lose carbon with harvests in subsequent periods. For long- and short-rotation forestation, there is a second sharp decline in 2070-2080 period as land caps are reached in other regions. The combined effect of these responses is that

Figure 10. Scenario 2 (\$10+5%/year) Sensitivity Analysis: Change in Carbon Stock for a 10% Increase in Reference Case Forestation and Deforested Area



the net carbon gain declines from 9.5% in 2010 to about 1% in 2100. In summary, planting 10% higher land area and deforesting 10% more in the reference case would result in progressively less carbon gain over the model time horizon relative to the core scenario run. The carbon gains reported in the model are more sensitive to changes in the deforestation rate than in the forestation rate.

6. CONCLUSIONS

This paper describes a dynamic partial equilibrium global forest-sector model (GCOMAP) incorporating a reference case based on bottom-up data for the tropics from the COMAP model, region-specific data from several sources for the temperate countries, and FAO data on regional forestation and deforestation rates. The model estimates the additional land area that will be forested, and/or the additional deforestation that will be avoided, in response to potential future carbon prices. It tracks changes in carbon stocks in vegetation, soils and products over time.

By 2100, for six carbon price scenarios, the model estimates a global gain in carbon benefits between 50.9 Gt C and 113.2 Gt C. The time profile of carbon gains follows the carbon price trajectory; higher prices earlier lead to more carbon gain sooner, and vice versa. Reduced deforestation emerges as a dominant mitigation option. It accounts for 51% to 78% of carbon benefits gained by 2100. The percentage contribution generally increases from Scenarios 1, 2 and 3, which have low initial carbon price and/or a slowly rising one, to Scenarios 5 and 6 with higher initial prices.

Several analytic and policy implications of this analysis emerge. First, avoiding deforestation could be a significant, near-term option in Africa in particular. The ability of policymakers, local communities, and NGOs to assess existing land use practices and socioeconomic conditions, and to develop practical alternatives acceptable to land users, could determine whether this option is feasible.

Second, the potential for avoided deforestation is heavily dependent on levels of projected forest land use change, estimates of which remain uncertain, and on assumptions of future trends of land use and forest loss, which vary across analyses. Detailed assessment of the complex assumptions within the IPCC SRES scenarios of land use change over time, by region, and of potential alternatives to them, is needed to improve estimates in a range of models of the potential for reducing deforestation and of land availability for forestation. A range of simple sensitivity analyses may offer a first step forward.

Third, our estimates of land availability are crucial to the estimates of carbon gains for the forestation options. Thus our ability to estimate land allocation and costs, and identify the conditions when land is biophysically, economically, and institutionally available, drives the potential realization of forestation options. Land use competition among the forest, agriculture and grazing sectors is needed to improve land availability assumptions. A better determination of the availability of wastelands in the tropics (estimated in GCOMAP, but not in

some other sectoral and CGE models) would strengthen estimates of the quantity and cost of what appear to be very large-scale forestation mitigation options in tropical regions.

Fourth, the use of biofuel timber products as a substitute for fossil fuels offers a way to greatly expand the potential for carbon mitigation from forestry. Thus, a land use cap would not put an absolute limit on a region's forestry mitigation potential, but would only place a limit on the annual magnitude of avoidance of carbon emissions from fossil fuel combustion.

Fifth, improved, regionally disaggregated data are needed on the price elasticity of forest land, and the elasticities of timber demand and supply. Only scant and dated data are available, but the elasticities assumed are central to the analyses presented here and in other models.

Sixth, even the modest carbon prices of Scenario 3 (\$10 initially, rising at 3%/year) could generate as much as 50.9 Gt C by 2100, the majority from avoided deforestation. If economic incentives of this level could be introduced over the period of this analysis, and we can identify the conditions where such options are feasible, a substantial reduction of carbon emissions or increased sequestration could be produced. Additional analysis is needed of the socioeconomic and biophysical conditions under which specific, introduced economic incentives are likely to be efficient and implemented successfully, as well as the necessary infrastructural and technology transfer or training requirements.

Finally, mitigation activities to reduce emissions or increase sequestration in the land use sector will need to address the timing (i.e., the start and duration) as well as magnitude of economic incentives, since delays in incentives tend to delay land use change decisions.

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APPENDIX A

Table A1. Input data for Africa and Central America

(Cost and price data are in 2000 US\$, converted from local currency using market exchange rates)

	Notes	Africa		Central America	
<i>Variable Name</i>		<i>SR*</i>	<i>LR*</i>	<i>SR</i>	<i>LR</i>
Initial Cost (Land cost + Establishment Cost) (\$/ha)	a	871	1104	415	394
Recurrent Cost (\$/ha/yr)	b	121	116	30	17
Monitoring Cost (\$/ha/yr)	c	0	0	8	24
Harvesting and Transport Cost(\$/m3)	d	38	38	60	80
Timber domestic market price(\$/m3)	e	63	150	35	98
Timber international market price (\$/m3)	f	128	242	65	175
% of timber exported	g	10.50%	26.50%	6.50%	12.30%
Max area dedicated to SR & LR afforestation (mi ha)	h	80	120	20	21.5
Area planted so far (mi ha)	i	3.3	4.8	0.3	1
Planting rate in base year (Kha/yr)	j	80	115	20.3	61
Base-year Vegetation C-stock (t C/ha)	k	56.8	38.8	30.2	42
Rotation Period (Yrs)	l	13	29	7	20
Mean annual increment (t biomass/ha/yr)	m	29.1	18.5	8.7	4.9
Deforestation rate (Kha/yr)	n	5264		958	

*SR: Short-rotation, LR: Long-rotation.

Africa

a, b, d: From Makundi (2001) and adjusted by wage index for the region.

c: Monitoring is combined with recurrent cost.

e, f: Data for exports from United Nations Food and Agricultural Organization (FAO (2002)), and for domestic prices from FAO (2000).

g: Based on 2000 exports and domestic production data from (FAO, 2002).

h: Annual deforestation rate of 4 mi ha in the last 30 years is projected to persist up to 2020. We assume that 50% of the deforested land will be available for forestation. We also assume that at least another 100 mi ha of grassland and abandoned agricultural land will also be available for reforestation. : FRA2000.

i: FAO (2000), Global Forest Products Outlook Study (GFPOS).

j: Planting rate for 2000 FAO (2003a), Table 4 FAO (2001). We used annual planting rate for 2000 since historical forestation rates have been relatively low **k:** Data used in COMAP, analysis Makundi (2001).

l, m: Weighted average for existing plantation species in the region, FAO (2000).

n: FAO (2003b) Table 2, annual average for 1990 –2000

Central America

a, b, c: Fearnside (1995).Brazil data was adjusted by wage index for the region.

d: Mexico data Masera et: al (2001) was used for all of the region.

e, f: Tropical Timber Market Report, Jan 1 2003, Brazil Pine sawlog price From International

Tropical Timber Organization (ITTO (2003)).

g:: From State of the World's Forests, FAO (2003). The data is for 2000.

h: Includes degraded and deforested lands. From Forest Resource Assessment 2000 (FRA2000), FAO (2001).

i: FAO (1997), Chapter 3, Table 3-1. Assume 75% was for planting SR species.

j: From ITTO Annual Review Issues 1990 – 2000, Table 6-1, for annual planting rate.

k: Fearnside (1995) Table I. The value is for Brazil deforested areas

l, m: Masera (2001) Table IX estimate Mexico is applied for the region.

n: FAO (1993; 2001). Average for 1980-2000.

Table A1 (continued). Input data for China and India

(Cost and price data are in 2000 US\$, converted from local currency using market exchange rates)

<i>Variable Name</i>	<i>Notes</i>	China		India	
		<i>SR*</i>	<i>LR*</i>	<i>SR</i>	<i>LR</i>
Initial Cost (Land cost + Establishment Cost) (\$/ha)	a	245	245	340	778
Recurrent Cost (\$/ha/yr)	b	12	3	19	19
Monitoring Cost (\$/ha/yr)	c	12	3	2	2
Harvesting and Transport Cost(\$/m3)	d	60	40	49	40
Timber domestic market price(\$/m3)	e	150	200	123	421
Timber international market price (\$/m3)	f	250	450	483	915
% of timber exported	g	5.00%	1%	0.50%	0.50%
Max area dedicated to SR & LR afforestation (mi ha)	h	35.9	27.1	10.2	11.6
Area planted so far (mi ha)	i	27.2	20.5	15.2	16.8
Planting rate in base year (Kha/yr)	j	814	614	307.4	346.6
Base-year Vegetation C-stock(t C/ha)	k	25	25	1	1
Rotation Period (Yrs)	l	15	42	14	34
Mean annual increment (t biomass/ha/yr)	m	9.9	6.5	18.9	9
Deforestation rate (Kha/yr)	n	NA	NA	NA	NA

* SR: Short-rotation, LR: Long-rotation

China

a, b, c: Weighted average for NE, SE & SW regions. From Xu et al,(2001).

d: Xu and Zhang (2002), estimate that 40% of the product price goes towards harvesting and transport

e, f: FAO (2002) Forest Products Year book, 2000 and Xu et al, (2001).

g: Average for 1996-2000, FAO (2002)

h: According to China's Long-term Nationwide Environmental Restoration Plan (PEER), China plans to raise the forest area to 26% of the land area which would involve adding 117 mi ha of forests by 2050, of which 63 mi ha will be for timber production. . Compiled from National Forest Resources Inventories (NFRI) I – IV, with the planting schedules adjusted for survival rate, minus the 11.5 mi ha of non-timber forests e.g. bamboos and orchards. From FAO (2001); CMOF (2000).

i: FAO (2000) – Global Forest Products Outlook Study.

j: Current stated planting rate adjusted for survival rate of 80% (Zang, 2001).

k: Original COMAP runs for wastelands.

l, m: Weighted average for individual spp, with LR/SR decided on the basis of rotation age.
n: Deforestation rate is assumed to be negligible.

India

a: Sum of Investment cost + Discounted value of costs in years 1 & 2 – Ravindranath et al (2001).
b: From COMAP: 500 Rupees/ha/yr @42Rupees/\$, Source: Ravindranath, (2001).
c: From COMAP: 100 Rupees/ha/yr @42Rupees/\$, Source: Ravindranath, (2001).
d: We estimate 40% of millsite domestic log price for SR & 10% of LR price mostly due to price differential while cost of operations, machinery and fuel is still as high as that of LR.
e: LR average for Teak, Sal & Shisan, girth 91-120 cm, SR average Sal, Eucalyptus and Populus, all f.o.b. at Agra, Chandagar and Ambala from RSMD (2001).
f: LR average for Teak, Sal and Shisan grade A (girth 151cm), SR Shorea Robusta all f.o.b. at Agra, Bareilly & Shahampur: Source FRI 2000 Market Report, (2001).
g: Average RWE for 1996-2000. India exports 3% of Wood-based products and 1% of Pulp output.
h: National Action Plan proposes to increase Forest Cover by 33% (21.8 mi ha) over 20 yrs- FAO, (2001).
i: Sum of all areas under forest plantations up to 2000 (FAO, 2001).
j: Same target as NFAP of 1.09 mi ha/yr, adjusted by survival rate of 60% and existing LR: SR ratios.
k: Mostly, shrub and grass wastelands (Ravindranath, 2001).
l, m: Weighted average (by area) for all major plantation species in India – Source FSI (1999). **n:** NA – Not applicable. Net zero deforestation assumed.

Table A1. Input data for Rest of Asia and South America

(Cost and price data are in 2000 US\$, converted from local currency using market exchange rates)

<i>Variable Name</i>	<i>Notes</i>	Rest of Asia		South America	
		<i>SR*</i>	<i>LR*</i>	<i>SR</i>	<i>LR</i>
Initial Cost (Land cost + Establishment Cost) (\$/ha)	a	467	1034	716	716
Recurrent Cost (\$/ha/yr)	b	13	27	34	30
Monitoring Cost (\$/ha/yr)	c	39	40	28	24
Harvesting and Transport Cost(\$/m3)	d	64	64	0	0
Timber domestic market price(\$/m3)	e	80	161	6	15
Timber international market price (\$/m3)	f	250	250	6	60
% of timber exported	g	15%	26.50%	28.10%	16.60%
Max area dedicated to SR & LR afforestation (mi ha)	h	50	150	150	150
Area planted so far (mi ha)	i	6.4	19.2	7.8	2.6
Planting rate in base year (Kha/yr)	j	365	1095	283.5	79.5
Base-year Vegetation C-stock(t C/ha)	k	74	74	30.2	30.2
Rotation Period (Yrs)	l	10	35	6	25
Mean annual increment (t biomass/ha/yr)	m	17.6	14.0	13	8.6
Deforestation rate (Kha/yr)	n	2235		3711	

* SR: Short-rotation, LR: Long-rotation

Rest of Asia

a, b, c, d: Data for Indonesia adjusted by Wage rate index for the region – Boer (2001).

e, f: FAO (2002), 2000 Indonesia f.o.b. prices.

g: FAO 2002 average export data 1996 - 2000

h: A portion of the vast degraded forests and grasslands, especially in Indonesia, Malaysia and other continental SE Asian countries e.g. Myanmar, Laos, Thailand, Cambodia etc – FAO (1993; 2001).

i: FAO, (2001), also from GFPOS FAO,(2000). **j:** Average from FAO,(2003) Table VI, State of Forests.

k: ITTO Table VI Annual Review Issues 1990-2000.

l, m: Weighted average for Indonesian plantation species with 75%LR. Assumes Indonesia biomass data is representative of the region.

n: FAO, (2001) Data is average for 1990-2000

South America

a, b, c: Data for Brazil adjusted by wage index for the region: Fearnside, (2001).

d: The price used is stumpage, as such we exclude harvesting and transport.

e, f: Tropical Timber Market Report, Jan 1 2003, Brazil Pine sawlog stumpage price. (ITTO (2003)).

g: FAO (2003) export data.

h: Mostly from deforested lands and cerrados. The Brazilian Amazon alone had 42.7 million ha deforested through 1991 from the original 500 mi ha of the Legal Amazon (Fearnside, 1997).

i, j: From FAO (1997) Chapter 3, Table 3.1. From ITTO Table 6-1, Annual Review, 1990 - 2000 annual planting rate. We assume 75% will be in short rotation. In 1995 95% of afforestation in Brazil was in SR (Fearnside, 1997)

k: From Fearnside (1995), Table 1.

l, m: Fearnside,(1995) Time between harvests is 6 years; 3 coppices, 24 year replanting cycle.

n: FAO (2001) Deforestation area is annual average for the period 1990-2000

Table A1. Input data for the EU and Oceania

(Cost and price data are in 2000 US\$, converted from local currency using market exchange rates)

<i>Variable Name</i>	Notes	EU		Oceania	
		<i>SR*</i>	<i>LR*</i>	<i>SR</i>	<i>LR</i>
Initial Cost (Land cost + Establishment Cost)(\$/ha)	a	1068	1068	1598	1897
Recurrent Cost (\$/ha/yr)	b	80	80	11	11
Monitoring Cost (\$/ha/yr)	c	13	13	1	1
Harvesting and Transport Cost (\$/m3)	d	42	42	7	7
Timber domestic market price (\$/m3)	e	127	93	27	53
Timber international market price (\$/m3)	f	160	110	53	86
% of timber exported	g	52%	52%	38%	38%
Max area dedicated to SR& LR afforestation (mi ha)	h	40	50	28	42
Area planted so far (mi ha)	i	3	6.1	71	106.4
Planting rate in base year (Kha/yr)	j	63.7	148.6	3	10.7
Base-year Vegetation C-stock (t C/ha)	k	59	8.8	64	64
Rotation Period (Yrs)	l	45	100	19	44
Mean annual increment (t biomass/ha/yr)	m	11.6	6.9	18.5	10.1

* SR: Short-rotation, LR: Long-rotation

EU

a, b, c: Based on EU agricultural subsidy data for land rental. FAO (2000). Recurrent cost source IMAGE.

d: We assumed the cost is the same as that used for the US.

e, f: Timber trade statistics, FAO (2002)

g: Roundwood equivalent (RWE) weighted average of Industrial roundwood, Sawnwood, Wood-based panels, Pulp, paper and Paperboard for year 2000 (FAO, 2002)

h: EU has woodlands estimated at 133 mi ha (ECE/FAO, 1992).

i: Land planted with Industrial forest plantations since 1930 – up to 1998. From: Appendix 3, GFPOS, 1999.

j: Average rate between 1981-1995. Source: FAO (2000)

k: For SR we used average standing biomass in EU forestlands and LR we assume will be on sparsely wooded lands pasturelands and abandoned croplands Source of data: ECE/FAO 1992.

l, m: Average for Populus spp, Eucalyptus, Salix, Picea and Abies for SR, and for LR for mixed and coniferous forests, with Rotation age at 100 though some of the species have much longer rotation age.

Oceania

a: Includes land rental and establishment cost. Estimates for industrial plantations in Australia and New Zealand (excluding fencing). Sources: Dixon et al (1991) and Lyons (1997a; 1997b).

b, c: Equivalent to costs for management plans, consultancy, etc for Southwest Australia industrial plantations. Monitoring is estimated at 10% of recurrent cost.

d: Costs for New England region (NSW) of Australia, 2002. Average for 100 km distance to the mill or port: Source: Lyons, (1997a,b).

e: Average for NZ on South and North island. Source: NZ Forest Industries (June 2002); MAF (2002).

f: Export price for Industrial Roundwood Wood for Australia.

g: Average Roundwood equivalent for 2000. FAO, (2002) (FP Yearbook.

h: Assume 20% of Australia sparse forest area, with the rest from croplands and grasslands. Papua New Guinea from deforested lands and 5 mi ha each from New Zealand and Japan.

i, j: FAO, (2000). Average planting rate 1970-1990.

k, l, m: Vegetation Stock from ECE/FAO, (1992). MAI and Rotation average for spp in Australia & NZ.

Table A1. Input data for Russia and the US

(Cost and price data are in 2000 US\$, converted from local currency using market exchange rates)

<i>Variable Name</i>	Notes	Russia		USA	
		<i>SR*</i>	<i>LR*</i>	<i>SR</i>	<i>LR</i>
Initial Cost (Land cost + Establishment Cost)(\$/ha)	a	123	123	1744	2277
Recurrent Cost (\$/ha/yr)	b	1	1	30	29
Monitoring Cost (\$/ha/yr)	c	1	1	13	13
Harvesting and Transport Cost (\$/m3)	d	16	16	42	42
Timber domestic market price (\$/m3)	e	49	20	127	93
Timber international market price (\$/m3)	f	78	31	160	110
% of timber exported	g	27%	30%	16%	16%

continued

Table A1. Input data for Russia and the US (continued)

Max area dedicated to SR&LR afforestation (mi ha)	h	37.5	20.2	50.1	65.9
Area planted so far (mi ha)	i	7.4	4	18.2	24.1
Planting rate in base year (Kha/yr)	j	371	200	417.3	548.6
Base-year Vegetation C-stock (t C/ha)	k	21	21	8.8	8.8
Rotation Period (Yrs)	l	60	100	45	100
Mean annual increment (t biomass/ha/yr)	M	2.7	3.6	6.3	8.1

* SR: Short-rotation, LR: Long-rotation

Russia:

a: Based on cost data from Khosika Project (KFE, 2000) and Petrov, (2001).

b, d: Data from Vologda Reforestation Project (VOLOGDA 1994) and Saratov Afforestation Project (RUSAFOR, 1994).

c: Excludes project development monitoring cost - (KFE, 2000) and VOLOGDA (1994).

e, f: Source: Petrov (2001) for inland exports (c.i.f. Finland millgate) and other export timber from FAO (2002).

g: From FAO, (2002), data for 2000, with SR represented by non-coniferous industrial roundwood.

h: Reforestation rate is 26% the unforested land (degraded from past activities) under Federal Forest Service (FFS, 1995) and the rest is left for natural regeneration) (NEAP, 1997). We assume this rate will rise to 50%.

i, l, m: Data from US Country Study Final Report, (Izrael and Avdjushin, (1997).

j: Used average rate for 1983-93 (NEAP 1997).

k: From Russian Forestry Handbook, (1995) and Israel and Avdjushin, (1997).

USA:

a: Present Value@7% of weighted average of land rental and establishment cost. Compiled from data for Cropland & Pasture on Wet soils and all non-grazing forestland from the major land use regions in US, i.e., North East, Appalachian, South East, Lake States, Corn Belt, Delta States, Northern Plains, Southern Plains Mountain and Pacific (Moulton and Richards, 1990). The Discount rate is equal to the cost of capital in forest investments in the US (Dale, 2003).

b: Assumed 10% of establishment cost: EPRI (2000) estimate of max \$5/acre for certification and audits in Central and Western US mine land reclamation programs. file <http://www.wws.princeton.edu/cgi-bin/byteserv.prl/~ota>

d: Harvest and transport as per Weyerhaeuser operation in Appalachia. Source: Roskovensky (June 2000). Also from Kerstetter and Lyons, (2001).

e, f: Forest product prices Pacific North West (PNW) for export and Southern States for domestic prices. (Timber price Statistics).

g: Current export ratio for Industrial roundwood, Sawnwood, wood-based panels, pulp, paper and paperboard in RWE, weighted by volume using standard conversion factors. (FAO 2002)

h: Total available cropland, pastureland under wet and dry soils plus non-grazing forest lands. (Moulton and Richards, 1990)

i: Area planted between 1930-2000. (Moulton et al, 1996; FAO 2000).

j: Average planting rate 1975-1995. (Moulton, 1996).

k: Standing biomass of woodland for woodland, pastureland and cropland respectively (max 1.4, 0.3, 0.1), averaging 0.6 m³/ha/yr over the rotation), with a 1.2 Expansion factor, adjusted for wood density.

l, m: Weighted average from the main plantation species grown in the 10 regions listed in "a" above (Moulton and Richards, 1990)



Flexible Multi-gas Climate Policies

Jesper Jensen

I analyse the costs of policies aimed at stabilising global climate change. I show that abatement of all major greenhouse gases is important to the costs of climate policies and that flexible reduction of methane and other non-CO₂ gases may reduce costs significantly. The non-CO₂ gases offer many low-cost abatement options and this reduces the need for abatement of CO₂ to stabilise climate change. Multi-gas flexibility may be important if climate policies reflect not only long-term stabilisation, but also the rate at which the climate changes, as the latter may require large reductions in emissions in the short-term.

1. INTRODUCTION

The concerns for global climate change have many different faces. Some concerns relate to the *rate* of climate change, e.g., how much temperature increases within a decade. Other concerns relate to *absolute* climate change, e.g., how much temperature has increased since the industrial revolution.

I analyse scenarios that reflect the concerns for both the rate of climate change and absolute climate change. The scenarios specifically focus on the importance of flexible abatement of the major gases causing climate change. This flexibility is important as the gases differ widely with respect to their radiative forcing (their effects on warming), their lifetime in the atmosphere, and their abatement potential (in terms of both quantity and costs).

The analysis covers carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O) and the so-called industrial F-gases HFCs, PFCs and SF₆. CO₂ is by-far

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quantitatively most important, and is therefore the single most important target for climate policies aimed at reducing both climate change and costs. But I show that flexible reductions of all gases may significantly help minimise costs. The non-CO₂ gases offer many low-cost abatement options and this reduces the need for abatement of CO₂ to stabilise climate change.

Methane plays an important role as it has most of the abatement options among the non-CO₂ gases. It also has a stronger warming effect than CO₂, i.e., emissions of one ton of methane increases warming more than emissions of one ton of CO₂. The large set of abatement options and the strong warming effect is important if we want to slow the rate of climate change as methane abatement may substitute CO₂ abatement, reducing the costs of climate policies.

Methane also has a very short lifetime in the atmosphere. If we want to reduce the risks of exceeding a threshold value for absolute climate change, e.g., a 2 degree temperature increase by the year 2100, future methane abatement may substitute short-term CO₂ abatement, as it takes longer for CO₂ to disappear from the atmosphere. This also reduces the costs of climate policies.

These conclusions are based on an analysis with a revised version of the EDGE model.¹ Specifically, this version of the model has been developed for the EMF 21 working group on “Multi-Gas Mitigation and Climate Change” and has been revised with the most recent data on emissions and abatement options for all of the gases mentioned above.² I also develop an interface between long-term integrated assessment models of global climate change and the short-term EDGE model to enable analysis of climate change targets in the EDGE model. In short, the interface translates the long-term targets for radiative forcing (or temperature) to 5-year budgets for greenhouse gas emissions. I show that the EDGE model captures some of the long-term climate dynamics, and that comprehensive analysis of the climate impacts requires a full-blown climate model.

The next section presents the EDGE model, which is the computational framework in the paper. I provide an overview the key features of the model and focus particularly on the improved representation of the non-CO₂ gases in the model. The following section outlines the implementation of the EMF 21 scenarios. The paper then presents and interprets the economic and environmental impacts of the scenarios, and it concludes with a discussion of limitations of the analysis and suggestions for extensions.

2. THE EDGE MODEL

This analysis is based on the EDGE model. The following overview focuses on the model features with particular relevance for this analysis. Particular

1. See Jensen (2004) for model documentation and Jensen and Thelle (2001) for an application of the model.

2. The analysis thus covers all gases included in the Kyoto Protocol.

attention is given to the improved representation of the non-CO₂ gases. Full model documentation is provided in Jensen (2004).

2.1 The EDGE Model: An Overview

The EDGE model is a dynamic, multi-region general equilibrium model of emissions, international trade, and energy production and consumption. The model covers the period 2000-2030 in six five-year periods, and the dynamic features include forward-looking investment and savings decisions by households and firms. Specifically, their decisions account for intertemporal linkages via their budget constraints and capital stocks. All decisions therefore account for both current and future climate policies.

Another dynamic feature is the putty-clay description of the capital stock. This feature captures time lags in the responses to changes in energy prices, reflecting that energy consumption is closely linked with long-lived capital stock such as power plants. In other words, as the stock of clay capital depreciates over time, energy demand elasticities increase and CO₂ emissions respond stronger to climate policies.

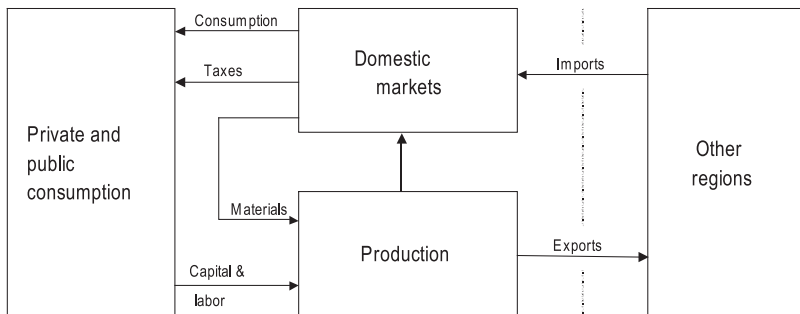
The model divides the world into 8 regions and each region distinguishes 7 sectors with production of goods and services (see Table 1 for a list of regions and sectors). The regional breakdown represents the major geopolitical regions involved in the climate policy negotiations. The sectoral breakdown reflects two important distinctions: First, CO₂ emissions differ mainly between coal, oil and natural gas. Second, emissions policies will affect energy-intensive industries more than other non-energy producing sectors.

Each of the regions has a representative consumer, a government and a production sector for each of the goods and services. Figure 1 gives an overview of the markets, the agents and the flows of goods, services and factors in the

Table 1. Regions and Sectors in the EDGE Model

Regions	Sectors
Annex B regions:	Energy:
1. European Union	1. Coal
2. United States	2. Petroleum
3. Japan	3. Crude oil
4. Eastern Europe and Former Soviet Union	4. Natural gas
5. Rest of the OECD	5. Electricity
Non-Annex B regions:	Non-energy:
6. China	6. Energy intensive sectors
7. Major oil exporters	7. All other sectors
8. Rest of the world	

Note: The major data sources for the model include data on economic transactions and CO₂ emissions from the GTAP5 database (Dimaranan (2002)), baseline data from the European Commission (2003), Schaefer et al. (2004) and Scheehle and Kruger (2004).

Figure 1. Overview of the EDGE Model

model. Firms producing goods and services represent the supply side of the model. All goods and services are being produced with materials, including energy, and primary factors capital and labour. Firms are assumed to maximize profits and there is perfect competition in all markets. A representative agent represents final demand and he finances his consumption with income from sales of capital and labour. A government agent provides public goods financed through taxes. Finally, all regions are connected via international trade in all goods.

The model captures emissions of all greenhouse gases covered by the Kyoto Protocol. CO_2 emissions are directly linked to the use of coal, oil and gas, whereas the modelling of the emissions of the other gases is more complicated (discussed below). Climate policies are linked to the emissions of all gases via emissions allowances. That is, one unit (e.g., a ton) of emissions of a gas require an allowance. Government set the overall cap on emissions and the market then determines the price of allowances.

Climate policies may allow trading of allowances to minimise costs. Generally, trading minimises costs by letting the market price of allowances determine the location of abatement options with the lowest costs. For example, if a firm has abatement options with costs lower than the allowance prices, the firm would gain from reducing emissions and selling the allowances that it would otherwise need to cover the emissions. Conversely, a firm with high cost options would gain from buying allowances instead of reducing emissions.³

Policy makers may exploit this flexibility by allowing trading both within their own countries, across countries (international trade), and across gases. The model allows analysis of all these policies. In the case of allowance trading for a single gas (e.g., CO_2), this corresponds to trade with a perfectly homogenous commodity. In the case of trading with a basket of gases, a choice has to be made with respect to how allowances for the different gases may be exchanged. The EDGE model adapts the simple assumption that all gases are converted into CO_2 -equivalents using the 100-year global warming potentials from Houghton *et al.* (1996).

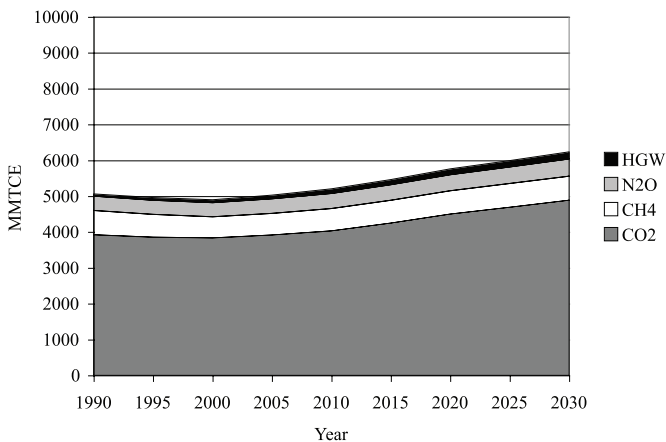
3. See Weyant (1999) for a graphical exposition of these arguments.

2.2 Economic Analysis of Multi-gas Abatement

The EDGE model covers emissions of all greenhouse gases covered by the Kyoto Protocol. In the previous version of the model, the quality of the CO₂ data was significantly better than the quality of the data for all the non-CO₂ gases.⁴ The model has now been updated and revised to include the most recent data on both emissions and abatement options for CH₄, N₂O, HFCs, PFCs and SF₆, with the latter three being grouped into one composite gas labelled HGW for high global warming potential.⁵

Emissions of non-CO₂ gases constitute a significant share of total greenhouse gas emissions in most countries. Globally, non-CO₂ gases account for around 30% of total emissions, higher in the developing countries and lower in the developed countries. In both groups of countries, CH₄ dominates the non-CO₂ gases. Figure 2 and Figure 3 present an overview for Annex B and non-Annex B countries, respectively.⁶ Emissions growth in the developing countries far exceeds growth in the developed countries, and the developing countries will after 2010 account for more than 50% of total greenhouse gas emissions. This directly shows that control of global emissions towards a long-term climate targets necessarily must involve the developing countries not too far from now in order to be effective.

Figure 2. Reference Annex B Emissions

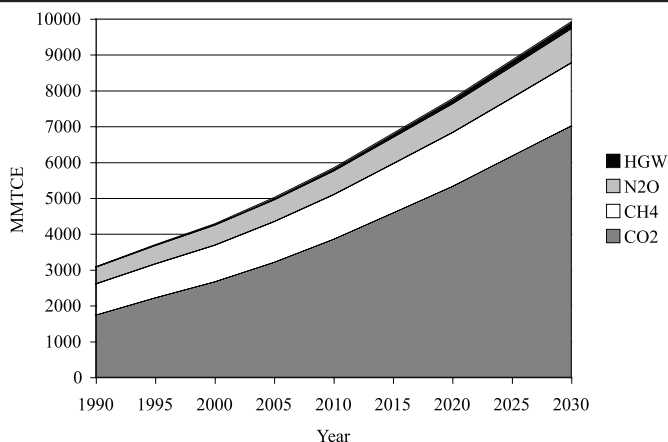


Source: The EDGE model

4. See Jensen and Thelle (2001).

5. This simplifying assumption reduces model complexity significantly without missing important effects in the present analysis. Radiative forcing and atmospheric life-times differ widely across the basket of gases HFCs, PFCs and SF₆, but these gases are not quantitatively important relative to the other greenhouse gases.

6. Annex B countries refer to the countries listed in Annex B in the Kyoto Protocol. This is also the list of countries that originally committed to emissions targets in the protocol.

Figure 3. Reference Non-Annex B Emissions

Source: The EDGE model

The modelling of emissions and their associated abatement options differ between CO₂ and non-CO₂. Almost all CO₂ emissions are linked directly to the combustion of fossil fuels. Furthermore, each of the main fossil fuels; coal, oil and gas, have their own roughly constant emissions factor, and one abatement option currently dominates: Reduced combustion.⁷

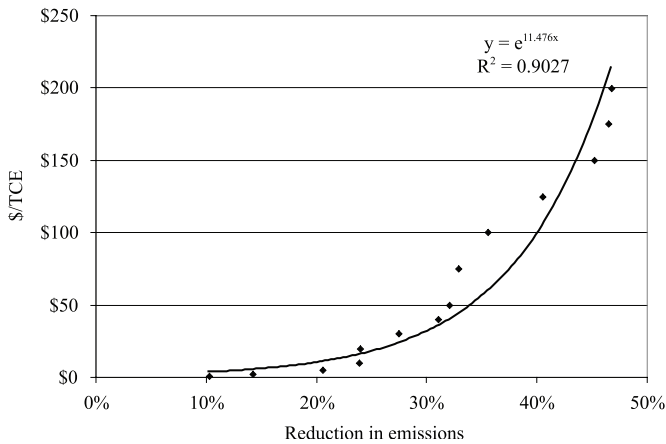
The model captures CO₂ emissions via separate modelling of the three fuel markets. The emissions of a given fuel are then calculated directly as quantity times the emissions factor. The model also captures the potential for substitution between fuels, e.g., away from the emissions-intensive coal to the less emissions-intensive oil and gas. This substitution furthermore differs by production sector and region.

The modelling of non-CO₂ emissions is significantly more challenging. Emissions come from many different sources. For example, CH₄ emissions come from both mining of coal, enteric fermentation, waste management, transportation of gas, and rice production. Proper representation of the emissions thus requires a level of technological detail not present in most economy-wide models, including the EDGE model. Aggregate economic activity in an aggregate economic sector, e.g., agricultural production, may therefore be a misleading emissions driver.

Multiple abatement options complicate the modelling challenge further. In addition to lower use, most of the non-CO₂ gases may both be recovered and recycled. That is, increased use may not necessarily be associated with increased emissions.

Rather than trying to capture all these details in a stylized manner, the EDGE model employs the following simplifying assumptions. First, it is assumed

7. Storage and in particular sequestration of CO₂ are also important options. The EDGE model does allow for sequestration (also known as sinks), but this feature is not applied here due to the lack of long-term data for both baseline sequestration and sequestration costs. See Jensen and Thelle (2001) for an analysis of the Kyoto Protocol, which incorporates sinks.

Figure 4. Estimation of Continuous Marginal Abatement Cost Functions

Source: The EDGE model

that emissions of non-CO₂ gases are independent of other policies. For example, there are no interaction effects between CO₂ policies and non-CO₂ emissions. Second, the model employs continuous cost functions to characterise the abatement options. The detailed abatement cost data show the abatement potential and the costs associated with alternative abatement technologies. When ordered by their costs the data points characterise a marginal abatement cost schedule, which can be incorporated in the model.

The cost functions have been estimated assuming that no abatement takes place below 1 \$/TCe and that the cost functions takes exponential form $p = e^{\alpha x}$, where p is the marginal abatement costs in \$/TCe, α is the estimated parameter, and x is the abatement effort measured as the percentage reduction in emissions with reduction potential.⁸ Figure 4 illustrates the estimation for methane in 2010 in the EU15, where the points are given by the data set and where the solid line is the estimated function. The appendix contains the detailed estimation results by region.

The model endogenously determines the gas-specific reductions in emissions that minimises costs across gases. That is, the model determines emissions of each gas such that the marginal abatement cost of reducing emissions by one unit is equal across all gases. Finally, the model incorporates the total costs of abatement of non-CO₂ gases by calculating the area below the cost curve for each gas. For simplicity and due to the lack of data, the cost functions are assumed to have fixed coefficients for capital (1/3) and labour (2/3).

8. The data for N₂O shows that the full abatement potential can be realised at costs below 10 \$/TCe, but the data is not sufficiently detailed to allow estimation of a continuous function. It is therefore assumed that the full abatement potential for N₂O can be realised at 5 \$/TCe.

2.3 Interface with Long-term Integrated Assessment Models

The horizon of the EDGE model ends by 2030. Detailed analysis of long-term climate targets requires models with horizons of a century or more. The EDGE model therefore relies on an interface with long-term models for analysis of long-term climate targets. In short, the interface translates long-term climate targets to 5-year budgets for greenhouse gas emissions. The idea of 5-year budgets reflects the style of targets adopted in the Kyoto Protocol.

The first step from the stabilisation target is to develop least-cost emissions paths. This is output from the long-term models and results in gas-specific emissions paths for both the cases of no climate target (the model reference emissions path) and of alternative climate targets.

The second step is the construction of total 5-year greenhouse gas budgets in the EDGE model. The model uses the results from the long-term models to calculate total 5-year emissions using the 100-year global warming potentials. To derive the emissions targets in the EDGE model, the *relative* change in emissions between the reference case and the policy case (both originally from the long-term model) is then applied to the EDGE reference case.^{9, 10}

3. POLICY SCENARIOS AND RESULTS

We begin with two long-term scenarios with global country participation. They both share the same climate change target: Stabilise radiative forcing at 4.5 Wm^{-2} relative to pre-industrial times by 2150. The key difference between the two scenarios is the set of mitigation options: The multi-gas scenario includes mitigation of all greenhouse gases, whereas the CO_2 -only scenario includes mitigation of, yes, CO_2 only. We can then evaluate the significance of multi-gas mitigation by comparing the two scenarios.

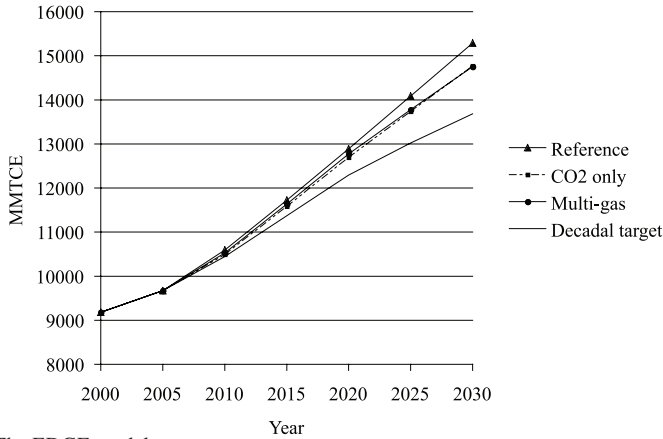
Figure 5 summarizes the global emissions profiles for the reference scenario and for three policy scenarios (we will return to the scenario “Decadal target” below). In the reference scenario, emissions increase by more than 50% between 2000 and 2030.¹¹ This is mainly due strong emissions growth in the developing countries. The multi-gas scenario allows higher emissions than the CO_2 -only scenario because of the differences in life-times between CO_2 (varies between 5 and 200 years) and methane (12 years).¹² The longer life-time of CO_2 implies that abatement in the CO_2 only scenario need to start early to meet the long-term stabilisation target. In the multi-gas scenario non- CO_2 abatement reduces the need for CO_2 abatement. Furthermore, the short life-time of methane implies that

9. The reference emissions paths generally differ across models and the interface therefore uses relative changes from the reference paths instead of absolute changes.

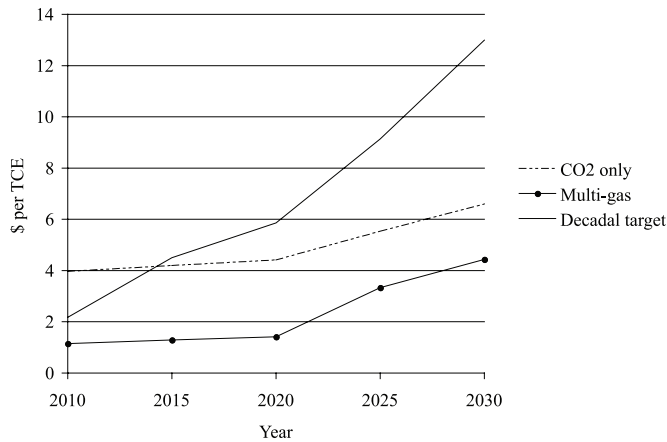
10. The Kyoto Protocol is *not* in the reference scenario for the scenarios. This is partly due to the uncertainties about how countries will implement the Kyoto Protocol.

11. All the long-term emissions profiles are based on output from the GRAPE model.

12. The lifetime of CO_2 differ across removal processes due to difference in the rate of uptake.

Figure 5. Global Emissions

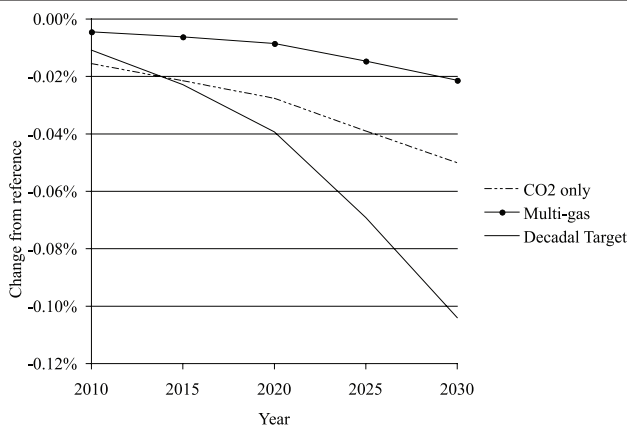
Source: The EDGE model

Figure 6. Marginal Abatement Costs

Source: The EDGE model

the abatement needs not to take place before close to target year (2150) to meet the stabilisation target.

The marginal costs of abatement (see Figure 6) reflect the emissions profiles. Two factors help explain the lower costs in the multi-gas scenario: more abatement options and lower abatement requirements. Even as the abatement requirements are only marginally lower in the multi-gas scenario, costs decrease significantly as the non-CO₂ gases offer additional abatement options. The same factors also explain the differences in total costs (measured as changes in GDP in Figure 7).

Figure 7. World GDP

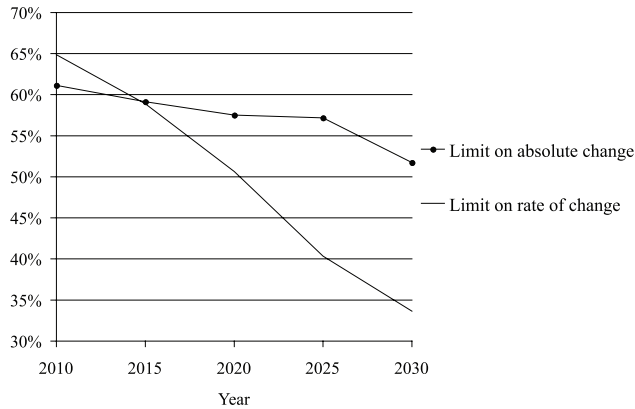
Source: The EDGE model

3.1 Limiting the Rate of Climate Change

The final scenario reflects a concern for both the rate of climate change and absolute climate change. The scenario specifically adopts the same long term climate change as above, but also limits the increase in the global mean temperature to an average decadal rate of 0.2 degree C over the period 2000 to 2050 and then again for the period 2051 to 2100. In line with the EMF scenario specifications (and the assumptions underlying the calculation of the long-term emissions profiles in the GRAPE model), the scenario only considers the multi-gas case.

The scenario requires large reductions in emissions in the short run (see Figure 5). In 2020, the reductions are 5% and in 2030 the reductions are above 10%. The large reductions also imply high marginal abatement costs (see Figure 6). The putty-clay formulation of the capital stock implies that energy demand elasticities are increasing over time. The low short-run elasticities make it costly to substitute fuels, e.g., in electricity production. In the long run, retirement of existing capital make is it less costly to substitute fuels, which in turn moderates the costs even as the reduction requirements are large. The large reductions are also costly in terms of lower GDP (see Figure 7). In other words, limiting the rate of climate in addition to limiting long-term climate change may increase costs significantly.

The non-CO₂ gases are important in the short run, when the reduction requirements are small. Figure 8 shows the share of total reductions coming from reductions in the non-CO₂ gases. In the long run, when larger reductions in emissions are required, the importance of non-CO₂ gases decreases mainly due to their small share in total emissions. The results are similar for both the scenarios of stabilisation of climate change and of limits on the rate of change.

Figure 8. Share of Total Reductions from Reductions in Non-CO₂ Gases

Source: The EDGE model

4. CONCLUDING REMARKS

Several insights emerge from the analysis. First, the non-CO₂ gases offer many low-cost abatement options and this reduces the need for abatement of CO₂ to stabilise climate change. Flexible multi-gas policies can have a major impact on costs, but does not change the fact that

CO₂ is the single most important target for climate policies aimed at reducing both climate change and costs. Second, multi-gas flexibility may be important if climate policies reflect not only long-term stabilisation, but also the rate at which the climate changes, as the latter may require large reductions in emissions in the short-term.

Several issues are not covered by the analysis and call for further analysis. One is that the analysis assumes flexible and competitive markets. In reality, markets do not adjust instantaneously and the cost estimates provided may therefore underestimate the true costs. Also, not all markets are competitive. The international oil markets are of particular relevance for this analysis. An interesting issue is thus the response by the OPEC countries to lower oil demands. Will the OPEC countries restrict supply further and may climate policies affect the stability of the cartel?

Another issue relates to the assumption about efficient policies, i.e., policies that minimise the costs by choosing directly or indirectly the abatement options according to costs. Market based policies, e.g., tradable emissions allowances, have the potential to minimise costs, at least in theory, but these policies may not always be politically and practically feasible. Less efficient policies may therefore in practice increase costs and have lower environmental effectiveness.

The complexity of particularly non-CO₂ emissions suggests that there are significant benefits from developing models with technology details. More detailed models should be able to properly capture that the emissions come from many different sources and that there already exists many different abatement options, including lower use, recovery and recycling.

APPENDIX

Table A.1 Estimation Results for CH₄

Region in dataset	2010	2020	Model region
Australia & New Zealand	7.0455	7.2936	Rest of the OECD
China	5.9231	5.9538	China Rest of the World
EU-15	11.476	11.841	European Union
Japan	6.0639	6.3646	Japan
OPEC	10.839	10.794	Major oil exporters
Russia	10.853	11.171	Eastern Europe and Former Soviet Union
United States	8.0132	8.3729	United States

Note: The table present estimates of α in the cost function $p=e^{\alpha x}$, where p is the marginal abatement costs in \$/TCe, and x is the abatement effort measured as the percentage reduction in emissions with reduction potential.

Source: Estimates based on Schaefer et al. (2004) and Scheehle and Kruger (2004).

Table A.2 Estimation Results for HGW

Region in dataset	2010	2020	Model region
Canada	10.983	9.795	Rest of the OECD
China	6.935	6.1658	China Rest of the world
EU-15	17.128	10.527	European Union
Japan	15.433	11.221	Japan
OPEC	15.066	7.0659	Major oil exporters
Russian Federation	11.003	8.5361	Eastern Europe and Former Soviet Union
United States	15.644	8.9627	United States

Note: The table present estimates of α in the cost function $p=e^{\alpha x}$, where p is the marginal abatement costs in \$/TCe, and x is the abatement effort measured as the percentage reduction in emissions with reduction potential.

Source: Estimates based on data from Schaefer et al. (2004) and Scheehle and Kruger (2004).

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The Role of Non-CO₂ Greenhouse Gases in Climate Change Mitigation: Long-term Scenarios for the 21st Century

Shilpa Rao* and Keywan Riahi*

The non-CO₂ greenhouse gases have so far jointly contributed around 40 percent to overall global warming. In this paper we examine the role of non-CO₂ greenhouse gases in meeting long-term climate change targets. For this purpose, we develop climate mitigation scenarios aimed at achieving long-term stabilization of global radiative forcing. We use the MESSAGE model for a thorough bottom-up representation of the six Kyoto greenhouse gases and corresponding mitigation technologies. This approach endogenizes energy feedback effects from mitigation of non-CO₂ gases and takes into account the interplay and side benefits that exist across GHGs. We analyze two mitigation scenarios that stabilize global radiative forcing at 4.5 W/m² as compared to pre-industrial times—one allowing only for CO₂ mitigation and another with multigas mitigation. In addition, we also investigate a lower stabilization level of 3 W/m² and look into the implications this has for abatement strategies. Our approach helps us to identify a portfolio of measures in the energy, industry and agricultural sectors for achieving a proposed climate target. We find that considering the full basket of GHGs improves the effectiveness of the mitigation portfolio resulting in significantly lower costs, especially in the short term. In the long run, the bulk of the emissions reductions are still found to come from CO₂ and this effect becomes more pronounced under the more stringent climate target. This emphasizes the importance of a diverse mitigation portfolio that includes both CO₂ and non-CO₂ related abatement options in meeting long-term climate targets.

1. INTRODUCTION

The United Nations Framework Convention on Climate Change (UNFCCC) calls for the stabilization of greenhouse gas (GHG) concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference

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

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

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

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

2. SCENARIO DESCRIPTION

The baseline used in this analysis is the B2 scenario derived from IPCC's Special Report on Emissions (SRES 2000; Nakicenovic (ed.) 2000). The B2 storyline has been well documented (Riahi and Roerhl 2000). It describes a world in which the main emphasis is on local solutions to economic, social and environmental sustainability. We develop three mitigation scenarios based on this baseline. Our central cases comprise a CO₂-only scenario and a multigas scenario (including carbon sinks) aiming at the stabilization of radiative forcing at an intermediate level of about 4.5 W/m². In addition, a sensitivity case explores multigas strategies for attaining a low stabilization target of about 3 W/m².

In the CO₂-only central mitigation scenario, the system is constrained to meet a radiative forcing of 4.5 W/m² (in 2100 as compared to pre-industrial times) by reducing only fossil-fuel related CO₂ emissions. We then calculate the 'total carbon equivalent' of all GHGs from the CO₂-only scenario (using 100-year GWPs¹) use these in developing a multigas scenario that achieves the same radiative forcing but with all six GHGs involved in the mitigation response. In addition, we also include forest (carbon) sinks as an explicit mitigation option for this multigas scenario.

We use the MESSAGE model (Messner and Strubegger 1995) as the basis for our analysis. MESSAGE is a bottom-up systems engineering model based on a least cost optimization framework. The model maps the entire energy system with all its interdependencies from resource extraction, imports and exports, conversion, transport and distribution to end-use services. It is a long-term global model with a time horizon of a century (1990-2100). The main outputs of the model are primary energy and emissions of GHGs (primarily CO₂ and energy related CH₄) and local pollutants like SO_x and NO_x. For this specific analysis, MESSAGE was further extended to include all six Kyoto GHGs, their drivers and mitigation technologies and details of the underlying assumptions and methodologies are described in Section 3. In addition, MESSAGE includes a simplified carbon cycle model for the estimation of atmospheric CO₂ concentrations.

In order to develop scenarios consistent with the proposed forcing target, we use MAGICC (Model for Greenhouse gas Induced Climate Change) version 4.0 (Wigley et al., 2002). MAGICC calculates the annual-mean global surface air temperature and global-mean sea level implications of emissions scenarios for greenhouse gases and sulfur dioxide (Raper et al., 1996). A MESSAGE-MAGICC iterative linkage is established whereby all GHG emissions, local pollutants and initial concentrations (to achieve stabilization) from MESSAGE are fed to MAGICC. Next, MAGICC calculates the imputed forcing due to the input

1. The global warming potential (GWP) is defined as the cumulative radiative forcing-both indirect and direct effects-integrated over a period of time from the emission of a unit mass of gas relative to some reference gas (CO₂) (IPCC 1996a). We use IPCC Second Assessment Report (IPCC 1996a) radiative forcing equivalents for all gases except the HFCs for which we use revised IPCC Third Assessment Report (IPCC 2001a) values.

emissions, on the basis of which a new CO₂ concentration limit is calculated and returned back to MESSAGE. This process is repeated until consistency between the GHG emissions from MESSAGE and the forcing target is achieved. In order to obtain a consistent multigas scenario, 100-year global warming potentials (GWPs)³ are used- i.e., we calculate the ‘total carbon equivalent (TCE)’ of all GHGs from the CO₂-only scenario and use this to develop a multigas case that achieves the same radiative forcing.²

3. EMISSION SOURCES AND MITIGATION

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

As mentioned earlier, there are various factors that influence future emission profiles for different gases. In this analysis, we adopt an approach that tries to take into account as many of these issues as possible. MESSAGE directly calculates CO₂ emissions due to fossil fuels, cement production and gas flaring. For the non-CO₂ gases, we use Delhotal et al., (2005) Schaefer et al., (2005) and DeAngelo et al., (2005) for emission estimates from the various sources until 2030. Thereafter, we use a range of economic drivers to model long-term emission profiles (for details see Appendix I to this paper available on the web at http://www.iiasa.ac.at/~riahi/Multigas_Mitigation/). Examples include population; gross domestic product (GDP); and agricultural & industrial gross value added (GVA). It is important to recognize that the emissions are not always linear with the drivers. In many sectors, emissions are already decreasing or expected to do so, due to ongoing environmental initiatives. An example is the SF₆ Emissions Reduction Partnership for Electric Power Systems’- a voluntary partnership between industry and the United States Environmental Protection Agency (<http://www.epa.gov/highgwp1/sf6/>). Also for many of the non-CO₂ sources, there exists a close relation between productivity and emissions. For instance, ruminant animals with low levels of production efficiency have relatively high methane emissions per unit of product (FAO 2000). Increasing wealth and modern practices will lead to improved animal and agricultural productivity and indirectly to decreasing emission intensities from such sources. Based on such trends, we consider declining emission factors for many of the sources in the baseline itself.

For the mitigation scenarios, wherever possible we employ a bottom-up modeling approach based on specific inclusion of the costs and efficiencies of the different mitigation technologies. This information is obtained from various sector specific reports, as well as the technology-specific data sets provided

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

by Delhotal et al., (2005) and Schaefer et al., (2005). This bottom-up approach allows us to examine the optimal mix of technologies across the different gases and sectors; endogenize energy feedbacks from mitigation³ as well as capture any resulting ancillary benefits⁴. We also take into account differences in technology performance and costs between industrialized and developing countries. Another important factor of the scenario analysis is the technological change in the system. Technological change is important to achieve the cost reductions and performance improvements necessary for a technology to become competitive in the long run (Grübler and Messner 1998). In this analysis, we model technological change exogenously, thus accounting for improvements in performance and declines in costs over time.

For mitigation from the livestock and agricultural sector (enteric fermentation, rice cultivation and soil management), we adopt a more top-down approach and directly implement marginal abatement cost curves (MACs) based on DeAngelo et al. (2005). Based on the large uncertainties that exist in the feasibility and costs of many of the mitigation options in this sector, we do not assume any major changes of the mitigation potential in the long run with the MACs⁵, thus limiting the long-term mitigation potential in this sector. Future assessment of agricultural sources will require improved accounting for heterogeneity of emissions and yields, adoption feasibility and commodity market effects into mitigation decisions (DeAngelo et al., 2005)

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

3.1 CO₂

CO₂ is the largest contributor to anthropogenic changes in global warming with a share of 60 percent. Current emissions are about 7 GTC, of which 6 GTC comes from fossil fuel combustion, while the remaining is due to land use changes (mainly deforestation).

The electricity sector is responsible for more than 35 percent of total energy-related CO₂ emissions worldwide. Other contributing sectors include transportation (25 percent) and direct use of fossil fuel in industry, residential and commercial sectors.

There are a number of options for reducing energy-related CO₂ emissions in the long term. These include switching from fossil fuels to renewable or nuclear power; efficiency improvements; fuel shifting (from coal to gas); and carbon capture. The entire portfolio of CO₂-reduction options-advanced nuclear, wind, biomass, solar, and hydrogen-based fuel cells is available to the model. Technological change in the form of cost declines and efficiency improvements

3. For example, decreased coal use will indirectly lead to reduced CH₄.

4. Imposing a CO₂-only constraint will lead to some reductions in energy-related CH₄, N₂O and SF₆.

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

are an important part of the assumptions, thus leading to a significantly high penetration of renewable technologies in the baseline scenario itself. In addition, we include various pre-combustion and post-combustion capture technologies for fossil fuel plants (see Riahi et al. 2004). We recognize that issues of storage potentials and leakage rates (see e.g. Parson and Keith, 1998) may limit the long-term adoption of such technologies. However, given the huge uncertainties that exist in the reported estimates, we have not imposed an upper bound for storage capacity in the model⁶ and also do not consider leakage rates⁷. We also include in this analysis, biomass energy with carbon sequestration (BECS) - a combination of biomass gasification technology for power/hydrogen generation with carbon capture and storage permitting the production of energy with negative emissions. (see Obersteiner et al. 2002, Makihira et al. 2003).

While CO₂ emissions from land-use change are accounted for exogenously in our baseline scenario, carbon (forest) sinks are introduced as an additional mitigation option in the multigas scenario. We use an iterative approach between MESSAGE and the model developed by Sohnegen & Sedjo (2005)⁸ to estimate the potential for forest sinks in the given scenario.

3.2 CH₄

CH₄ is the second largest contributor to global warming with a share of around 20 percent. Sources include both, energy related ones like the production and transport of coal, natural gas, and oil, as well as non-energy related ones like livestock, municipal solid waste, manure management, rice cultivation, wastewater, and crop residue burning. The energy sector presently contributes more than a quarter of overall CH₄ emissions, while enteric fermentation is the largest contributor in the non-energy sector making up more than 30 percent of total CH₄ emissions.

We endogenize energy-related CH₄ sources by linking appropriate emission coefficients to various activity variables in the model. These include coal, oil and gas extraction and transportation; and energy-related (includes transportation) fossil fuel and biomass combustion. We assume gradual technological improvements for these energy-related sources in the baseline.

For livestock and agriculture related CH₄ emissions, we mostly use sector specific economic drivers to develop the baseline emissions (see Appendix

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

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

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

I at http://www.iiasa.ac.at/~riahi/Multigas_Mitigation/). As mentioned earlier, we assume declining emission factors for these sources based on projected productivity improvements in livestock management and agricultural production. In the baseline scenario, we do not explicitly account for other factors like shifts in cultivation practices and agricultural land availability.

For CH₄ emissions from solid waste, we use IPCC country-specific mass-balance methodology (IPCC 2000) to obtain estimates of current emissions. We then examine long-term trends in waste generation rates, recycling, gas recovery etc. to develop long-term emissions. For example, based on land availability constraints and current trends in most developed countries, the rates of recycling and incineration are assumed to increase around the world, thus leading to less waste being dumped in the landfills. We also assume better management of landfills in the future i.e. a transition from open dumping to covered landfills.

CH₄ mitigation from the energy sector is represented through improved coal and oil extraction technologies and reduced leakages from gas pipelines. For the non-energy CH₄ sources, we consider diverse mitigation options depending on the source of emissions and the applicability of technologies (see Appendix II at http://www.iiasa.ac.at/~riahi/Multigas_Mitigation/). The technical complexity of these source reduction options can vary significantly, although this does not necessarily influence their effectiveness (IPCC 1996). For example in the solid waste sector, labor-intensive composting is more common (and effective) in developing countries as compared to high-skill machinery in developed countries. Some options are also climate specific like farm-scale digesters in manure management and this is taken into account. For mitigation of CH₄ emissions from enteric fermentation and rice cultivation, we use the MACs from DeAngelo et al. (2005), which account for a number of factors including shifts in cultivation practices.

Recovery of CH₄ is an important factor in both energy and non-energy sectors. We assume that the shift from surface to deep coal mining is balanced by increased recovery of CH₄ (through degasification systems) which is fed back into the energy system. In the solid waste sector, the recovered CH₄ from landfills is directly used as gas by nearby industries or converted to electricity for end-use.⁹

3.3 N₂O

N₂O contributes about 6 percent of the global warming (IPCC 2001a). Important sources include agricultural soil, animal manure, sewage, industry, automobiles and biomass burning.

Agricultural soil is the largest source of N₂O, contributing over 70 percent of overall emissions. Although N₂O is produced naturally in soils through microbial processes, many soil management activities affect the soil nitrogen (N) content and hence related N₂O emissions. Primary among those is

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

N-fertilizer application. Nitrogen fertilizer production provides more than half of all anthropogenic fixed nitrogen (Socolow 1999). Based on the relation between fertilizer production and productivity, we use Agricultural Gross Value Added (GVA) as the driver for N_2O emissions. However we recognize that future N-fertilizer use may become more efficient¹⁰ and may indirectly lead to lower N_2O emissions. In order to account for SUCH efficiency improvements, based on Frink et al. (1999), we assume a 1 percent emission factor improvement per year in the baseline scenario. For all other sources of N_2O , we develop baseline emissions based on various drivers listed in Appendix I of this paper publicly available at http://www.iiasa.ac.at/~riahi/Multigas_Mitigation/.

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

3.4 SF_6 and Perfluorocarbons (PFCs)

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

The electric transmission and distribution activity levels in MESSAGE are assumed to drive SF_6 emissions from switchgear. The recent boom in primary production of magnesium and high demand growth for magnesium die casting in the automobile industry are likely to drive SF_6 emissions from magnesium production (see <http://www.climatevision.gov/sectors/magnesium>). Based on this, we use light-vehicle transportation demand from MESSAGE¹¹ as the driver for these emissions. In industrialized countries many SF_6 reduction initiatives are already underway. To account for these trends, we assume an annual emission factor decline of 1 percent in the baseline. Mitigation options are based on Schaefer et al. (2005) and include recycling of SF_6 and replacement of SF_6 as a cover gas with SO_2 (for details see Appendix II at http://www.iiasa.ac.at/~riahi/Multigas_Mitigation/).

Many countries have undertaken initiatives (industry/government) to reduce PFC emissions from aluminum smelting. In order to account for this global decrease in PFC emissions, we assume an emission factor decline of 1 percent per

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

11. Includes light-oil and hydrogen based transportation technologies

year in the baseline. The main mitigation option we consider for PFCs is retrofitting (see Appendix II at http://www.iiasa.ac.at/~riahi/Multigas_Mitigation/).

3.5 Hydrofluorocarbons (HFC)

The sources for these emissions are diverse and include refrigeration and air-conditioning; insulation foams; fire extinguishers; medical and non-medical aerosols; HFC-22 production; and solvents. Traditionally, ozone-depleting substances (ODS) like chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) have been used in many of these applications. However since the Montreal Protocol (UNEP, 2000) mandates phase-out of these gases in the next few decades, HFCs are replacing them in most applications. Based on Schaefer et al., (2005), we assume that emissions of ODS substitutes will continue their rapid increase until 2030 in developed countries and 2040 in developing countries and then slow down. Already, HFC emissions management is occurring through voluntary measures and industry-government partnerships.

For HFC emissions from residential and commercial air-conditioners, mobile air-conditioners and insulation foams, we use various activity levels¹² from MESSAGE to drive the future emissions. In order to account for the expected phase out of these emissions, we assume a 1 percent annual decline in emission factors after 2030. The other HFC emissions are projected using various economic drivers. Mitigation options that we include are refrigerant recovery and leak repairs (for details on drivers and abatement technologies see Appendix II at http://www.iiasa.ac.at/~riahi/Multigas_Mitigation/).

4. SCENARIO RESULTS

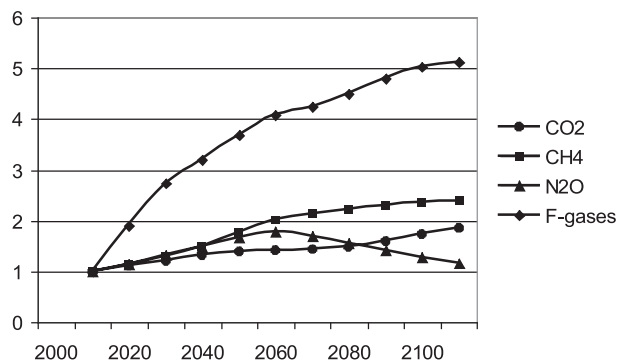
In this section, we first present the quantification of our baseline scenario. We then discuss the results for the central mitigation scenarios, aimed at achieving long-term stabilization of global radiative forcing at 4.5 W/m² by 2100 as compared to pre-industrial times. .

In spite of assumptions on decreasing emission factors in many sectors, there is an overall increase in the baseline GHG emissions. Figure 1 shows the growth in emissions indexed to 2000 levels. By 2100 CO₂ emissions increase about two times from 2000 levels although the energy intensity of emissions actually declines from 17 kgC/GJ to 10 kgC/GJ in 2100 due to technological improvements and structural changes in the energy system. CH₄ emissions show a similar increase, driven by increasing fossil fuel use and growing importance of agriculture and landfills. while N₂O emissions peak in 2070 and then start to decline due to improved efficiency in fertilizer use. The F-gases increase rapidly, with the main

12. Residential and commercial electricity and thermal end-use, transportation (for mobile air conditioners).

Figure 1. Increase in Global GHG Emissions in the Baseline from 2000-2100

All emissions are indexed to 2000 values.



source being growing HFC emissions from use of refrigerators and air-conditioning fuelled by increasing affluence, especially in developing countries.

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

Table 1. Baseline GHG Emissions in Currently Industrialized and Developing Countries

Emissions are shown both by sector and gas. Absolute values are given in MTCE, while the numbers in parentheses show the contributions of the different sectors (gases) in the overall mix.

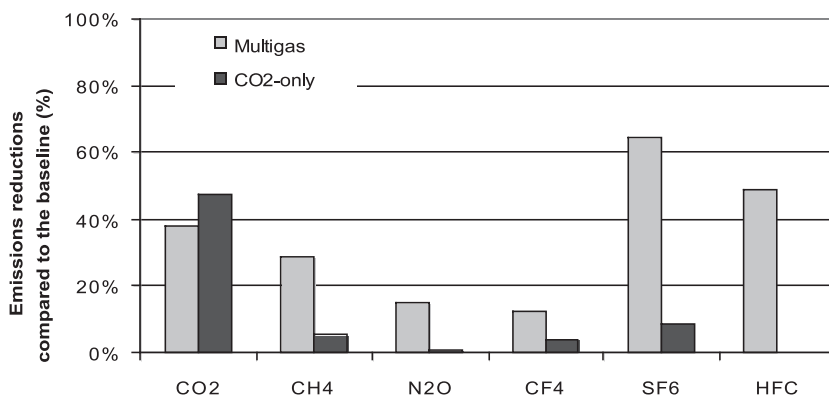
By Sector	Industrialized			Developing		
	2000	2050	2100	2000	2050	2100
Agriculture	398 (8)	406 (7)	205 (4)	1005 (25)	23449 (23)	1739 (12)
Energy	4262 (86)	4798 (85)	4878 (89)	2665 (65)	6601 (65)	10331 (72)
Industry & Others	293 (6)	428 (8)	366 (7)	403 (10)	1202 (12)	1897 (14)
By Gas						
CO ₂	4013 (81)	4505 (80)	4512 (83)	2425 (60)	6191 (60)	9545 (68)
CH ₄	555 (11)	634 (11)	594 (11)	1000 (24)	2487 (24)	3133 (22)
N ₂ O	316 (6)	318 (6)	174 (3)	624 (15)	1354 (12)	916 (7)
F-gases	48 (2)	165 (3)	161 (3)	25 (1)	251 (2)	373 (3)

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

We now turn towards the two central mitigation scenarios. Figure 2 shows the cumulative emissions reductions in the CO₂-only and multigas 4.5 W/m² forcing scenarios as compared to the baseline. In a CO₂-only case, there are a number of ancillary benefits of CO₂ emissions reductions that lead to lower CH₄, N₂O and SF₆ emissions. These are due to structural changes in the energy system including shifts towards lower use of coal and higher use of gas as well as a move towards decentralized renewable electricity generation that in turn causes an overall reduction in the electricity transmitted and distributed in the energy system. In the multigas case, while CO₂ reductions are about 10 percent lower than the CO₂-only case (see Figure 2), there are considerable reductions in the other non-CO₂ GHGs. The mitigation options available for the other gases in the multigas scenario give the system more flexibility in meeting the same climate constraint. For example SF₆ emissions in the multigas scenario are reduced by around 60 percent as compared to the baseline (see Figure 2) mainly due to high technical efficiency of the mitigation options in this sector (see Appendix II at http://www.iiasa.ac.at/~riahi/Multigas_Mitigation/ for mitigation technology description).

Figure 2. Cumulative Emissions Reductions in the Mitigation Scenarios

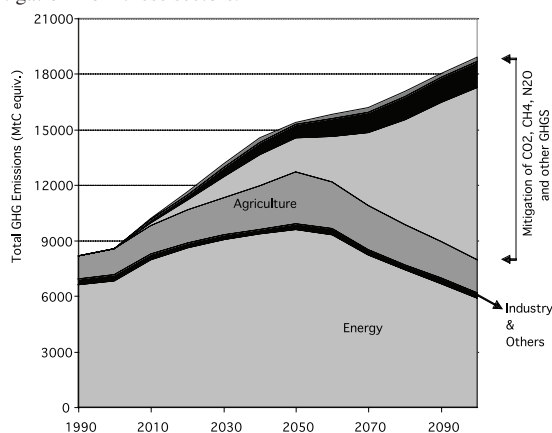
The bars indicate the cumulative percentage reductions from the baseline by GHG from 2000 to 2100. The CO₂-only case leads to ancillary benefits for non-CO₂ GHGs. CO₂ reductions in the multigas case are about 10 percent lower than in CO₂-only, due to large contributions from other gases.



It is important to take into account the sources of reductions of the different GHGs. Figure 3 shows the wedge between baseline emissions and the multigas scenario and the contributions of the different sectors to the mitigation. The energy sector makes up the bulk of the reductions. The majority of this is reductions in fossil fuel related CO₂ emissions but energy-related CH₄, N₂O and SF₆ also decrease in total by almost 30 percent as compared to the baseline. For industrial N₂O and solid waste related CH₄, overall mitigation is large due to the high efficiencies of associated mitigation options (Delhotal et al. 2005). Although agriculture is a larger source of CH₄ and N₂O emissions, the mitigation in this sector

Figure 3. Sector-wise Sources of Multigas Mitigation

Composition of the different sectors in the total emissions of the multigas scenario and the corresponding mitigation from these sectors.



is limited (DeAngelo et al. 2005)¹³. Less than 10 percent of overall emissions from this sector (includes manure management, enteric fermentation, rice cultivation and soil management) are mitigated. This low mitigation potential is mainly due to the linkages with agricultural productivity that cause uncertainties in the exact potentials and costs for the mitigation technologies in this sector.

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

Table 2. Mitigation in Currently Industrialized and Developing Countries

The emission reductions are shown in MTCE. The figures in parentheses show the shares of the different sectors in the overall mitigation.

By Sector	Industrialized			Developing			Reduction ratio (industrialized to developing)		
	2020	2050	2100	2020	2050	2100	2020	2050	2100
Agriculture	22 (6)	58 (4)	43 (1)	57 (13)	255 (10)	202 (3)	0.39	0.23	0.28
Energy	278 (70)	1258 (84)	3203 (94)	220 (52)	1794 (67)	5712 (80)	1.3	0.70	0.56
Industry & Others	96 (24)	181 (12)	168 (5)	150 (35)	622 (23)	1225 (17)	0.64	0.29	0.12

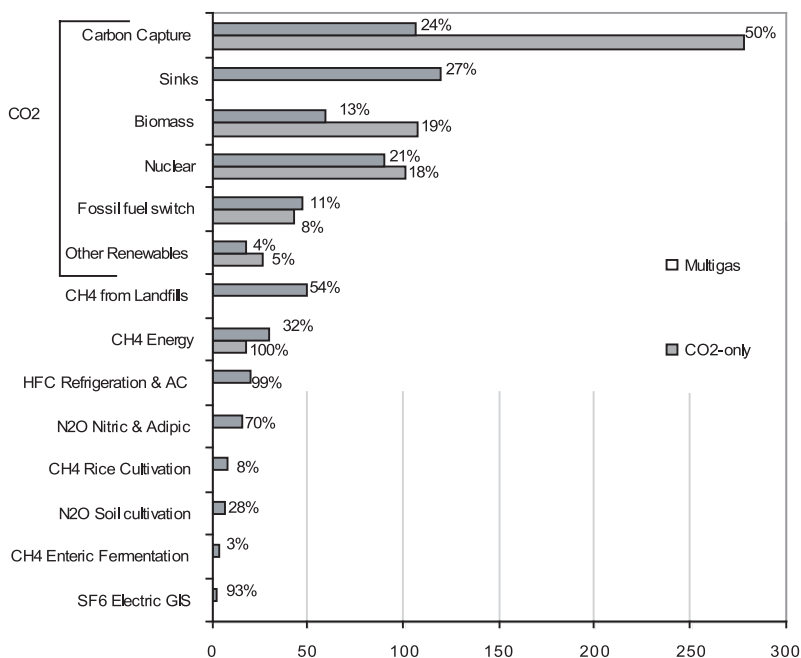
13. We do not assume any technological change in the MACs. See footnote 5.

This indicates that multigas/multisector mitigation policies can be important in designing climate mitigation responses in developing countries.

Another interesting aspect of this analysis is the added technological flexibility offered by the inclusion of non-CO₂ mitigation technologies. Figure 4 shows the ranking of the most important technologies that contribute to overall mitigation in both the CO₂-only as well as the multigas scenarios.

Figure 4. Ranking of Main Groups of Mitigation Technologies

The technologies are ranked according to the cumulative TCE reductions between 2000-2100. The percentages indicate the cumulative share of the technologies in total cumulative emissions reductions of the respective gas.

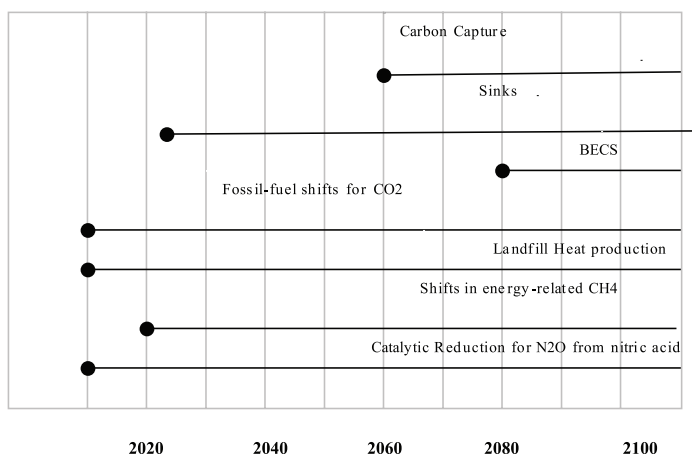


Carbon capture is the dominant technology for CO₂ reductions in the CO₂-only scenario and also plays an important role in the multigas case. Shifts in the energy system towards increased biomass (includes biomass-based carbon capture and storage systems) and nuclear use as well as fossil-fuel shifts from coal to gas are important contributors in both scenarios as an important contributor to overall mitigation, thus highlighting the role of this option in climate stabilization. In the multigas case, the solid waste sector dominates CH₄ mitigation with the CH₄ captured from landfills being fed back into the energy system directly as gas or after conversion to electricity. Forest sinks are an important source of carbon mitigation in the multigas scenario, thus highlighting the importance of this option

in achieving climate stabilization. Rice cultivation and enteric fermentation also offer some potential for CH_4 mitigation. The industrial sectors (nitric & adipic acid) dominate N_2O reductions. Only a small share of overall N_2O mitigation (around 8 percent) comes from soil management techniques, due to the limited mitigation possibilities assumed in this sector. Low-cost residential refrigeration and air-conditioning related mitigation technologies contribute close to all of the HFC reductions.

Also important in this analysis is the timing of mitigation options. Figure 5 shows the time scale for deployment of some of the important mitigation technologies i.e. the period in which they start making significant contributions. We define this as the point when the contribution of the technologies is more than 10 percent of the overall mitigation from the related GHG. Many non- CO_2 technologies start to contribute early in the century. Some of these include CH_4 technologies in the landfill sector (due to CH_4 capture for heat production); CH_4 related energy technologies¹⁴; and the high efficiency catalytic reduction technologies in the nitric acid sector. The higher-cost CO_2 reduction technologies like carbon capture begin to make significant contributions in overall reductions in the latter half of the century but go on to become an important part of the overall mitigation profile.

Figure 5. Timing of Selected Mitigation Technologies in the Multigas Scenario



We now turn towards the climate implications of the above scenarios in terms of radiative forcing, temperature and concentrations. As mentioned earlier, both central mitigation scenarios are constrained to stabilize radiative forcing

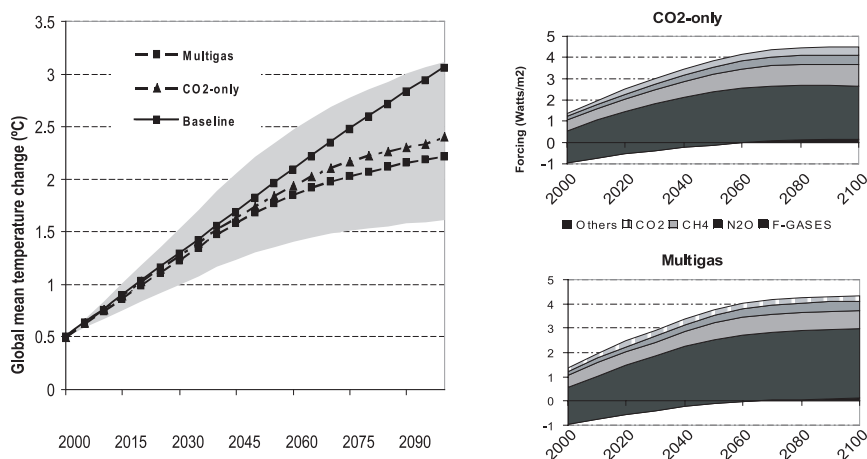
14. Although there is a shift from surface to deep mining with higher CH_4 coefficients, this is balanced by increased recovery of CH_4 from these mines.

at 4.5 W/m² compared to pre-industrial times. This corresponds to roughly a stabilization of global mean temperature change at about 2.5 degrees at median climate sensitivity¹⁵ (see Figure 6a). Figure 6b shows the differences in the contribution of GHGs to the total radiative response in the mitigation scenarios.

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

Figure 6.

a) Left Panel: Development of global temperature change in the scenarios as compared to pre-industrial times (left-hand side). The shaded area illustrates the uncertainty range for the temperature change in the multigas scenario due to the variation of climate sensitivity between 1.5 and 4.5 degrees C. b) Right Panel: Contribution of different GHGs to overall radiative forcing in the CO₂-only and multigas scenarios.



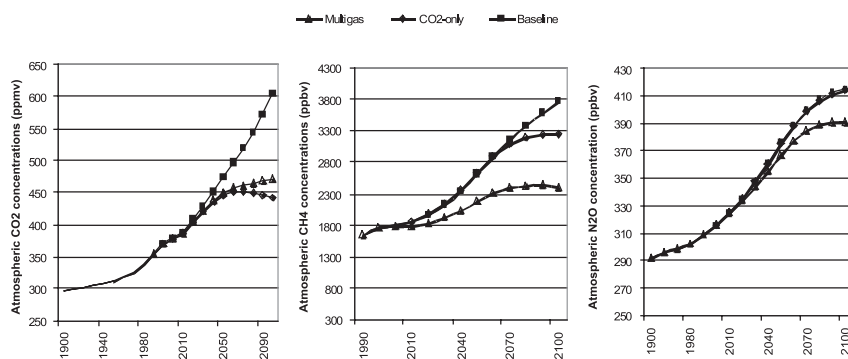
One important feature of our model is the assumed full spatial and temporal flexibility of emissions reductions. The model is flexible as to when and where and from which GHG source emissions should be reduced to achieve the forcing constraint at optimal costs. The internal decision mechanism is driven by price equalization across mitigation options based on the GWP of the alternative greenhouse gases. This leads to alternative paths for the GHG emissions in

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

the multigas and CO₂-only cases and also to alternative developments for their concentrations over time. We next discuss the implications for the concentrations of each of the main GHGs (CO₂, CH₄, and N₂O).

Atmospheric CO₂ concentrations in the baseline increase rapidly from about 378 ppmv in 2000 to about 600 ppmv at the end of this century (see Figure 7). The concentration path is headed upwards at the end of the time horizon, indicating that this trend would continue in the absence of any GHG emissions mitigation. Comparing the concentration trajectories of the CO₂-only and the multigas scenario shows that the stabilization of radiative forcing at 4.5 W/m² can be achieved with different CO₂ concentration pathways. It shows also that the CO₂ concentration level largely depends on the development assumed for the other non-CO₂ gases. If non-CO₂ gases continue rising without abatement, over proportional cutbacks in CO₂ become necessary, which in turn also lead to lower CO₂ concentration levels. A salient feature of both mitigation scenarios is that the CO₂ concentrations follow a long term stabilization path. CO₂ in the multigas scenario is stabilized at relatively higher levels (475 ppmv in 2150) as compared to the CO₂-only case (435 ppmv in 2150). Due to the full ‘when and where’ flexibility assumed in the model, CO₂ emissions in both scenarios are mainly reduced in the later half of the century.

Figure 7. Development of Atmospheric Concentrations of CO₂, CH₄, and N₂O



Due to increasing emissions, particularly in the non-energy sectors, atmospheric CH₄ concentrations in the baseline increase steadily from 1768 ppbv in 2000 to 3800 ppbv in 2100. As illustrated in Figure 7, a mitigation strategy focusing on CO₂ only, does not lead to any significant concentration changes in the short term. Only in the latter half of the century some associated benefits of carbon emissions reductions lead to CH₄ concentrations that depart from the baseline, resulting in 3300 ppbv in the long term. Clearly, the most pronounced changes in CH₄ concentrations are achieved in the multigas scenario due to direct mitigation aimed at the reduction of mainly non-energy CH₄ emissions.

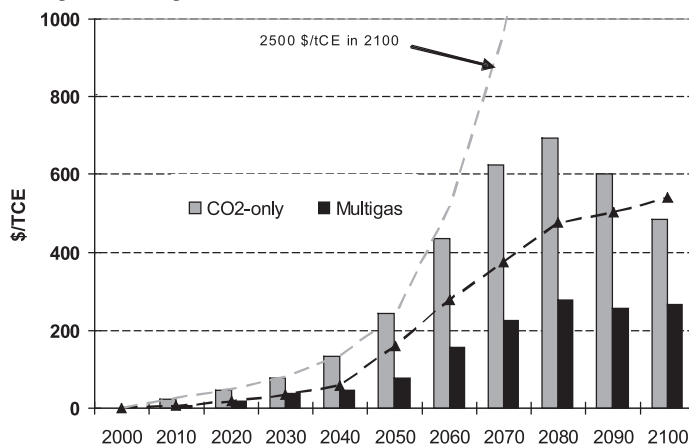
The combined effect of various low-cost mitigation options and the relatively short atmospheric lifetime of CH₄ (about 12 years) results in sizable reductions of concentrations already in the first few decades. In the long run, the CH₄ emissions reductions lead in the multigas scenario to cutbacks of concentrations of about 40 percent, corresponding to the stabilization of atmospheric concentrations at below 2400 ppbv (see Figure 7).

As to N₂O concentrations, the difference between the baseline and the mitigation cases is less pronounced (see Figure 7). None of the mitigation strategies leads to stabilization. In particular, there are very minor associated benefits from CO₂ emissions reductions and hardly any change in N₂O concentrations in the CO₂-only case (compared to the baseline). Also the N₂O concentrations in the multigas case are just reduced by 5 percent in the long run (by 2100), which is partly due to the long residence times, but also due to earlier mentioned conservative assumptions concerning the potential of N₂O mitigation for those sources where large uncertainties exist (such as agricultural soil).

Figure 8 shows the development of the global shadow prices of emissions reductions on a carbon-equivalent basis. Considering non-CO₂ mitigation options increases the flexibility of the system in meeting reduction requirements and leads to lower overall costs of mitigation. Consequently, the multigas scenario is seen to be significantly cheaper than the CO₂-only one.

Figure 8. Development of GHG Shadow Prices

Bars indicate the shadow prices in the CO₂-only and multigas mitigation scenarios. Dashed lines show the development of the prices for the same scenarios without BECS.



The relative price difference between the CO₂-only and the multigas scenario is more pronounced in the short and medium term. In the very long term, the bulk of the emissions reductions in the multigas scenario also stem from CO₂ and the disparity in prices between the scenarios become less significant. We find three

main reasons for this trend. First, the high inertia of the energy system due its long-lived infrastructure (lifetimes > 30 years) make deep reductions in CO₂ (for example, premature phase-out of power plants) comparatively costly in the short term. Secondly as mentioned earlier there are a large number of cheap (below 10\$/TCE)¹⁶ non-CO₂ mitigation options available in the short-term, making them more attractive than relatively costly CO₂ reductions. The third effect comprises the comparatively limited long term mitigation potential of the non-CO₂ sources as compared to CO₂. Only one third of the baseline's total emissions in 2100 come from non-CO₂ sources. Consequently, as the emissions constraint becomes more stringent over time, deeper cutbacks of CO₂ become necessary in the multigas scenario, driving the overall price of mitigation closer to the one in the CO₂-only case.

Another decisive factor for the GHG price in the long term is the aggregated effect of technological change in the energy system, and the dynamics and pace at which advanced and clean technologies are diffusing into the market. For example, in the latter half of the century an important part of the mitigation portfolio in both scenarios consists of BECS, i.e., biomass-based negative emissions technologies. Assuming that these technologies would not be available to the system would significantly impact the GHG prices. As shown in Figure 8, the long-term GHG price without BECS increases in 2100 by a factor of 6 in the CO₂-only and a factor of 2 in the multigas scenario. This result not only illustrates the vital role that biomass-based negative emissions might play in the long term, but perhaps more importantly highlights the importance of technological change (Grübler, 1998), its path dependency (Roehrl and Riahi, 2000), and the necessity of research and development in new emissions control technologies.

5. SENSITIVITY ANALYSIS FOR LOW STABILIZATION TARGETS

A number of scientific studies (Azar and Rhode, 1997; Hansen, 2005) as well as government bodies (European Council, 2005) argue that achieving extremely low stabilization targets would be necessary to avoid the risk of dangerous interference with the climate system. This section explores the mitigation related implications of achieving stabilization of radiative forcing at a level of about 3 W/m². This target is approximately consistent with a temperature change of below 2°C compared to pre-industrial times.¹⁷ We examine the associated multigas abatement strategy under such an alternate stabilization level.¹⁸

The baseline and mitigation scenarios presented here adopt the same assumptions for main emissions drivers as the central multigas case explained in detail in Section 4. They differ however with respect to two main aspects. First, we account for macroeconomic feedbacks of climate mitigation by estimating price-induced changes of GDP and energy demand using an optimal growth

16. Prices are given in 2000 US\$ ton carbon equivalent.

17. Assuming an intermediate climate sensitivity of 2.5 °C for a doubling of CO₂ concentrations.

18. We do not run a CO₂-only scenario for this target

model of the economy (Manne and Richels, 1992; Messner and Schrattenholzer, 2000). Secondly, given the important role of bioenergy and negative emissions technologies as well as forest sinks in the mitigation portfolio, we use for this sensitivity analysis a spatially explicit global model of forest sink management and bioenergy supply (Obersteiner et al., 2005; Rokityanskiy et al., 2006) to provide a more detailed account of local conditions that may limit the potential use of these options.¹⁹ Due to these changes the emissions profile of the baseline scenario is changed slightly, depicting higher growth in the first half of this century (compared to the baseline scenario presented in Section 4).

The four panels of Figure 9 summarize the main results of the 3 W/m² scenarios. Panel (a) illustrates the contribution of the principal mitigation measures. Panel (b) shows the evolution of the primary energy carriers and the deployment of carbon capture and storage for fossil fuels as well as biomass energy carriers. The resulting change in global mean surface temperature and the imputed GHG price (\$/tC eq.) are given in Panels (c) and (d) respectively. For illustrative purposes panels (c) and (d) give also the results from a stabilization scenario for 4.5 W/m² sharing the same modified assumptions (compared to the scenarios presented in Section 4). A comprehensive data appendix (Appendix III) including regional results for all GHGs and main emissions drivers may be found at http://www.iiasa.ac.at/~riahi/Multigas_Mitigation/.

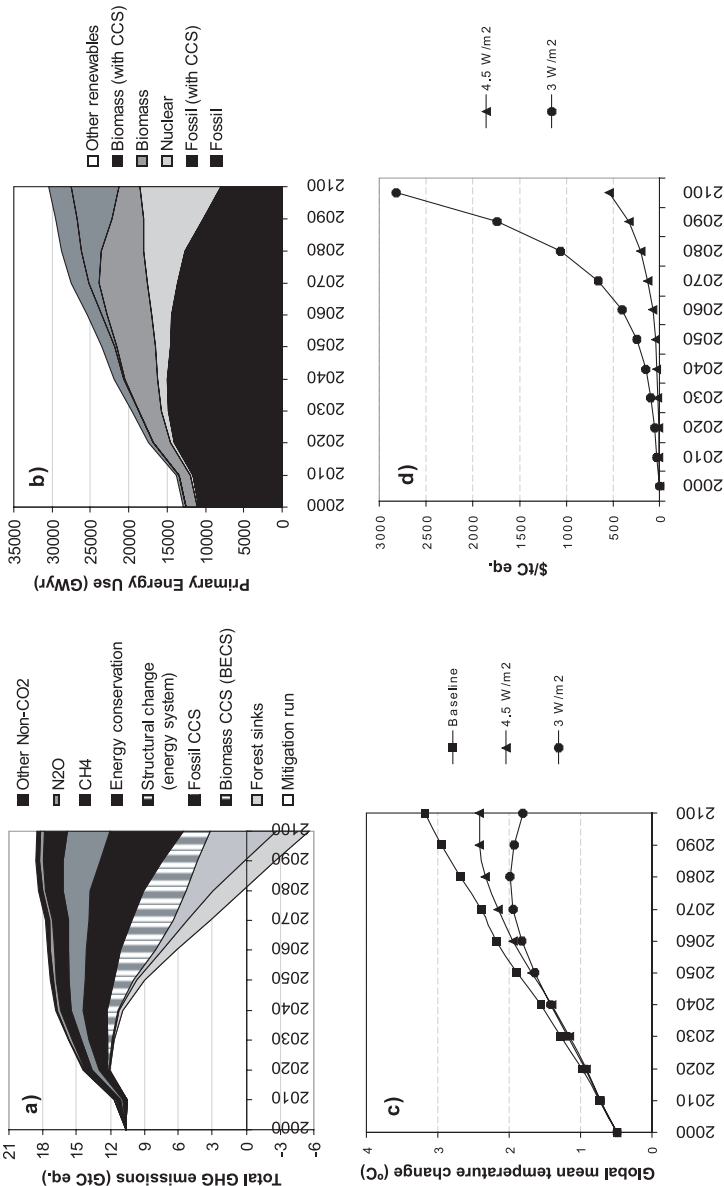
Achieving a stabilization target as low as 3 W/m² requires early mitigation as well as the rapid adoption of a wide portfolio of mitigation measures. As illustrated by Figure 9a, total GHG emissions peak already by 2020 and are headed downwards over the course of the century. Eventually, by 2100, emissions even become negative due to the widespread deployment of biomass-based carbon capture and storage (BECS) technologies and global efforts towards forest sink enhancement. These options together account for about 275 GtC eq. or 30 percent of the total cumulative mitigation burden (by 2100). It is important to note that although the bulk of the emissions reductions (70 percent) still stem from options other than BECS or forest sinks and include important contributions from non-CO₂ technologies, a 3 W/m² stabilization target is found to be unattainable in our modeling analysis without at least one of these options.

Another important difference here as compared to earlier results from the multigas 4.5 W/m² central case is that more of the emissions reductions are now achieved through cut-backs in CO₂ in the energy sector. Thus, the relative importance of non-CO₂ gases is seen to be smaller (but still significant) at more stringent stabilization levels, primarily due to saturation effects of CH₄ and N₂O mitigation options in the agricultural sector. Principal CO₂-related mitigation measures are enhanced energy conservation and structural changes of the energy system, including shifts from carbon-intensive coal to natural gas, nuclear, and

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

Figure 9. Sensitivity Analysis for a Low Stabilization Target

Panel a: Contribution of main mitigation measures for achieving a stabilization target of 3 W/m². Panel b: Development of primary energy carriers including the contribution of CCS (stabilization target of 3 W/m²). Panel c: Development of mean temperature change. Panel d: Development of GHG shadow prices.



renewables (Figure 9a). These options in total account for about 55 % of total cumulative reductions by 2100.

Carbon capture and storage from fossil fuels (CCS) and biomass (BECS) account for more than 38 percent of total mitigation over the course of the century.²⁰ As illustrated by Figure 9b, CCS is predominantly fossil-based during the first half of the century, while the contribution of BECS increases rapidly in the latter half of the century driven by the need to achieve the stringent target. Cumulative storage of CO₂ in the low stabilization scenario is about 340 GtC, still well below the “best guess” estimate for global geologic storage potential of about 500 GtC (IPCC, 2005).

Carbon (eq.) prices for achieving this low stabilization level increase over the course of the century to about 2,800 US\$/tC (Figure 9b). This is roughly the same carbon price as computed for the 4.5 W/m²CO₂-only mitigation scenario assuming that negative emissions technologies (BECS) will not become available (see Figure 8). A more comprehensive measure for the mitigation costs is given by the loss in GDP or welfare (compared to the baseline).²¹ The loss in GDP is seen to be relatively modest, increasing to about 3.9% by 2100 for achieving the low stabilization target of 3 W/m² (compared to 1.9 % for achieving 4.5 W/m²).

6. CONCLUSION

In summary, we find that non-CO₂ mitigation plays a particularly important role in the short and medium term, bridging a cost-effective transition to a less GHG intensive long-term future. However in a scenario that includes multigas and forest sink responses, the bulk of reductions in the long term still come from CO₂, due to the comparatively limited mitigation potential assumed for the non-CO₂ gases. The relative contributions of CO₂ and non-CO₂ gases in the mitigation profile are found to also depend on the stringency of the climate target under consideration.

20. Costs of fossil CCS systems are based on same assumptions as reported by Riahi et al., 2005. For BECS we assume limited initial up-scaling potential for energy conversion plants in the next three decades, after which plant sizes of 100 to 200 MWe become attainable. The costs of BECS are thus assumed to be about 30 to 70 percent higher than equivalent coal-based CCS systems. In addition, we assume that CO₂ from BECS has to be transported over larger distances than CO₂ from fossil power plants, thus accounting for the fact that a large share of biomass power plants will be located in relative closer proximity of the biomass supply rather than prospective storage sites. Thus, costs of CO₂ transportation are seen to be higher than those from coal by more than a factor of two.

21. In addition to MESSAGE we use for this study MACRO, a top-down macroeconomic equilibrium model (Manne and Richels, 1992). The capital stock, available labor, and energy inputs determine the total output of an economy according to a nested constant elasticity of substitution (CES) production function. MESSAGE and MACRO are linked iteratively to include the impact of policies on energy costs, GDP and on energy demand. The result is a fully consistent evolution of energy demand quantities, prices, and macroeconomic indicators (such as GDP, investments and savings). A detailed description of the link between the two models can be found in Messner and Schrattenholzer (2000).

We particularly emphasize the diversity of the mitigation portfolio in a multigas scenario. The bottom-up modeling methodology that we use enables us to evaluate optimum and point source technology strategies for reductions. Some promising technologies in the short term include recovery of CH₄ from landfills and reduction of N₂O from nitric acid production while carbon capture and sequestration, while forest sinks and BECS contribute significantly in the longer term.

The multigas scenario is seen to be significantly cheaper than the CO₂-only one. The relative price difference between the CO₂-only and the multigas scenario is more pronounced in the short and medium term. The evolution of long term prices in our analysis is largely driven by the assumptions on technological change and the adoption of advanced technologies in the system. While the exact path of this change is somewhat uncertain, we find that the deployment of advanced technologies including both CO₂ and non-CO₂ options is essential in enabling cost-effective climate change mitigation in the long term. Advanced technologies like biomass energy in combination with carbon capture and storage (BECS) are seen to increase in importance with stringent climate targets, due to their large potential in reducing the overall costs of mitigation. Thus a diverse mitigation portfolio including a range of CO₂ and non-CO₂ technologies is found to be central in achieving very low stabilization levels consistent with a temperature change of below 2°C.

We recognize that there are many uncertainties in both emission inventories for non-CO₂ GHGs, as well as the actual costs and potentials of the associated mitigation options. A better understanding of these uncertainties is essential in formulating multi-sector cost-effective policies that would gain acceptance by policy-makers and the public alike.

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

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This paper presents a set of multi-gas mitigation scenarios that aim for stabilisation of greenhouse gas radiative forcing in 2150 at levels from 3.7 to 5.3 W/m². At the moment, non-CO₂ gasses (methane, nitrous oxide, PFCs, HFCs and SF₆) contribute to about a quarter of the global emissions. The analysis shows that including these non-CO₂ gases in mitigation analysis is crucial in formulating a cost-effective response. For stabilisation at 4.5 W/m², a multi-gas approach leads to 40% lower costs than an approach that would focus at CO₂-only. Within the assumptions used in this study, the non-CO₂ gasses contribution to total reduction is very large under less stringent targets (up to 60%), but declines under stringent targets. While stabilising at 3.7 W/m² obviously leads to larger environmental benefits than the 4.5 W/m² case (temperature increase in 2100 are 1.9 and 2.3°C, respectively), the costs of the lower target are higher (0.80% and 0.34% of GDP in 2100, respectively). Improving knowledge on how future reduction potential for non-CO₂ gasses could develop is shown to be a crucial research question.

1. INTRODUCTION

Increasing atmospheric concentrations of carbon dioxide (CO₂) are, by far, the most important driving force of the enhanced greenhouse effect. In that context, most mitigation studies so far have concentrated on this gas only. At the same time, however, human activities cause emissions of several other greenhouse gases (GHGs), including methane (CH₄), nitrous oxide (N₂O) and fluorinated and chlorinated hydrocarbons (halocarbons, HFC, PFC, SF₆). In order to 'stabilise greenhouse gas concentrations in the atmosphere at a level

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that would prevent dangerous anthropogenic interference with the climate system' (UNFCCC 1992) these gases need to be accounted for as well. In 1997, policy-makers acknowledged this by formulating the Kyoto targets in terms of a 'basket' of greenhouse gases¹ (allowing full substitution among these gases), thus making a multi-gas abatement strategy operational. Interestingly, most studies on the implications of a multi-gas strategy are more recent. An important reason is that consistent information on reduction potential for the non-CO₂ gases has been lacking. Available studies exploring the impacts of including non-CO₂ gases nevertheless find important advantages in terms of reduction of costs and in terms of avoiding climate impacts.

For 'CO₂-only' stabilization, available information now allows for a reasonably good understanding of mitigation potential and the associated range of costs across a wide range of climate targets (as a function of a wide range of assumptions and modeling approaches) (see Hourcade and Shukla (2001)). A similar situation certainly does not exist for multi-gas stabilisation, as the number of individual studies is still rather low, methodologies have not been compared and studies have hardly assessed multiple stabilisation targets. The context of a large modeling comparison study (EMF- 21) and the data that has been collected in this context on marginal abatement costs for non-CO₂ (Kyoto) gases now provide an opportunity for change. In this paper, we will develop a set of mitigation scenarios that aim to stabilise radiative forcing of greenhouse gases using the IMAGE 2.2 Integrated Assessment model in combination with the climate-policy model, FAIR 2.0 (for a description of both models see Section 2). The analysis focuses on two crucial questions:

1. What are the differences in abatement costs and environmental impacts between a long-term multi-gas mitigation strategy (including all Kyoto gasses) and a CO₂-only strategy aiming for a similar climate stabilisation target?
2. How do the mitigation efforts, abatement costs and environmental impacts differ for multi-gas mitigation scenarios that aim for less and more stringent stabilisation targets?

To answer these questions, three methodological questions directly arise: 1) how to define the stabilisation target for a multi-gas stabilisation scenario; 2) how to allow for substitution among the different greenhouse gases; and 3) how to incorporate abatement of non-CO₂ gases into the modeling framework. The third question will be dealt with in our analysis, while the first two questions will be discussed here.

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

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

Hourcade and Shukla 2001; Swart et al. 2002). For multi-gas studies, one could use a similar long-term climate target but now integrating the different gases (accounting, for instance, their different radiative properties and atmospheric lifetimes). In general, selecting such a target early in the cause-effect chain from human activities to climate change impacts (e.g. emissions) increases the certainty of required reduction measures, but decreases the certainty on climate impacts. Selecting a climate target further down the cause-effect chain (e.g. temperature change, or even to be avoided climate impacts) increases certainty on impacts, but decreases certainty on required reduction measures (UNFCCC 2002). Analogy with the CO₂ concentration suggests formulating targets in terms of radiative forcing, which is equivalent to the concentrations of the different gases weighted for their radiative properties. The advantage of choosing radiative forcing targets over temperature targets is that the calculation of radiative forcing does not depend on climate sensitivity, which is the major uncertain factor in the cause-effect chain (Matthews and van Ypersele 2003). The downside is, of course, that a wide range of temperature impacts are possible for the same radiative forcing level. Given the fact that this study concentrates on comparing changes in abatement action, radiative forcing targets have been chosen. In these targets, we have included the forcing of the 'Kyoto' gases, but also those of CFCs (including their indirect radiative effect), tropospheric ozone, sulphur dioxide and other aerosols. As shown in this article (see Table 3), the contribution of the non-Kyoto radiative agents (mentioned in the list above) tend to cancel each other out at the long-term (2100) in the stabilisation scenarios. As the central long-term climate target for our analysis, we have chosen stabilisation at 4.5 W/m² in 2150, with 3.7 and 5.3 W/m² as alternative targets². A radiative forcing target of 4.5 W/m² more or less equates to a CO₂ concentration at 550 ppmv (the standard case in most earlier work), assuming 1 W/m² additional forcing for the non-CO₂ gases (Wigley and Raper 2001).

For the second methodological question, a measure is needed in which the emissions of different greenhouse gases with different atmospheric lifetimes and different radiative properties can be compared. Ideally, such a measure would allow for substitution among different gases (in order to achieve cost reductions) but ensures equivalence in climate impact. Fuglestad et al. (2003) provide a comprehensive overview of the different methods that have been proposed, and the advantages and disadvantages of using them. One of these, CO₂-equivalent emissions based on the Global Warming Potentials (GWP), has been adopted in most current climate policies, such as the Kyoto Protocol, and US climate policy (White-House 2002). Despite the continuous scientific debate on the use of GWPs (particularly as they do not explicitly specify for economic dimension of the problem and are based on a rather arbitrary time horizon), the concept is

2. Radiative forcing can also be expressed by the equivalent CO₂ concentration that would result in a similar forcing. The three radiative forcing levels explored here, 3.6, 4.5 and 5.3 W/m², correspond to an equivalent CO₂ concentration of 550, 650 and 750 ppmv CO₂-eq., respectively.

mostly regarded as convenient and to date no alternative measure has attained a comparable status. In fact, O'Neill (2003) and Person et al. (2004) have argued that the disadvantages of GWPs are likely to be outweighed by their strong points. In this paper, we will use the 100 year GWPs (Ramaswamy 2001) to substitute among the different gases. The mitigation analysis covers the group of Kyoto greenhouse gasses.

Thus, to answer our two focal questions, five different scenarios have been developed, i.e. the baseline scenario, a scenario that stabilizes radiative forcing at 4.5 W/m^2 in 2150 using a multi-gas approach, a scenario that mitigates 'CO₂-only' using the CO₂-equivalent emissions of the multi-gas 4.5 W/m^2 scenario as a gap³, and two multi-gas scenarios stabilizing the radiative forcing at 5.3 W/m^2 in 2150 and 3.7 W/m^2 in 2100. In addition to these scenarios, sensitivity cases have been explored – in particular, on technology assumptions for the abatement potential of the non-CO₂ gases. In the next section, we present the overall methodology that has been used for this analysis. Section 3 discusses the results for the baseline. Section 4 presents the analysis on the differences between a CO₂-only and multigas approach (focal question 1), while section 5 presents the analysis for various stabilisation targets (focal question 2). In section 6, we show the results of the sensitivity analysis that has been performed. The final section draws up several conclusions.

2. METHODOLOGY

2.1 General Methodology

In our methodology we used the IMAGE 2.2 Integrated Assessment model (IMAGE-team 2001), the TIMER 1.0 energy model (which is part of the IMAGE 2.2 framework) (de Vries et al. 2002) and the FAIR 2.0 climate policy model (den Elzen and Lucas 2005). The IMAGE 2.2 model is an integrated assessment model, consisting of a set of linked and integrated models that together describe important elements of the long-term dynamics of global environmental change, such as agriculture and energy use, atmospheric emissions of greenhouse gases and air pollutants, climate change, land-use change and environmental impacts. The global energy model, TIMER, as part of the IMAGE model, describes the primary and secondary demand and production of energy and the related emissions of greenhouse gasses and regional air pollutants. Finally, FAIR is a policy decision-support tool developed to explore and evaluate the environmental and abatement costs implications of various international climate regimes for differentiation of future commitments for meeting long-term climate targets. In this study, only the (multi-gas) abatement costs model of FAIR is used.

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

The analysis consists of five major steps:

1. Using the IMAGE and IMAGE/TIMER models to construct the baseline scenario, i.e. potential greenhouse gas emissions in the absence of climate policies (see Section 2.2), with both models providing information on the potential costs of reducing emissions from different sources.
2. Employing, in addition, the IMAGE model to develop the global CO₂-equivalent emission profiles, leading to a stabilization of the GHG concentration at a radiative forcing of 3.7, 4.5 and 5.3 W/m² (see Section 2.3).
3. Using the abatement costs sub-model of FAIR to distribute the global emission reduction objective (i.e. difference between the global baseline scenario and global emissions profile) over the different regions, gases and sources following a least-cost approach on the basis of Marginal Abatement Cost (MAC) curves. The model includes a set of endogenously MACs (energy and sinks CO₂ derived from by TIMER or IMAGE) and exogenously determined MACs of the EMF 21 project (non- CO₂) (see Section 3.4).
4. Forwarding the international marginal price for carbon emissions from energy and industrial sources, and the required abatements for the non-CO₂ gases, to the IMAGE/TIMER model to determine the changes in emission levels.
5. Finally, assessing the climate impacts using the IMAGE 2.2 climate model.

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

The modeling framework as used in this study has a hybrid approach with respect to the use of MAC curves. For agricultural sources, a pure MAC approach is used—in which the current price of reducing one unit of CO₂-equivalent emissions determines the reduction rate of one specific source. For all energy-related sources, a mixed approach is used, in which first MAC curves are derived in the energy model; next, the marginal price (based on MACs) are determined;

and finally these are fed back into the energy model. The energy model takes care of the interactions that result from the greenhouse gas constraint. For instance, changes in energy production as a result of reducing CO₂ emissions will also reduce methane emissions emitted from energy production and transport. Using this hybrid MAC approach has the advantage of transparency and flexibility. However, the approach also faces a number of limitations. First of all, we do not model direct linkages to the overall economy; and as a result we calculate abatement costs but no impacts on GDP or utility losses. Furthermore, using the MAC curves methodology for agricultural emissions will not lead to structural changes of the system, resulting in unaffected agricultural production levels. Finally, for the interactions between the MAC-based approach and the energy model, only one iteration is made, which would preferably repeated a number of times to better incorporate the path dependency in the energy sector (see also section 2.3).

An essential element of the modeling framework is that it concentrates on a system dynamics description of physical entities and flows, and their relationships. This means that the drivers of emission changes in the model are those that also drive emissions in the real world such as number of animals and the feed consumed, fertilizer application, harvested areas and energy production rather than monetary proxies for the drivers (as used often in general computable equilibrium models). Using the IMAGE model also allows us to calculate consequences of mitigation action in terms of atmospheric changes and climate impacts. The remainder of this section concentrates on crucial steps in the analysis, i.e. 1) the description non-CO₂ emissions, 2) the development of stabilisation profiles, 3) the determination of the cost-optimal implementation of reduction measures and 4) the incorporation of estimates for carbon sequestration by forests (sinks) into the model.

2.2 Emissions in IMAGE 2.2

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

- greenhouse gases covered by the Kyoto Protocol (CO₂, CH₄, N₂O, HFCs, PFCs and SF₆)
- ozone precursors (NO_x, CO, NMVOC)
- other important substances for radiative forcing (CFCs, aerosols)
- acidifying compounds (SO₂)

For the calibration period (1970-1995) both emission factors and activity levels are determined on the basis of available data sources, i.e. in particular FAO (agriculture, FAO 1999), IEA (energy, IEA 2000 and EDGAR (emissions Olivier and Berdowski 2001. The supplementary information to this paper⁴ provides an overview of the agricultural emission sources, and the activity drivers used within the model. In the scenario period, both the activity levels and emission factors change over time. For the emission factors, it is (in general) assumed that the higher emission factors in less-industrialised countries slowly evolve to the emission factors in industrialised countries. For industrialised countries, trajectories are followed on the basis of historical rates of change – and assumed possible improvements (determined by the scenario context). Concentrating on the non-CO₂ gasses CH₄ and N₂O, their emissions mostly originate from agricultural activities (50% and 90%, respectively). In IMAGE, these activities are influenced by population growth, increases in per capita caloric intake, dietary practices, and agricultural production methods and yields. The largest source, CH₄ emissions from animals (enteric fermentation) depends on the number of cattle (which is a function of meat demand, trade and animal size) and an animal-dependent emission factor. The second large source, CH₄ emissions from rice fields is based on the harvested areas of irrigated, rainfed and deepwater rice and regional emission factors. It should be noted that for the baseline emissions of the halocarbons, no independent modeling was done, but exogenously set scenarios are used from the IPCC SRES A1b scenario (Fenhann 2000).

2.3 Development of Stabilisation Profiles in Terms of CO₂-equivalent Emissions

A set of global emission profiles has been developed that lead to stabilizing greenhouse gas forcing at 3.7, 4.5 and 5.3 W/m². These profiles are determined in terms of CO₂-equivalent emissions and used as caps for the cost-optimal implementation of reduction measures. The method for developing the profiles and the results are described in detail in Eickhout et al. (2003). The profiles are based on three phases. First, until 2012, existing climate change policies are implemented—in particular—the Kyoto targets for most Annex-I countries and the Bush Climate Action Plan for the USA (see White-House 2002). All other regions follow the baseline. For the period from 2012-2040 we assume a linearly increasing reduction rate. From 2040, onwards, we use the inverse CO₂ concentration calculations of Enting et al. (1994) and similar reduction rates for non-CO₂ gases that result in stabilisation of radiative forcing in 2150. We did not allow for overshooting the specific stabilization target—which implies that to reach the 3.7 W/m² target, rather steep reductions are required early on in the scenario. For the other two stabilization levels, much more flexibility in the timing of emission reductions is allowed; the profiles chosen should be regarded

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

as being representative of medium reduction paths. As shown by Eickhout et al. (2003), emissions of different gases can be reasonably well substituted under these profiles, still leading to stabilisation of radiative forcing.

2.4 Determining the Cost-optimal Implementation of Reduction Measures

The required mitigation action to reach the different stabilisation profiles is analyzed using the abatement cost model of FAIR 2.0 (den Elzen and Lucas 2005). The abatement cost model determines the cost-optimal implementation of the required global reductions over the different gases, sources and regions, using aggregated permit demand and supply curves. The permit demand and supply curves are derived from reduction cost curves on the basis of the same methodology as applied by Ellerman and Decaux (1998). For the non-CO₂ GHG emissions, MAC curves from EMF-21 (see Table 1) are used; these are based on detailed abatement options. For the energy and industry-related CO₂ emissions, response curves from the TIMER energy system model (Van Vuuren et al. 2004) are used, including technological developments, learning effects and system inertia.⁵

The non-CO₂ MACs were constructed mainly for 2010, and do not include technological improvements in time. Furthermore, the curves were constructed against a hypothetical baseline that assumes no measures to be taken in the absence of climate policy ('frozen emission factors' (see Table 1 for the relevant references). Therefore, the following steps were made before the MACs were used in the costs calculations (see Figure 2):

- The MAC curves were translated into relative reductions from the original baseline and projected on our own baseline to create curves consistent with this scenario.
- Improvements in emission factors under the baseline scenario (representing mitigation measures implemented for other reasons than climate policy) were subtracted from the MACs in order to avoid double counting⁶. This baseline correction removed most of the negative costs parts of the EMF-21 curves. Remaining negative costs options in the EMF-21 were set at zero costs.
- Increases in the abatements potential due to technology progress and removal of implementation barriers were accounted for by multiplying the MAC curves by a technological improvement rate.

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

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

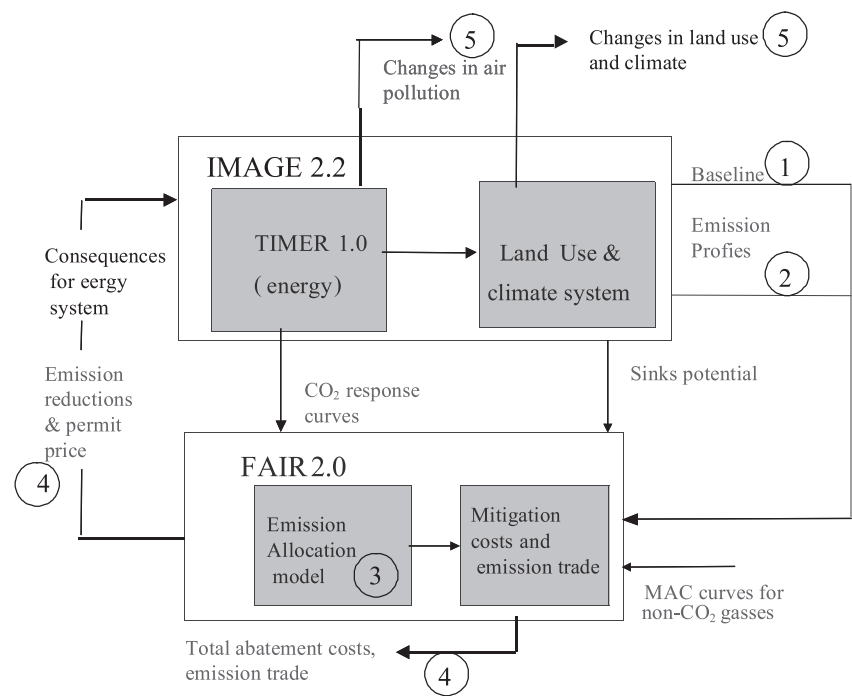
Table 1. Source of Information on Marginal Abatement Costs

<i>Emission category (Non-CO₂ gasses)</i>	<i>Source of information on marginal abatement costs</i>	<i>Reduction potential of main sources (2010)</i>	<i>Assumed annual increase of potential</i>
CH ₄ and N ₂ O from agricultural sources	DeAngelo et al. (2006) and Graus et al. (2004) for development of potential in 2010-2050 period.	N ₂ O soil: 7% CH ₄ animals: 7% CH ₄ rice: 20%* CH ₄ manure : 17%	3.9% until 2050 3.9% until 2050 1.5% until 2050 2.4% until 2050; 0.4% 2050-2100
CH ₄ and N ₂ O emissions from industrial and energy-related sources	Delhotal et al. (2006) (*)	CH ₄ total : 65% N ₂ O process : 90-95%	0.4%
Halocarbons	Schaefer et al. (2006)	Total reduction of 40%	0.4%
<i>Emission category (CO₂)</i>	<i>Source of information on marginal abatement costs</i>	<i>Reduction potential of main sources</i>	<i>Assumed annual increase of potential</i>
CO ₂ from energy use and production	Time-dependent MACs iterating between FAIR and TIMER (Van Vuuren et al. 2004)	2010: Around 50% 2100: Around 80%	—
Sinks	Based on IMAGE calculations (Graveland et al. 2002)	Potential increases to 0.4 GtC annually in 2050	—
Forest management	Conservative assumptions based on the extension of the Marrakesh Accords as described in Van Vuuren et al. (2003)	A total amount of 135 MtC-eq annually is assumed.	—

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

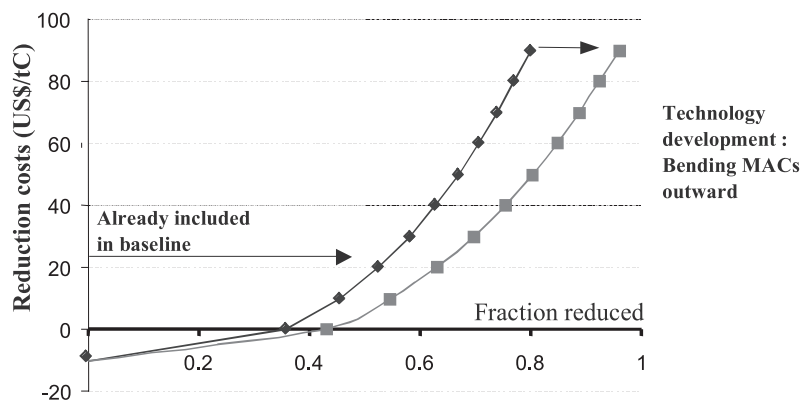
A crucial uncertainty here is the rate at which the MAC curves move out in time. Unfortunately, little information is available on the possible improvement of the MAC curves after 2020. In addition to further development of existing technologies and development of new technologies, reduction of implementation barriers for current mitigation measures represent an important factor increasing abatement potential in time. Processes that decrease such barriers include time (overcoming limited capital turnover), changes in farming systems (from small scale, subsistence, farming systems to larger, commercial systems), increases in investment opportunities and development of systems that pool small-scale reduction options in order to reduce the transaction costs. Graus et al. (2004) indicate, on the basis of the detailed technology information underlying the EMF-21 data, that removal of implementation barriers could lead to an increase of

Figure 1. Overview of the Modeling Approach Used



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

Figure 2. Incorporation of Marginal Abatement Curves in FAIR 2.0



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

global reduction potential for N₂O emissions from fertiliser use from 7% in 2010 (EMF-21) to 32% in 2050, for CH₄ emissions from enteric fermentation from 7% to 32%, for CH₄ emissions from manure from 17% to 44% and for CH₄ emissions from rice cultivation from 20% to 37% in 2050. Their numbers have been used to calibrate the rate of changes in MAC curves for these sources. For other non-CO₂ emission sources, long-term emission reduction potential could in theory be estimated in a similar way. However, such studies are still lacking. Instead, other technology development processes can be taken as a reference. For instance, the reductions in CO₂ emission in the energy model TIMER increase by about 1-2% annually in the first 20 years after introduction of a carbon tax mostly as a result of overcoming inertia. After that period, the rate of increases is 0.5-1.0%, dominated by technological progress dynamics (Van Vuuren et al. 2004). Another example is the experienced efficiency improvement of end-use technology over the last 30 years (0.5-1.5% per year) (Schipper et al. 1997). Based on these numbers, we have assumed a relatively conservative value of an increasing potential (at constant costs) for all other non-CO₂ MACs of 0.4% per year.

2.5 Incorporating Sinks Estimates Based on the IMAGE 2.2 Model

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

To determine the potential for reforestation, we first determine future land-use for food, feed, timber and biofuels. In IMAGE, the demand for these products is driven by population size, dietary preferences, income and trade. Yield changes in the agricultural sector subsequently determines how much land is required. As population growth slows down and agricultural yields further improve, land tends to become available that is no longer used for other purposes. The IMAGE model subsequently determines how much carbon can potentially be sequestered in that area. This, however, needs to be corrected for the amount of carbon that would be sequestered by regrowing natural vegetation in this area anyway. This is captured by the concept of Surplus Potential Productivity (SPP), which represents the net C sequestration by the plantation minus that of the original vegetation (see Figure 3). The carbon plantations are assumed to be implemented only in areas that 1) have a positive SPP and 2) have no other use for

a 50-year period given the baseline. The net annual C sequestration is calculated as a mean during a 50-year period and aggregated from the grid level to the level of the IMAGE regions⁷. The carbon supply curves form the basis of the sink MAC curves by taking into account grid-level land costs, forest establishment costs, and operation and maintenance costs. The costs are based on the literature overview provided by IPCC (1996). For, operation and maintenance costs a reference value for Western Europe of 95 US\$ per hectare is used and varied for the other regions on the basis of per capita income. The overall annual potential sink derived in this way amounts in 2050 to about 1.5 GtC. However, the potential sink area is reduced by a factor to represent implementation barriers. We have assumed that these barriers cause a reduction the total potential to 10% in 2010 and 30% in 2030 and onward (see also Graveland et al. 2002).

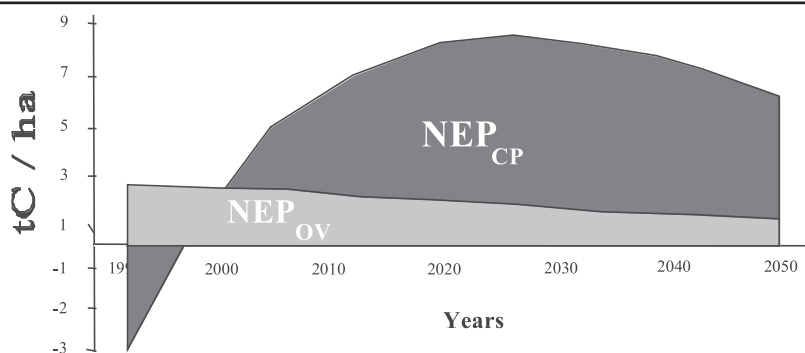
The result of our approach is a changing MAC for each region over time based on a detailed land-use assessment, with each point in the MAC representing a grid cell with a positive SPP (see Figure 4; the 4 regions shown are selected as examples). The potential of OECD regions (like Western Europe) is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

3. THE COMMON POLES IMAGE BASELINE

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

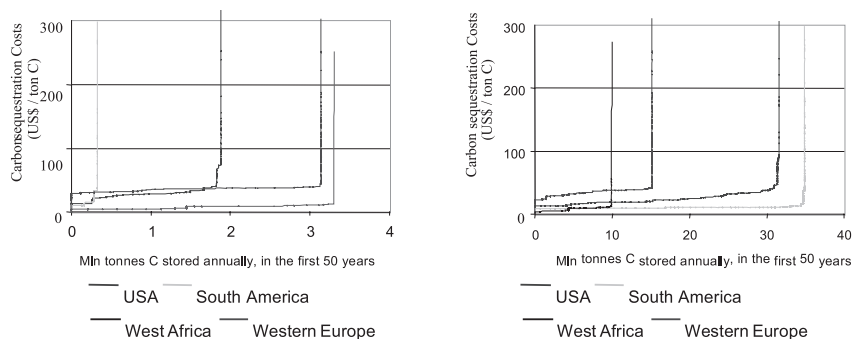
7. All model calculations are performed at the level of 17 IMAGE regions or at the 0.5 x 0.5 grid (environmental variables and land-use). The IMAGE regions are Canada, USA, Central America, South America, Northern Africa, Western Africa, Eastern Africa, Southern Africa, Western Europe, Central Europe,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

Figure 3. Schematic Representation of the Calculation of the Surplus Potential Productivity (SPP)



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

Figure 4. Sinks MAC Curves for Four Regions in 2010 (left) and 2050 (right)



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

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

The actual mix, obviously, strongly differs among regions – with some regions relying on natural gas to fuel their electric power sector and others on coal.

As a result, energy-related carbon dioxide emissions increase sharply from 6.3 GtC in 2000 to 14.9 GtC in 2050, then level off to reach 15.4 GtC in 2100 (see Table 2 and Supplementary Information) and continue to be the major source of GHG emissions. After 2050, stabilising population levels also slow down further growth in carbon dioxide emissions. In terms of land-use change, worldwide, population growth and shifts to more meat and poultry in people's diets lead to an additional need for agricultural land in the first half of century, despite improvements in agricultural production. Later, further productivity gains result in a surplus of agricultural land, in particular, land in high-income regions that can be converted into forest areas. As a result, carbon dioxide emissions from land-use increase slightly between 1995 and 2040, but decrease afterwards. Most of the land-use related emissions originate in developing regions, in particular, due to population growth that leads to a higher agricultural demand and hence deforestation. The rate of deforestation in each region is also a good proxy for the amount of land that becomes available for carbon plantation.

Total CH₄ and N₂O emissions increase up to 2050, after which they remain more-or-less constant (Table 2). Over the century, their contribution in total greenhouse gases drops from 23% to 18%, as their growth rate is slower than that of CO₂. This is caused by the fact that most land-use-related drivers of these emissions have strong saturation tendencies. For CH₄, only emissions from animal husbandry, gas production and landfills are likely to grow rapidly, in the absence of climate policies. For coal and oil production, changes in production levels and capture of methane for economic and safety reasons reduces CH₄ emissions. Wetland rice emissions remain more-or-less constant as not much expansion occurs in wetland rice cultivation and yields improve. For N₂O, only growing fertiliser use is expected to lead to increasing N₂O emissions. Halocarbons (chlorinated and fluorinated gases) form by far the fastest growing category of emissions. The reasons for their increase include rapid growth rates of some emitting industries (semi-conductors, electricity production) and replacement of ozone-depleting substances by HFCs. It should be noted that despite the rapid increases, emissions in absolute terms remain relatively small compared to other sources.

Changes also occur in terms of the regional emissions. For all sources, emissions from non-Annex I countries grow considerably faster than those from Annex I countries. Looking at CO₂ emissions only, the share of emissions from Annex-I countries declines from 60% in 2000 to 20% in 2100. For all greenhouse gas emissions, the share of non-Annex I countries is already lower, i.e. nearly 50% in 2000. Here, as well, the share of Annex I countries declines to 20% in 2100.

The projections of IMAGE 2.2 are model based, but seem to compare well to scenarios that have been developed on the basis of specific country projections such as the recent scenario from EPA (Scheele and Kruger 2006). For the short-term period up to 2020, global methane emission increase by 33% in the EPA scenario between 2000 and 2020, and by 36% in the IMAGE CPI scenario.

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

	CPI-baseline						Multi-gas 4.5 W/m ² stabilization scenario					
	Emissions (in GtC-eq)			Share in emissions (%)			Emissions (in GtC-eq)			Change compared to baseline (%)		
Gases	2000	2050	2100	2000	2050	2100	2000	2050	2100	2000	2050	2100
CO ₂	7.74	16.12	15.15	76%	78%	78%	7.72	9.83	5.02	100%	65%	36%
CH ₄	1.91	3.00	2.77	19%	15%	14%	1.91	1.82	1.52	100%	61%	55%
N ₂ O	0.44	0.64	0.68	4%	3%	3%	0.44	0.48	0.52	100%	76%	77%
HFC	0.07	0.601	0.675	1%	3%	3%	0.07	0.258	0.237	100%	43%	35%
PFC												
&SF ₆	0.069	0.193	0.195	1%	1%	1%	0.069	0.083	0.068	100%	43%	35%

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

For N₂O, these numbers are 32% and 29%, respectively. For the fluorinated gases, both scenarios finally indicate an increase of nearly 120% in 2020 in terms of CO₂-equivalent emissions.

4. STABILISING RADIATIVE FORCING AT 4.5 W/M²: MULTI-GAS VERSUS CO₂-ONLY

4.1 Emissions Reductions and Cost

In order to reach the selected emission profile that leads to stabilisation of the greenhouse gas radiative forcing at 4.5 W/m², greenhouse gas emissions (measured in terms of CO₂-equivalents) under the multi-gas scenario need to be reduced by about 15% in 2025, 35% in 2050 and 60% in 2100 in comparison to the baseline emissions. The same equivalent emission profile was used for the CO₂-only run. Figure 5 compares the CO₂-only and multi-gas emission scenarios that have been developed under this stabilization target. It can be seen that for the CO₂-only scenario a small part of the emission reductions are, in fact, achieved through reduction of methane, as the systemic changes in the energy system, induced by putting a price on carbon, also reduces these emissions. CO₂ emissions are reduced by about 80% in 2100 compared to baseline.

In the Multi-gas scenario, less stringent reductions of CO₂ are obviously required (around 60% in 2100), although the figure also shows that still by far the largest contribution comes from reductions of CO₂ emissions. It should be noted that the reduction rates are not distributed evenly across the different gases and the contribution of different gasses changes sharply over time (Table 2; Figure 5). For the Kyoto period, the majority of reductions can cost-optimally be achieved by reductions for the non-CO₂ gases and by using sinks. Only 10% of the reductions

would be obtained from reducing energy-related CO₂ emissions (see also Lucas et al., (2005)). The disproportional contribution of non-CO₂ abatement at low prices is caused mainly by relatively low-cost abatement options that have been identified for these gases (e.g. reducing methane emissions from energy production and N₂O emissions from adipic and acrylic acid industries).

After 2015 the share of the non-CO₂ emissions in total reductions is slowly reduced. In part, this shift simply reflects that non-CO₂ represents only a fifth or so of total greenhouse gas emissions, and that reduction becomes more proportional to the emissions. In addition, however, it also reflects the underlying reduction potential estimates. A large number of non-CO₂ emission sources have a limited (identified) abatement potential (such as N₂O emissions from fertiliser application or CH₄ emissions from enteric fermentation). There are, at least in theory, other options to reduce these emissions that have not been accounted for in the abatement potential such as changes in consumption patterns (e.g. a reduction of meat consumption) or radical changes in production patterns (bio-engineering). In contrast, other sources can be reduced substantially (sometimes by a combination of changes in energy use and end-of-pipe measures such as CH₄ emissions from energy production, which are reduced by 50-70%). The total abatement potential for non-CO₂ gases after 2050 is virtually exhausted. As a result, by the end of the century, the reductions for CO₂ are slightly higher than the average emission reductions. Overall, total greenhouse gas emissions are reduced by 60% in 2100, while the reduction of CO₂ is nearly 65%. For CH₄, relatively large reductions are obtained for landfills and production of coal, oil and gas. The latter are not only due to end-of-pipe measures but also include the impact of more systemic changes in the energy system. Overall, CH₄ emissions are reduced by approximately 40% in 2050 and 45% in 2100. For N₂O, the most substantial reductions are achieved from the production of acrylic and adipic acid (up to 70% reduction). For fertiliser use, some small reductions occur, but these are mostly offset by increases in emissions from agricultural lands due to biofuel production. For most N₂O sources, no marginal abatement curves were available and emissions simply follow the baseline. Emissions of the halocarbons are reduced by 65% for the total group. Finally, the maximum amount of carbon sequestration for sinks is achieved by 2050, i.e. 0.4 GtC annually.

The marginal costs associated with these changes are presented in Figure 6. In both scenarios, the increase in marginal price follows a rather smooth path over most of the century. These costs range, however, from 310 US\$/tCeq in 2100 for the multi-gas variant and 580 US\$/tCeq for the CO₂-only scenario (nearly a factor 2 difference). These numbers are 138 and 175 US\$/tCeq, respectively, in 2050 (30% difference). Two important reasons for the differences in marginal cost levels between the multi-gas and CO₂-only scenario exist. The first reason is that, early on in the scenario. The least-cost approach selects the relatively cheap emission reduction options which mainly exists of reductions in non-CO₂ sources. The second reason is that by the end of scenario period, the marginal costs of reducing CO₂ further has become so high that including more abatement

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

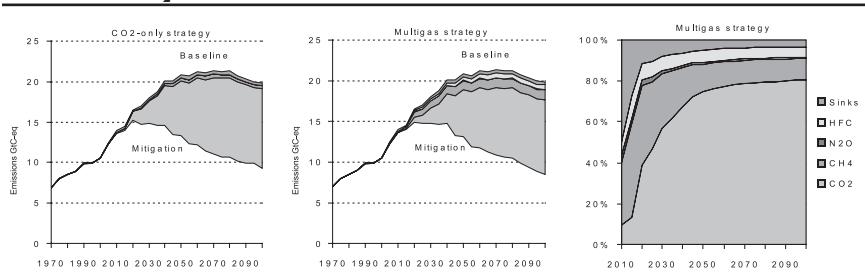
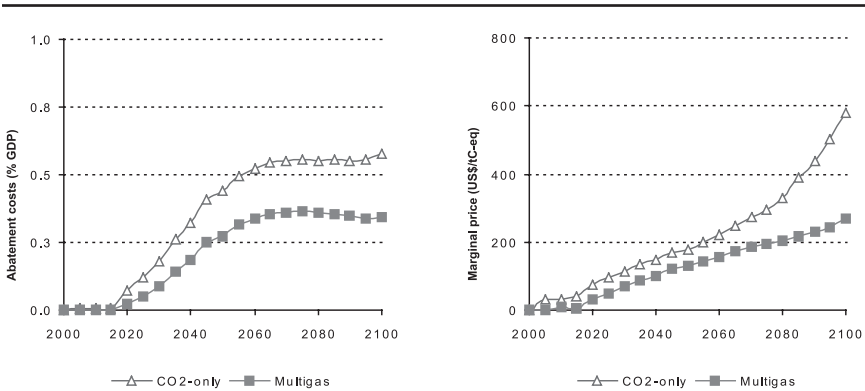


Figure 6. Global Abatement Costs as % of GDP (left) and Marginal Reduction Costs (right)



potential (by including the non-CO₂ sources) substantially decreases the marginal costs. As a result, the difference in marginal costs is large early in the scenario (in 2010, 6 US\$/tCeq versus 30 US\$/tCeq or a factor 5) and by the end of the century (nearly a factor 2). Halfway the scenario, however, the impact on marginal costs is smaller. In terms of fraction of GDP, total abatement costs for both scenarios are 0.38% and 0.58% of world GDP in 2100. Here, the impact by the end of the century is less pronounced.

4.2 Climate Impacts

Despite the fact that both the multi-gas and the CO₂-only scenario have the same CO₂ equivalent emissions, the scenarios do not lead to exactly the same climate outcomes. While the multi-gas scenarios stabilises radiative forcing at 4.5 W/m², the 2100 radiative forcing of the CO₂-only scenario is already 4.9 W/m². The increase in global mean temperature in 2100 is 2.3°C for the multi-gas scenario and 2.5°C for the CO₂-only scenario. There are several reasons for this difference. First of all, emission reductions for CH₄ (in the multi-gas scenario) result in a

faster reduction in GHG radiative forcing (due to its shorter lifetime) than for CO₂. As a result, temperature increase is somewhat lower throughout the century. Secondly, the CO₂ concentration of the CO₂-only scenario is somewhat lower than for the multi-gas strategy, which implies less absorption of CO₂ by oceans and the biosphere. Thirdly, reducing CO₂ by means of systemic changes in the energy system leads to several other emission reductions, among which a reduction of sulphur emissions from the energy system (leading to higher temperature change as sulphur aerosols have a net cooling effect) and ozone precursors (leading to lower temperature change by reducing ozone concentrations). Sygna et al. (2002) have shown that by extending the scenario further into the future (e.g. 2300), the situation could shift and the CO₂-only scenario might have the lowest temperature increase. In fact, we found a similar result by exploratively extending our results beyond 2100. The results shows that substitution among different greenhouse gases using their (100 year) GWPs does not lead to exactly similar climate outcomes in 2100. The differences, however, are relatively small.

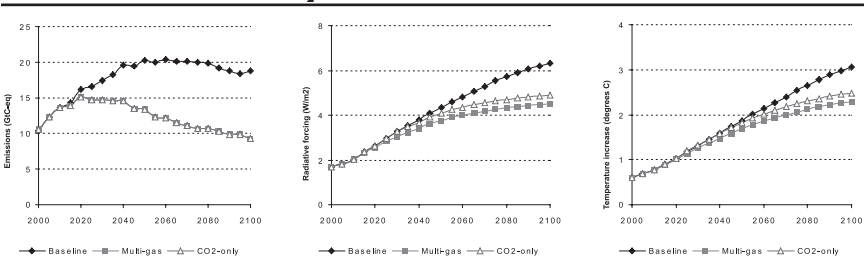
5. STABILISING RADIATIVE FORCING AT DIFFERENT LEVELS

5.1 Emission Reductions and Cost

Several researchers have established the cost increases as a result of a series of increasingly tight concentration targets for CO₂ (see Hourcade and Shukla 2001). Comparing these cost levels to the possible climate impacts associated with these levels allows stakeholders to assess (to some degree) the advantages and disadvantages of stabilising CO₂ concentration at different concentration levels. Given the results of the previous section, which showed that including non-CO₂ gases can lead to major cost reductions, it seems useful to redo such an analysis on the basis of a multi-gas approach for different levels of radiative forcing. Here, two additional scenarios are assessed, i.e. 3.7 and 5.3 W/m². Figure 8 shows the accompanying scenarios and marginal price levels for stabilising radiative forcing at these levels. Table 3 shows some of the main results for greenhouse gas emissions and temperature change.

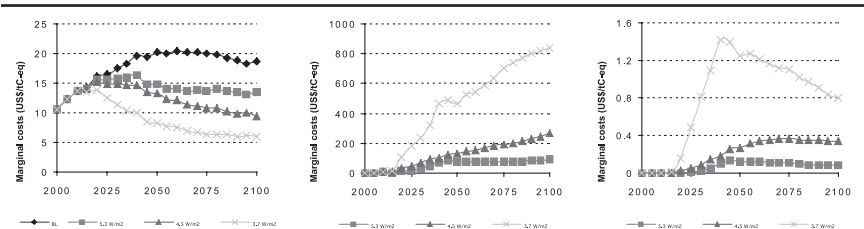
For this 5.3 W/m² stabilisation scenario, the marginal price increases more or less linearly to a level of 100 US\$/tCeq and remains constant thereafter, leading to a reduction of greenhouse gas emissions of 40% in 2100. CO₂ is reduced at a similar rate to the total greenhouse gases. The halocarbons are reduced more than proportionally (65%), while CH₄ (40%) and N₂O (14%) are reduced less than proportional. For the most ambitious climate target (3.7 W/m²) a different situation exists. First of all, emission reductions need to take place early in the scenario period in order to avoid an overshoot of the radiative forcing target. Moreover, in order to achieve the target, total 2100 emissions will need to be reduced by 75%. This implies that the amount of abatement potential for the non-CO₂ gases is crucial. Under our standard assumption, the carbon price needs to rise sharply, in order to avoid an overshoot of the radiative forcing level early

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



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

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



in the scenario. After 2050, the carbon price increases more slowly. The fact that the marginal price is considerably higher than for the 4.5 W/m² scenario can be explained by the exponential form of the global MAC curve with rapidly increasing prices for the higher emissions reductions. By far, the most reductions come from CO₂, which is reduced by 80% in 2100 (compared to 75% for total greenhouse gases). Reductions of methane amount to 55%.

For the 3.7 W/m² scenario abatement costs per unit of GDP increases very rapidly from 2010 to 2040 to a maximum level of 1.5% of global GDP, after which the ratio gradually decreases to 0.8-0.9%. For the 4.5 W/m² scenario, the relative costs increase gradually and stabilises after 2070 at 0.4% of GDP. For the 5.3 W/m² stabilisation scenario, finally, costs reach a level of about 0.1% of GDP. It should be noted, however, that in all cases the cost levels reported here are subject to considerable uncertainty (as indicated in section 6).

In terms of reductions among the different gases, the three scenarios more-or-less confirm the trend already found for the 4.5 W/m² scenario (Figure 9). For the less stringent climate target a larger share of reductions is achieved through reductions of non-CO₂ gases than the average reduction, while for the more stringent target, CO₂ emissions need to be reduced more than the average reduction, as

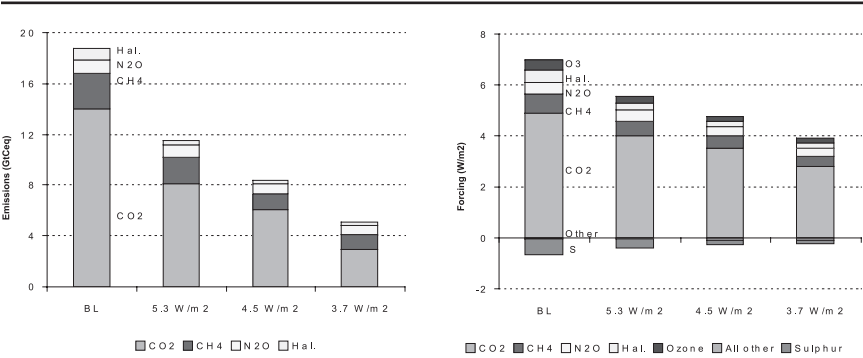
abatement options for the other gases have been exhausted. The radiative forcing of the different scenarios reflects the changes in terms of emission reductions. However, a few other important observations can be made. First, in terms of radiative forcing, the halocarbons become a considerable forcing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

5.2 Climate Impacts

The three multi-gas scenarios analysed here lead to clearly different temperature increases in 2100 (see Figure 10 and Table 3). Using the medium value for climate sensitivity (2.5 W/m^2), the 5.3 W/m^2 scenario leads to an increase of 2.6°C in 2100 over pre-industrial levels, i.e. 0.6°C less than in the baseline scenario. The 3.7 W/m^2 scenario, in contrast, leads to a 1.9°C increase. It should be noted that the EU has formulated as its objective of climate policy to limit global mean temperature increase to a maximum of 2.0°C warming. The 3.7 W/m^2 would just be able to meet that target in 2100 for a medium climate sensitivity value, but unless radiative forcing is reduced after 2100, global mean temperature would increase further to an equilibrium level of about 2.3°C . The 4.5 W/m^2 stabilisation scenario takes an intermediate position.

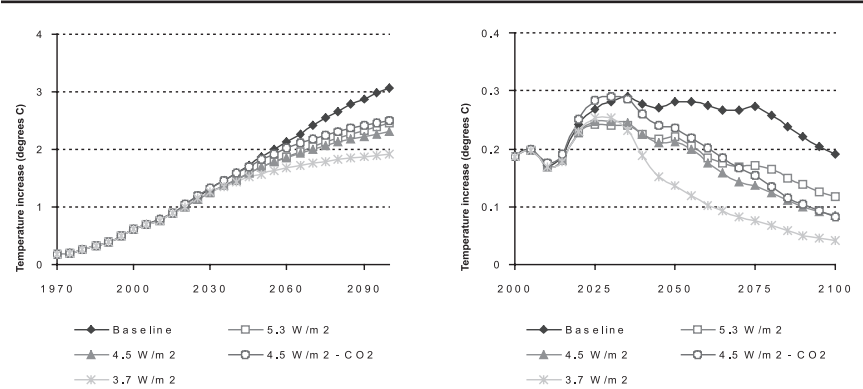
Another proxy for the risk of adverse impacts from climate change is the rate of temperature change. In this analysis, we have not specifically targeted for meeting any rate of change target, although the resulting rates can still be assessed. Figure 10 shows that for the baseline scenario, the rate of temperature change is around 0.25°C per decade for the whole of the century. In the mitigation scenarios the rate of temperature increase drops to below a rate of 0.2°C per decade. For the 4.5 W/m^2 and 5.3 W/m^2 scenarios this occurs around 2060, and for the 3.7 W/m^2 scenario in 2040. By the end of the century, rates of temperature increase are 0.05°C per decade for the 3.7 and 4.5 W/m^2 scenarios and just below 0.15°C per decade for the 5.3 W/m^2 scenario. In the early decades, however, the mitigation scenarios hardly do better than the baseline. The reason is that in the

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



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

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



mitigation scenarios changes in the energy system to reduce CO₂ emissions also lead to a reduction in sulphur-cooling (as already emphasised by Wigley (1991)). This occurs in particular in those scenarios that concentrate on CO₂ reduction. The multi-gas 4.5 W/m² and 5.3 W/m² scenarios, both show a lower rate of temperature increase between 2020 and 2040 than the baseline as a result of more than proportional reduction of methane emissions. This indicates that there might indeed be a possibility of meeting a rate of change target in the 2000-2040 period in the context of long-term stabilisation scenarios, by emphasising non-CO₂ emission reductions, partly in order to offset the decreased aerosol cooling

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

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

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

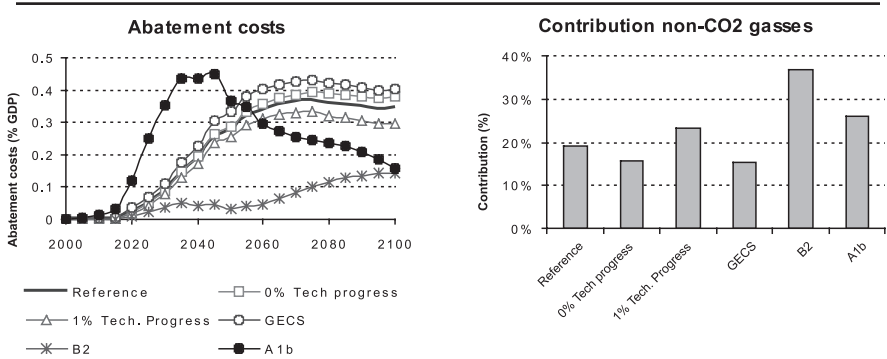
6. DISCUSSION AND SENSITIVITY ANALYSIS

Many studies indentify the uncertainties that influence the results of the mitigation analysis in terms of abatement action and costs (Hourcade and Shukla 2001; Morita and Robinson 2001). In this section, we will explore some of the uncertainties that are important for our results for non-CO₂ gasses after 2010. The sensitivity of our results against these will be explored below. Other crucial uncertainties that impact costs include the assumptions on technology development for CO₂ abatement potential, the timing of mitigation action and the formation of an effective coalition to implement climate policy. As these, however, have been covered elsewhere (see for instance den Elzen et al 2005 and van Vuuren et al. 2004), we will not discuss them here. Instead, we will pay some attention to the role of using GWPs in our analysis. Moreover, we will discuss the impact of the uncertainty about climate sensitivity on the climate results. Finally, in the previous section we noted that the lowest of the stabilization targets (3.7 W/ m²) has only a small chance of limiting global mean temperature increase to 2°C compared to pre-industrial levels. This is, however, the official target of climate policy for the EU. Moreover, several studies indicated that considerable climate change impacts may already occur at global mean temperature increase of 2°C (see IPCC 2001). In this context, we will briefly discuss whether alternative scenarios could be developed that have a higher chance of meeting such target; and in particular the type of assumptions needed to develop them.

6.1 Sensitivity to the Baseline Scenario

The emission levels assumed in the baseline scenario directly determine the reductions that are required to reach the emission profile for stabilisation. In addition, the scenario assumptions also indirectly influence the abatement potential, in particular, assumptions related to costs of different technologies. Finally, the economic assumptions obviously influence the relative cost measures such as GDP losses or abatement costs as percentage of GDP. Figure 11 shows that the consequences of using a different baseline for global abatement costs and the contribution of non-CO₂ gasses in total emission reduction. In our analysis, we have used the IPCC SRES A1b and B2 scenarios as implemented by IMAGE 2.2 (IMAGE-team 2001) instead of the CPI baseline used so-far. The Figure shows that this has a very strong influence on costs. In case of the A1b scenario (a high economic growth scenario) rapidly rising emissions (in the absence of climate policy) imply that reaching a profile that leads to stabilisation at 4.5 W/m² requires strongly increasing costs levels during the first half of the century. In the second half, however, the relative costs to GDP decrease as continuing GDP growth offset costs increases and population decreases (the population decrease assumed under this scenario leads to decreasing baseline emissions). In the B2 scenario (a medium growth scenario with relatively low emissions), in contrast, costs develop much smoother as a result of a smaller gap between the baseline and the emission target. By the end of century, in both alternative scenarios, the baseline emissions levels are lower those of the CPI baseline. This leads to a smaller reduction obligation, resulting in a higher share of non-CO₂ gasses in total abatement and lower costs.

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



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

The rate at which the potential for non-CO₂ emission reductions develops after 2010 is a crucial uncertainty for the analysis performed here. Therefore, we explored two alternative scenarios, assuming no improvement in the total potential after 2010 and a faster improvement rate of 1% per year. In addition, a model run was performed in which the EMF-21 MAC curves for non-CO₂ gasses were totally replaced by those from the GECS project (the GECS project also developed global MAC curves for non-CO₂ gasses, see Criqui 2002). The analysis shows that these (relatively small) changes in the rate of increase of the reduction potential (certainly within the range of likely assumptions, see the discussion in Section 2.4) can have considerable influence on the outcome. The sensitivity run assuming faster technology development for non-CO₂ gas reduction potential indicates a drop of relative costs to GDP from 0.34% to 0.30% in 2100. At the same time, the share of non-CO₂ gasses in total emission reduction increases from 19% to over 25%. The run with no further improvement in the abatement potential obviously shows the opposite, with costs increasing to 0.40% of GDP. Replacing the EMF-21 set of MAC curves by the alternative GECS curves increases the overall costs level. So-far no detailed source-by-source comparison between the GECS and EMF-21 curves was made. The most important factor that leads to lower costs in case of EMF-21 than for the GECS curves is the fact that former also covers several agricultural sources.

It should finally be noted that for several non-CO₂ emission sources, no MAC curves are available (e.g. N₂O emissions from crop residues and animal waste). These emissions in total cover about 0.5 GtC. In our analysis, we consequently assumed that no abatement can be obtained for them. Whether abatement options (either technical options or via consumption changes) can be reduce emissions from these sources in the future is a major uncertainty (and one whose resolution would reduce costs further compared to CO₂-only strategies).

6.3 The Use of GWPs to Substitute Among Different Gases

In the introduction, some of the critique that has been brought forward against the use of GWPs as a metric for substitution has been discussed (e.g. their arbitrary time period, their dependency on the specific situation (atmosphere composition) and the assumed possibility to separate the economic and physical dimensions of climate policy). It was concluded, however, that today no alternative measure has attained a comparable status, and that several authors have argued that the shortcomings and costs are likely to be outweighed by the strengths (that is, to conveniently allow for development of multi-gas strategies). Although no specific analysis has been performed, the use of GWPs is a important assumption in our analysis. It was found for the extreme case of including no non-CO₂ abatement versus the multi-gas strategy (for the 4.5 W/m² stabilisation scenario) in reaching a profile defined on the basis of 100 year GWPs leads to some differences in terms of radiative forcing and temperature change. These differences, however,

are relatively small, and the scenarios will converge more after 2100. The main difference occurs in the first half of the century. In fact, one could argue that using GWPs has an additional advantage of not focussing on one particular target only (here a long-term stabilisation target), but also leads to considerable reductions of CH₄ early in the scenario period. Postponing this abatement (as would be suggested by flexible optimization) would lead to much higher rates of temperature in the 2000-2020 period as a result of additional changes in the energy sector, and associated reductions in sulphur cooling.

6.4 Uncertainties Influencing the Temperature Outcomes

There are a number of critical uncertainties in the climate system that determine the temperature outcomes of the scenarios. Important uncertainties include the uncertainties associated with the carbon cycle, the radiative forcing of various agents, land-use change (impacting both the carbon cycle and the albedo), climate sensitivity and the ocean-heat uptake. A key uncertainty is the climate sensitivity (Matthews and van Ypersele 2003). In our analysis, a climate sensitivity of 2.5°C has been used, which is the medium estimate provided by IPCC (Cubash and Meehl 2001). If instead, climate sensitivity is varied across the range of 1.5-4.5°C (Cubash and Meehl 2001), the 2100 temperature increase for stabilisation at 4.5 W/m² changes from 2.3°C (compared to pre-industrial) to a range from 1.5 – 3.5°C. For stabilisation at 3.7 W/m², the 1.9°C changes into a range from 1.3– 3.0°C. This large range in climate outcomes represents a major challenge in decision-making. It is important to note the difference indicated in Table 3 between the 2100 temperature increase and the equilibrium temperature. Stabilising radiative forcing implies that a substantial further temperature increase is still to come after 2100 (e.g. 4.5 W/m² leads to a 2100 temperature increase of 2.3°C, but an equilibrium temperature increase of 3.0°C). A considerable share of that difference can actually be avoided, by not only stabilising radiative forcing, but by actually reducing radiative forcing after the peak level has been reached. So far, not many (so-called) peaking scenarios have been explored, but they are likely to form part of a cost-effective long-term strategy to limit global temperature increase.

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

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

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

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

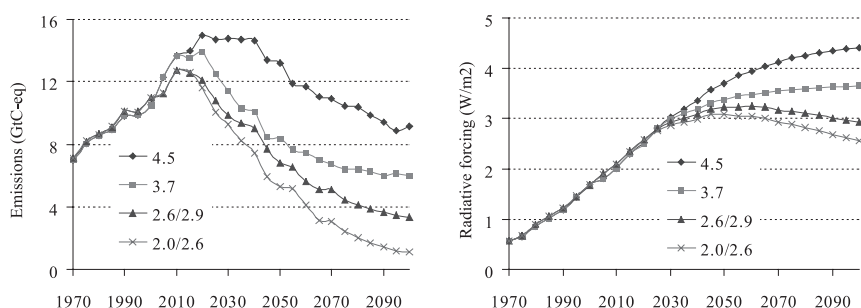
Thus, the next question is whether it is possible to extend the number of reduction options in the modeling framework so that it can meet low stabilization targets, based on a realistic assessment of existing literature? Van Vuuren et al. (in prep.) have looked into this question and describe in detail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

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

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

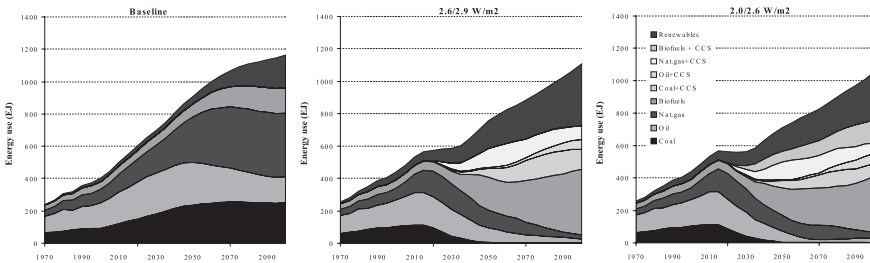
On the basis of the options discussed under a-c, it was found possible to develop a technically feasible scenario that would peak radiative forcing at 3.2

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



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

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



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

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

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

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

7. CONCLUSIONS

In this analysis, one baseline scenario and three multi-gas scenarios for stabilising radiative forcing at 3.7, 4.5 and 5.3 W/m² were developed. In addition, one scenario was developed with the same equivalent emission profile as the 4.5 W/m² multi-gas scenario, but now focussing reductions on CO₂-only. In the multi-gas stabilisation scenarios substitution among the different greenhouse gases was based on the marginal abatement costs and 100-year GWPs. The following conclusions can be drawn from the analysis:

Simple trend extrapolation does not suffice in developing non-CO₂ emissions scenarios: each source is driven by specific dynamic activity levels. While total CH₄ and N₂O emissions are projected to increase, their contribution in total emissions is likely to decline. Land-use related CO₂ emissions are expected to peak in the first half of the century and decline thereafter.

Each source of greenhouse emissions is driven by a complex web of drivers, including activity changes, technological changes and environmental policies. To describe these changes properly, it is necessary to specify how these drivers are likely to develop in the future in an integrated way. Emissions of most of the non-CO₂ gases are coupled strongly with agricultural activities, which are likely to show strong saturation tendencies over the next century (as population growth slows down, and productivity continues to improve). As a result, the contribution of CH₄ is likely to decline from 19% to 15%, while the contribution from N₂O remains constant at 4%. For CH₄, only emissions from animal husbandry, gas production and landfills are likely to grow rapidly in the absence of climate policies. In contrast, emissions of the halocarbons are likely to experience rapid growth rates but remain limited to 5% of total emissions in 2100. Finally, CO₂ emissions from deforestation are likely to peak before 2050 and decline thereafter. Factors that contribute to lower deforestation emissions are increasing scarcity of forests, slower population growth and further increases in agricultural productivity.

Under a multi-gas strategy using the 100-year GWPs, the contribution of the non-CO₂ gases in total reductions is very large early in the scenario period (50-60% in the first two decades). Later in the scenario period, the contribution of most gases becomes more proportional to their share in baseline emissions.

For most of the non-CO₂ gases, relatively cheap reduction options exist to reduce part of their emissions. A multi-gas approach using 100-year GWPs chooses to use these options for the non-CO₂ gases (which, in general, have high GWP values) as a crucial part of a cost-effective policy in the near term. As

a result, the contribution of CO₂ in the first two decades is limited to only 10-20% of total reductions, while the contribution of non-CO₂ gasses is 50-60% and sinks cover about 20-30% of the reductions. However, as overall, global reduction targets become increasingly tight with time, the lion's share of reductions needs to come from CO₂. A factor that contributes to this result, is that the current knowledge on abatement options for non-CO₂ gases for several sources only allows for reductions in the order of 20% of emissions (see further). This is, in particular, the case for hard-to-abate sources such as enteric fermentation and fertiliser application.

While the contribution of non-CO₂ gases in the mitigation scenarios remains limited to 20-30% by the end of the century, the impact of including non-CO₂ gases on total costs can be very large. In other words 'what flexibility' is very important in reducing costs.

In order to stabilise radiative forcing at 4.5 W/m², the marginal costs in 2100 of a multi-gas scenario is a factor of 2 lower than for the CO₂-only scenario. There are two important reasons for this. First of all, early in the scenario period the multi-gas approach strongly benefits from the low-cost non-CO₂ reduction options. Secondly, by the end of the scenario period, the reductions achieved by non-CO₂ abatement measures avoid the most expensive options for CO₂ that need to be taken for the CO₂-only scenario.

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

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

The contribution of other forcing agents—such as ozone and sulphur—are also impacted by the mitigation scenarios, even if policies do not target them deliberately.

The reduced negative forcing from sulphur aerosols increases total radiative forcing, while the reduced forcing from ozone might compensate this effect. The emissions from SO₂ (causing the formation of sulphur aerosols) and NO_x and VOC (the main precursors of ozone formations) all stem mainly from combustion of fossil fuels. The systematic changes in the energy sector induced by climate policies also reduce the emissions of these gases. As a result, both the negative forcing from sulphur and the positive forcing from tropospheric ozone seriously decreases for more stringent stabilisation scenarios. The impact on ozone forcing seems in the long term to offset the impact on sulphur. In the

first few decades, however, the impacts on sulphur forcing are considerably larger than those on ozone resulting in a relatively rapid rate of temperature increase (due to larger sulphur emissions and a more than proportional impact on the use of coal).

The abatement potential and reduction costs for non-CO₂ gases in the future represents a crucial uncertainty for current assessments on mitigation scenarios.

The information on non-CO₂ abatement options and their costs have been inventoried for EMF-21 mainly for 2010, and over a limited cost range of 0 to 200 US\$/tCeq. After 2010, the abatement potential of most gases is likely to increase as a result of technological progress and the reduction of implementation barriers. The rate at which these trends will evolve, however, are highly uncertain. Under the current implementation the cheap parts of the non-CO₂ MACs tend to get exhausted before the middle of the century in scenarios aiming to stabilise at 4.5 W/m² or below. This is reflected in the rapid drop in the share of the non-CO₂ gases in total reductions over time. It will be crucial to extend research on non-CO₂ emission reduction options beyond 2010. Questions are whether there are physical or economic barriers to reduce the non-CO₂ gases further; or whether technological development is likely to lead to major increases in the current abatement potential. We have assessed the impact of technology development in a series of sensitivity runs, showing the large impacts on the marginal price and overall costs.

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MULTI-GAS EMISSION REDUCTION FOR CLIMATE CHANGE POLICY: AN APPLICATION OF *FUND*

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Abstract

The costs of greenhouse gas emission reduction are investigated with abatement of carbon dioxide, methane, and nitrous oxide using the *FUND* model. The central policy scenario keeps anthropogenic radiative forcing below 4.5 Wm^{-2} . If CO_2 emission reduction were the only possibility to meet this target, the net present value of consumption losses would be \$45 trillion; with abatement of the other gases added, costs fall to \$33 trillion. The bulk of these costs savings can be ascribed to nitrous oxide. Because nitrous oxide is so much more important than methane, the choice of equivalence metric between the greenhouse gases does not matter much. Sensitivity analyses show that the shape of the cost curves for CH_4 and N_2O emission reduction matters, and that the inclusion of SO_2 and sulphate aerosols make policy targets substantially harder to achieve. The costs of emission reduction vary greatly with the choice of stabilisation target. A target of 4.5 Wm^{-2} is not justified by our current knowledge of the damage costs of climate change.

Key words

Climate change, emission reduction, carbon dioxide, methane, nitrous oxide

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1. Introduction

International climate policy has stalled. One of the reasons are the (perceived) high costs of implementation something like the Kyoto Protocol and the UNFCCC's ultimate aim of stabilising atmospheric concentrations of greenhouse gases. Options to reduce the costs of emission reduction are therefore worth investigating. Particularly, as oil prices are so high at the moment, options to reduce emissions without raising the price of petrol would increase the political feasibility of emission abatement. Reducing the emissions of methane (CH_4) and nitrous oxide (N_2O) are such options. Previous discussions have focussed on "where" flexibility (that is, the ability to shift emission reduction between countries) and on "when" flexibility (that is, the ability to shift emission reduction between periods). The ability to shift

emission reduction between gases may be referred to as “how” flexibility (Manne and Richels, 2000).

The economic literature on the costs of greenhouse gas emission reduction has focussed on carbon dioxide from industry and electricity (Hourcade *et al.*, 1996a,b, 2001). This is the largest single source of greenhouse gases. However, other sources are important too. Perhaps the explanation for the paucity of studies is that these other sources are hard to include into models that emphasize energy economics. Methane is emitted by coal mining and leakage from gas transport, but also by agriculture. Nitrous oxide originates from agriculture and a range of industrial processes. Another explanation is the lack of data on engineering solutions to CH₄ and N₂O emissions and their costs. Although there are a fair number of older of partial studies on emissions, options and costs (van Amstel, 1993; van Amstel *et al.*, 1993; EPA, 1993a,b,c, 1999; de Jager and Blok, 1993; van Ham, 1994, 2002; Kroeze, 1994; de Jager *et al.*, 1996a,b; AEAT, 1998; IEA GHG, 1998; Kruger *et al.*, 1998; Bates, 2000; Bates and Haworth, 2000), Tol (1999) and Tol *et al.* (2003)¹ had to extrapolate methane emission reduction costs curves from the Netherlands to the rest of the world. Reilly *et al.* (1999) were the first to report, albeit only graphically, an internally consistent, region specific set of cost curves. Things are changing rapidly now, particularly with the solid input from US EPA (2003). This new information is now being taken up by the models used for climate policy analysis. This study contributes to that.

A few previous studies have looked at multi-gas emission reduction. Tol (1999) looks at carbon dioxide and methane, finding that “how” flexibility is as important as “where” flexibility, with cost savings of up to 70%. Reilly *et al.* (1999) study emission reduction for all greenhouse gases, finding annual cost reductions of about 50%. They emphasize that emission reduction targets, if expressed relative to a base year, are sensitive to the gases included. The analysis of Manne and Richels (2000) is restricted to CO₂, CH₄ and N₂O. Their annual cost savings in 2010 are 20-50%, smaller than in Reilly *et al.* (1999). Jensen and Thelle (2001) include all Kyoto gases in a medium-term model; their welfare costs in the OECD fall by 20-35% due to the inclusion of other gases, but the countries of the former Soviet Union lose substantial revenue in the emission permit trade. The study by Tol *et al.* (2003) is restricted to carbon dioxide and methane. In contrast to the other multi-gas studies (including this one), it emphasizes the differences in the dynamics of the two gases in the economy, a factor that complicates the optimal trade-off between respective emission reductions. Tol *et al.* (2003) report cost savings of up to 70% by including methane only. Aaheim *et al.* (2004) use a simpler model than the previous studies. Their cost savings due to including the other gases is much smaller, only 10%, but their emission reduction target is much stricter. They also show that relative cost savings fall as the target gets stricter.

The current study differs from previous papers in using a different set of scenarios and sensitivity analyses, and using more reliable data on the costs of emission reduction. Nonetheless, new qualitative insights emerge as well. Section 2 presents the model used, *FUND2.7*. Section 3 shows the basic results and sensitivity analyses. Section 4 concludes.

2. The model

The model used is version 2.7 of the *Climate Framework for Uncertainty, Negotiation and Distribution (FUND)*. Version 2.7 of *FUND* corresponds to version 1.6, described and applied by Tol (1999a-e, 2001, 2002a), except for the impact module, which is described by Tol (2002b,c) and updated by Tol (2002d). A further difference is that the current version of the model distinguishes 16 instead of 9 regions. The current version of the model also includes

¹ Both studies were in fact done in 1998.

emission reduction for nitrous oxide (N₂O), not incorporated in earlier versions of *FUND*, as well as a new formulation of methane (CH₄) emission reduction.

Essentially, *FUND* consists of a set of exogenous scenarios and endogenous perturbations. The model distinguishes 16 major regions of the world, viz. the United States of America, Canada, Western Europe, Japan and South Korea, Australia and New Zealand, Central and Eastern Europe, the former Soviet Union, the Middle East, Central America, South America, South Asia, Southeast Asia, China, North Africa, Sub-Saharan Africa, and Small Island States. The model runs from 1950 to 2200 in time steps of one year. The prime reason for starting in 1950 is to initialize the climate change impact module. In *FUND*, the impacts of climate change are assumed to depend on the impact of the previous year, this way reflecting the process of adjustment to climate change. Because the initial values to be used for the year 1950 cannot be approximated very well, both physical and monetized impacts of climate change tend to be misrepresented in the first few decades of the model runs. The 22nd century is included to make sure that climate policies aimed at stabilizing concentrations indeed achieve that goal.

The period of 1950-1990 is used for the calibration of the model which is based on the *IMAGE* 100-year database (Batjes & Goldewijk, 1994). The climate scenarios for the period 2010-2200 are based on the EMF14 Standardized Scenario, which lies somewhere in between IS92a and IS92f (Leggett *et al.*, 1992).

The scenarios concern the rate of population growth, economic growth, autonomous energy efficiency improvements, the rate of decarbonization of the energy use (autonomous carbon efficiency improvements), and emissions of carbon dioxide from land use change, methane and nitrous oxide.

The scenarios of economic and population growth are perturbed by the impact of climatic change. Population decreases with increasing climate change related deaths that result from changes in heat stress, cold stress, malaria, and tropical cyclones. Heat and cold stress are assumed to have an effect only on the elderly, non-reproductive population. In contrast, the other sources of mortality also affect the number of births. Heat stress only affects the urban population. The share of the urban population among the total population is based on the World Resources Databases (WRI, 2000). It is extrapolated based on the statistical relationship between urbanization and per-capita income which are estimated from a cross-section of countries in 1995. Climate-induced migration between the regions of the world also cause the population sizes to change. Immigrants are assumed to assimilate immediately and completely with the respective host population.

The tangible impacts are dead-weight losses to the economy. Consumption and investment are reduced without changing the savings rate. Thus, climate change reduces the long-term economic growth, although for the short term the consumption is particularly affected. Economic growth is also reduced by carbon dioxide abatement measures.

The energy intensity of the economy and the carbon intensity of the energy supply autonomously decrease over time. This process can be accelerated by abatement policies.

The endogenous parts of *FUND* consist of the atmospheric concentrations of carbon dioxide, methane and nitrous oxide, the global mean temperature, the impact of carbon dioxide emission reductions on the economy and on emissions, and the impact of the damages to the economy and the population caused by climate change.

Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted:

$$(1) \quad C_t = C_{t-1} + \alpha E_t - \beta (C_{t-1} - C_{pre})$$

where C denotes the concentration, E the emissions, t the year, and pre the pre-industrial concentration. Table 1 lists the parameters for both gases.

The atmospheric concentration of carbon dioxide, measured in parts per million by volume, is derived from a five-box model:

$$(2a) \quad Box_{i,t} = \rho_i Box_{i,t-1} + 0.000471 \alpha_i E_t$$

where

$$(2b) \quad C_t = \sum_{i=1}^5 \alpha_i Box_{i,t}$$

Here α_i denotes the fraction of emissions E (in million metric tons of carbon) that is allocated to box i (0.13, 0.20, 0.32, 0.25 and 0.10 respectively) and ρ the rate of decay of the boxes ($\rho = \exp(-1 / \text{life time})$). The life times in the boxes are ∞ , 363, 74, 17, and 2 years respectively. This model is based on Maier-Reimer and Hasselmann (1987). Its parameters are taken from Hammitt *et al.* (1992). According to this model, 13 per cent of total emissions remain in the atmosphere indefinitely, while 10 per cent are removed within an average time period of two years.

The radiative forcing of carbon dioxide, methane and nitrous oxide is determined based on Shine *et al.* (1990). The global mean temperature T is governed by a geometric build-up to its equilibrium (determined by the radiative forcing RF), with a half-life of 50 years. In the base case, the global mean temperature rises in equilibrium by 2.5°C for a doubling of carbon dioxide equivalents, so:

$$(3) \quad T_t = \left(1 - \frac{1}{50}\right) T_{t-1} + \frac{1}{50} \frac{2.5}{6.3 \ln(2)} RF_t$$

Regional temperature follows from multiplying the global mean temperature by a fixed factor, which corresponds to the spatial climate change pattern averaged over 14 GCMs (Mendelsohn *et al.*, 2000). The global mean sea level is also geometric, with its equilibrium level determined by the temperature and a half-life of 50 years. Both temperature and sea level are calibrated to correspond to the best guess temperature and sea level for the IS92a scenario of Kattenberg *et al.* (1996).

The climate impact module is based on Tol (2002b,c). The following impact categories of climate change are considered: agriculture, forestry, sea level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhea, energy consumption, water resources, and unmanaged ecosystems.

People can die prematurely due to temperature stress or vector-borne diseases, or they can migrate because of sea level rise. Like all impacts of climate change, these effects are monetized. The value of a statistical life is set to be 200 times the annual per capita income. The resulting value of a statistical life lies in the middle of the observed range of values in the literature (cf. Cline, 1992). The value of emigration is set to be 3 times the per capita income (Tol, 1995, 1996), the value of immigration is 40 per cent of the per capita income in the host region (Cline, 1992). Losses of dryland and wetlands due to sea level rise are modeled explicitly. The monetary value of a loss of one square kilometer of dryland was on average \$4 million in OECD countries in 1990 (cf. Fankhauser, 1994). Dryland value is assumed to be proportional to GDP per square kilometer. Wetland losses are valued at \$2 million per square kilometer on average in the OECD in 1990 (cf. Fankhauser, 1994). The wetland value is assumed to have logistic relation to per capita income. Coastal protection is based on cost-

benefit analysis, including the value of additional wetland lost due to the construction of dikes and subsequent coastal squeeze.

Other impact categories, such as agriculture, forestry, energy, water, and ecosystems, are directly expressed in monetary values without an intermediate layer of impacts measured in their ‘natural’ units (cf. Tol, 2002b).

Climate change related damages can be attributed to either the rate of change (benchmarked at 0.04°C/yr) or the level of change (benchmarked at 1.0°C). Damages from the rate of temperature change slowly fade, reflecting adaptation (cf. Tol, 2002c).

Impacts of climate change on energy consumption, agriculture, and cardiovascular and respiratory diseases explicitly recognize that there is a climatic optimum which is determined by a variety of factors, including plant physiology and the behavior of farmers. Impacts are positive or negative depending on whether the actual climate conditions are moving closer to or away from that optimum climate. Impacts are larger if the initial climate conditions are further away from the optimum climate. The optimum climate is of importance with regard to the potential impacts. The actual impacts lag behind the potential impacts, depending on the speed of adaptation. The impacts of not being fully adapted to new climate conditions are always negative (cf. Tol, 2002c).

The impacts of climate change on coastal zones, forestry, unmanaged ecosystems, water resources, malaria, dengue fever, and schistosomiasis are modeled as simple power functions. Impacts are either negative or positive, and do not change sign (cf. Tol, 2002c).

Vulnerability to climate change changes with population growth, economic growth, and technological progress. Some systems are expected to become more vulnerable, such as water resources (with population growth), heat-related disorders (with urbanization), and ecosystems and health (with higher per capita incomes). Other systems are projected to become less vulnerable, such as energy consumption (with technological progress), agriculture (with economic growth) and vector- and water-borne diseases (with improved health care) (cf. Tol, 2002c).

Carbon dioxide emissions are calculated on the basis of the Kaya identity:

$$(4) \quad M_{r,t} = \frac{M_{r,t}}{E_{r,t}} \frac{E_{r,t}}{Y_{r,t}} \frac{Y_{r,t}}{P_{r,t}} P_{r,t} =: \psi_{r,t} \phi_{r,t} Y_{r,t}$$

where M denotes emissions, E denote energy use, Y denotes GPD and P denotes population; t is the index for time, r for region. The carbon intensity of energy use, and the energy intensity of production follow from:

$$(5) \quad \psi_{r,t} = g_{r,t-1}^{\psi} \psi_{r,t-1} - \alpha \tau_{r,t-1}^{\psi}$$

and

$$(6) \quad \phi_{r,t} = g_{r,t-1}^{\phi} \phi_{r,t-1} - \alpha \tau_{r,t-1}^{\phi}$$

where τ is policy intervention and α is a parameter. Policy also affects emissions via

$$(4') \quad M_{r,t} = (\psi_{r,t} - \chi_{r,t}^{\psi})(\phi_{r,t} - \chi_{r,t}^{\phi}) Y_{r,t}$$

$$(7) \quad \chi_{r,t}^{\psi} = \kappa_{\psi} \chi_{r,t-1}^{\psi} + (1 - \alpha) \tau_{r,t-1}^{\psi}$$

and

$$(8) \quad \chi_{r,t}^{\phi} = \kappa_{\phi} \chi_{r,t-1}^{\phi} + (1 - \alpha) \tau_{r,t-1}^{\phi}$$

Thus, the parameter $0 < \alpha < 1$ governs which part of emission reduction is *permanent* (reducing carbon and energy intensities at all future times) and which part of emission reduction is *temporary* (reducing current energy consumptions and carbon emissions), fading at a rate of $0 < \kappa < 1$. In the base case, $\alpha = 0.5$, $\kappa_{\psi} = \kappa_{\phi} = 0.9$. Alternatively, one may interpret the difference between permanent and temporary emission reduction as affecting commercial technologies and capital stocks, respectively. The behaviour of the emission reduction module is similar to that of the models of Grubb *et al.* (1995), Ha-Duong *et al.* (1997) and Hasselmann *et al.* (1997). It is a reduced form way of modelling that part of the emission reduction fades away after the policy intervention is reversed, but that another part remains through technological lock-in. Learning effects are described below.

The costs of emission reduction C are given by

$$(9) \quad \frac{C_{r,t}}{Y_{r,t}} = \frac{\beta_{r,t} \tau_{r,t}^2}{H_{r,t} H_t^g}$$

H denotes the stock of knowledge. Equation (9) gives the costs of emission reduction in a particular year for emission reduction in that year. In combination with Equations (5)-(8), emission reduction is cheaper if smeared out over a longer time period. The parameter β follows from

$$(10) \quad \beta_{r,t} = 1.57 - 0.17 \sqrt{\frac{M_{r,t}}{Y_{r,t}} - \min_s \frac{M_{s,t}}{Y_{s,t}}}$$

That is, emission reduction is relatively expensive for the region that has the lowest emission intensity.² The calibration is such that a 10% emission reduction cut in 2003 would cost 1.57% (1.38%) of GDP of the least (most) carbon-intensive region, and a 80% (85%) emission reduction would completely ruin its economy; later emission reductions are cheaper by Equations (10) and (11). Emission reduction is relatively cheap for regions with high emission intensities. The thought is that emission reduction is cheap in countries that use a lot of energy and rely heavily on fossil fuels, while other countries use less energy and less fossil fuels and are therefore closer to the technological frontier of emission abatement.³ The model has been calibrated to the results reported in Hourcade *et al.* (1996); for relatively small emission reduction, the costs in *FUND* correspond closely to those reported by other top-down models, but for higher emission reduction, *FUND* finds higher costs, because *FUND* does not include backstop technologies, that is, a carbon-free energy supply that is available in unlimited quantities at fixed average costs.

The regional and global knowledge stocks follow from

$$(11) \quad H_{r,t} = H_{r,t-1} \sqrt{1 + \gamma_R \tau_{r,t-1}}$$

and

$$(12) \quad H_t^G = H_{t-1}^G \sqrt{1 + \gamma_G \tau_{r,t}}$$

Knowledge accumulates with emission abatement. More knowledge implies lower emission reduction costs. Equations (9) and (11) together constitute learning by doing. The parameters γ determines which part of the knowledge is kept within the region, and which part spills over

² The model disregards potential advantages of leading in technology, e.g., through exports and patents.

³ Note that “cheap” should read “cheap per unit of emission reduction”; the total costs of emission reduction, of course, depend on the costs per unit as well as the total emission reduction obligation. The USA (EU) has high (low) costs under the Kyoto Protocol not because its emission reduction is expensive (cheap) but because its emission reduction target is high (low).

to other regions as well. In the base case, $\gamma_R=0.9$ and $\gamma_G=0.1$. The model is similar in structure and numbers to that of Goulder and Schneider (1999) and Goulder and Mathai (2000). Note that, although there is learning by doing – Equations (11) and (12) – technology diffusion – Equation (10) – as well as permanent effects of emission reduction on the growth path of the economy – Equations (7) and (8) – the model does assume that policy interventions are always costly, and that larger interventions are more costly.

The costs of methane and nitrous oxide emission reduction are based on the analysis of the USEPA (2003). They report supply curves of emission reduction, stating how much can be abatement at a certain price. First, these supply curves were shifted to exclude negative costs. Note that this increases costs. Second, emission reductions were expressed as fractions of baseline emissions. Third, total emission reduction costs (the area under the supply curve) was calculated, and expressed as a fraction of GDP. Fourth, the regional results of the EPA analysis was attributed to the *FUND* regions. Fifth, the bottom-up curve was approximated with a smooth exponential function. Sixth, the exponential curve was approximated with a quadratic curve. Note that this decreases costs. Table 2 shows the parameters for methane, Table 3 for nitrous oxide. Initially, the quadratic cost curve was supposed to function as sensitivity analysis. However, the quadratic cost curve has the advantage that both costs and marginal costs are zero at zero emission reduction. The exponential cost curve has total costs equal to zero at zero emission reduction, but marginal costs are greater than zero. This implies that, for a low carbon price, methane and nitrous oxide emission reduction are zero, while carbon dioxide emission reduction is not. On the other hand, large emission reduction is cheaper with the quadratic specification than with the exponential one. Nonetheless, we prefer the quadratic specification over the exponential one.

Another change in the model is the addition of sulphur dioxide (SO₂) emissions and sulphate aerosols concentrations. SO₂ emissions are calibrated to the IMAGE 2.2 model (IMAGE Team, 2001). SO₂ emissions are proportional to the amount of fossil fuel used and fall with per capita income, using an income elasticity of 0.45. Direct radiative forcing of sulphate aerosols is assumed to be linear in SO₂ emissions. Indirect radiative forcing is assumed to be logarithmic in emissions. The exact specification is

$$(x) \quad RF(SO_2) = \frac{0.3}{14.6} SO_2 + 0.8 \frac{\ln\left(1 + \frac{SO_2}{34.4}\right)}{\ln\left(1 + \frac{14.6}{34.4}\right)}$$

where 14.6 TgS are the anthropogenic emissions in 1950 and 34.4 TgS are the natural emissions, which are kept constant. The climate module is recalibrated so that the global mean temperature in the period 1950-2000 roughly matches observations.

3. Results

3.1. Emission reduction with 1, 2 and 3 gases

The central policy scenario aims to keep additional radiative forcing below 4.5 Wm⁻². We compare the result if this goal is met with only carbon dioxide emission reduction, with all three greenhouse gases, and with CO₂ plus one of the others. Figure 1 shows the atmospheric concentrations of carbon dioxide in case with CO₂ only and with the three gases; Figure 1 also includes the business as usual scenario. As expected, with the other two gases added, the cuts in CO₂ emissions are less; however, the difference is not that large, as the target of 4.5 Wm⁻² is fairly strict. Figure 2 shows the atmospheric concentrations of methane. Concentrations

would be cut substantially, particularly towards the end of the century, and even more so if nitrous oxide emission reduction is excluded. Figure 3 shows the atmospheric concentrations of nitrous oxide. Compared to methane, emission reduction is spread more smoothly over the century, while the omission of methane emission reduction has little effect.

Figure 4 shows the net present value of the loss of consumption due to emission reduction in the OECD, Eastern Europe and the former Soviet Union, and developing countries. With all three gases, meeting the target of 4.5 Wm^{-2} would cost \$32.9 trillion. This number is so high because the target is so strict. With CO_2 emission reduction only, the costs would rise to \$44.6 trillion. Methane and nitrous oxide emission reduction thus reduce costs by some 26%, substantially less than reported elsewhere (see Section 1). Most of the cost saving is due to nitrous oxide. Without N_2O , the costs would be \$41.4 trillion. Without CH_4 , the costs would be \$33.3 trillion.

Figure 5 shows the consumption losses over time, which reach about 9% in 2100 with all three gases and exceed 10% with CO_2 only; a 10% loss of consumption from baseline in a century represents a loss of 5 years of growth. Figure 5 also shows the cost savings due to the other greenhouse gases. In the earlier years, cost savings exceed 50% but this falls to 15% by 2100. The reason is that methane and nitrous oxide emission reductions are cheap compared to carbon dioxide emission reduction, but are only limited in scope: substantial greenhouse gas emission reduction requires substantial carbon dioxide emission reduction. The cost savings in the earlier years correspond much better to the previous literature.

3.2. Sulphur dioxide

Sulphur dioxide was not considered in previous versions of the *FUND* model, but it is in this one. Sulphur dioxide emissions are turned into sulphate aerosols which have only a short life time in the atmosphere, but have a substantial cooling effect nonetheless. Sulphur dioxide originates from fossil fuel burning, just like carbon dioxide does. Sulphur dioxide emissions would fall with carbon dioxide emissions, which may imply additional warming in the short run. Sulphur dioxide thus partly offsets carbon dioxide emission reduction, and would make radiative forcing targets harder to achieve.

Figure 6 shows the atmospheric concentrations of carbon dioxide for a policy aiming at a stabilisation at 4.5 Wm^{-2} , with and without CH_4 and N_2O , and with and without SO_2 . In all four cases, emissions are drastically cut because the target is stringent. With CO_2 only, the extra emission reduction due to SO_2 is smaller than with all three greenhouse gases. This is because, without CH_4 and N_2O , CO_2 and hence SO_2 emissions are lower. Without SO_2 , the gap between CO_2 only and 3G is larger than with SO_2 . This is because, as the target gets stricter (and it does so, albeit implicitly, by considering SO_2), CH_4 and N_2O emission reduction reach their technical potential earlier and more of the burden is shifted to CO_2 . Figure 7 shows the net present value of the consumption losses. Without SO_2 , costs would be \$28.2 (23.1) trillion less with all three gases (CO_2 only).

3.3. Alternative cost functions

In Section 2, the reasons for preferring a quadratic cost function over an exponential one are presented. Here, I show the result for an exponential cost curve. Tables 2 and 3 show the parameters. The main differences are that, with an exponential cost curve, the marginal costs of emission reduction are greater than nought at zero emission reduction, and that drastic emission reduction is more expensive. As a result, greenhouse gas emission reduction is more expensive in the early decades as well as in the later decades, but may be cheaper in between.

Figure 2 (methane) and Figure 3 (nitrous oxide) indeed show that the other gases are less reduced with an exponential cost function. As a result, emission reduction costs, as measured by the net present value of consumption loss, go up. As shown in Figure 7, costs increase by \$4.8 trillion.

3.4. Trade-offs between gases

Above, all trade-offs between the three greenhouse gases is based on the 100-year global warming potentials (GWPs) published by the IPCC; see Table 1. This is the set of equivalences accepted by the UNFCCC, but it is now widely acknowledged that GWPs have limited validity in the natural sciences (Smith and Wigley, 2000a,b), and no validity in economics or policy (Reilly and Richards, 1993; Schmalensee, 1993; Kandlikar, 1995, 1996; Hammitt *et al.*, 1996; Lashof, 2000; O'Neill, 2000; Manne and Richels, 2001; Godal and Fuglestad, 2002; Sygna *et al.*, 2002). In a cost-benefit analysis, the proper equivalence between CO₂ and, say, CH₄ is the ratio of the marginal damage costs. In a cost-effectiveness analysis (as is done here), the proper equivalence is the ratio of the shadow prices. With a radiative forcing target, alternative greenhouse gas share the same shadow price of the constraint, and the ratio is determined by the relative contribution to radiative forcing in the binding period. This particularly affects methane, which has a life-time that is much shorter than that of nitrous oxide and carbon dioxide. If the target is relatively far into the future, current methane emission reduction contributes much less than does carbon dioxide and nitrous oxide emission reduction.

With a target of 4.5 Wm⁻², the turning point lies around 2070. The dynamics of the baseline scenario and emission abatement are such that, if radiative forcing is below 4.5 Wm⁻² in 2070, it is below that target for the entire period. Therefore, emissions of the three gases are compared as to their contribution to radiative forcing in 2070 following the gas dynamics and radiative forcing as specified in *FUND*. Emissions after 2070 are treated as emissions in the period 2060-2070.

Figures 2 (methane) and 3 (nitrous oxide) show the results. As expected, methane emission reduction is less in the first decades but more in the later years. This allows for a slight reduction in abatement of carbon dioxide (results not shown) and nitrous oxide (see Figure 3). As a consequence, emission reduction costs fall. See Figure 7. However, the reduction in costs is only \$0.1 trillion. This is again due to the stringent target, which necessitates deep cuts in carbon dioxide (and nitrous oxide) emissions regardless of the cuts in methane emissions.

3.5. The choice of target

In the scenarios above, the radiative forcing target is 4.5 Wm⁻². This is a fairly ambitious target, as can be seen from the low CO₂ concentrations and the high costs. It roughly corresponds to the EU target of letting the global mean temperature not rise more than 2°C above today's temperatures. The justification for this target is very weak. It is based on the argument that this is the maximum temperature that the human species has experienced in its existence. However, subsidies to agriculture are also at its historical peak, as are democracy and communication technology, and the EU does not seem to object to that. I therefore vary the target.

Figure 8 shows the atmospheric concentration of carbon dioxide for radiative forcing targets of 4.0, 4.5, 5.5, 6.5 and 7.5 Wm⁻². The 4.0 Wm⁻² target is used rather than a 3.5 Wm⁻² target because the latter cannot be achieved. This is another indication that the 4.5 Wm⁻² is very

ambitious. Figure 8 also depicts the business as usual scenario, and an optimal control scenario. In the optimal control scenario, the target is not a random number but based on considerations of welfare maximisation. Based on a meta-analysis of 28 studies, Tol (forthcoming) estimates that the current Pigou tax on carbon dioxide emissions should be \$7/tC. This is the carbon tax used in 2010; the carbon tax increase by 5% per year after that. Under this scenario, radiative forcing reaches 7.5 Wm^{-2} in 2200, but peaks at 8.8 Wm^{-2} in 2130.

Figure 9 shows the net present value of the consumption losses. For the 4.5 Wm^{-2} target, costs are a hefty \$33 trillion; for the 4.0 Wm^{-2} target, this goes up to a staggering \$75 trillion. For 7.5 Wm^{-2} , costs fall to \$5 trillion, while the optimal policy costs only \$2 trillion. If the EU policy target is adopted, \$31 trillion would be overspent.

Figure 9 also shows the net present value of the consumption losses for the same targets with carbon dioxide emission reduction only. Costs increase substantially in all cases.⁴ The cost savings due to methane and nitrous oxide emission abatement change with the stringency of the target, but not monotonously so. If the target is very strict, meeting it with CO_2 only is almost impossible. If the target is somewhat less strict, the role of CH_4 and N_2O falls. However, if the target gets looser still, CH_4 and N_2O emission abatement options get saturated less quickly, and these gases increase in importance again. Finally, if the target gets even looser, CH_4 and N_2O become less important, because the need to drive CO_2 emissions to zero in the long term becomes the dominant effect. It can be expected that the relative importance of CH_4 and N_2O depends strongly on model and baseline scenario as well.

5. Discussion and conclusion

The following results emerge from the analyses above. First, how flexibility matters. It can help reducing the costs of greenhouse gas emission reduction by between 26 and 43% depending on the long-term abatement target. However, if the abatement target is stringent, methane and nitrous oxide emission reduction can only offset carbon dioxide emissions by so much. In fact, if the aim is to stabilise atmospheric stabilisation, then net emissions of carbon dioxide need to be reduced to (almost) zero, regardless of methane and nitrous oxide.

Second, nitrous oxide is more important than is methane. As a corollary, the discussion about the appropriate exchange rate between greenhouse gases is a fairly academic one, as alternative global warming potentials differ substantially for methane but much less for nitrous oxide.

Third, sulphate aerosols matter. Sulphate aerosols make climate policy substantially harder. Sulphate aerosols also make that radiative forcing, rather than concentrations, is the appropriate aim for climate policy.

The results in this paper should be interpreted with the usual caution. *FUND* is a fairly aggregate model, so that emissions from methane and nitrous oxide are not really tied to economic activity. This also hampers CH_4 and N_2O emission reduction. Emission reduction costs are static, reflecting neither technological change nor changes in economic structure. The current analysis neglects that carbon dioxide emission reduction is represented in the model as a mix of end-of-pipe and structural measures (so that, should policy stop, emissions would not bounce back to the business as usual scenario) while methane and nitrous oxide measures are end-of-pipe only (so that emissions would bounce back). The climate module of *FUND* is fairly simple, perhaps distorting the trade-offs between the greenhouse gases.

⁴ except the for “optimal” carbon tax; in this case, the costs of carbon dioxide emission reduction are the same, but the costs for methane and nitrous oxide emission reduction are zero in one case and positive in the other

Although a lot of research remains to be done, two conclusions are likely to be robust. First, methane and particularly nitrous oxide emission reduction are options to limit the total costs of greenhouse gas emission reduction and so increase the political feasibility of climate policy. Second, methane and nitrous oxide emission reductions offset only a part of carbon dioxide emission reduction.

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Table 1. Parameters of equation (1) (based on Schimel *et al.*, 1996)

gas	α^a	β^b	pre-industrial concentration	GWP
methane (CH ₄)	0.3597	1/8.6	790 ppbv	21
Nitrous oxide (N ₂ O)	0.2079	1/120	285 ppbv	310

^a The parameter α translates emissions in millions of metric tons of CH₄ or N₂O into concentrations in parts per billion by volume.

^b The parameter β determines how fast concentrations return to their pre-industrial (and assumed equilibrium) concentrations; the reciprocal of β is the atmospheric life time of the gases in years.

Table 2. Parameters of the methane emission reduction cost curve.

	Quadratic			Exponential - constant			Exponential - exponent		
USA	5.74E-04	(4.15E-04	7.90E-04)	5.43E-06	(4.44E-06	6.64E-06)	10.28	(9.66	10.90)
CAN	1.20E-03	(8.70E-04	1.64E-03)	7.69E-06	(6.30E-06	9.37E-06)	12.49	(11.75	13.23)
WEU	3.71E-04	(2.34E-04	5.80E-04)	1.82E-06	(1.37E-06	2.43E-06)	14.27	(13.10	15.45)
JPK	1.27E-04	(8.75E-05	1.84E-04)	4.19E-07	(3.32E-07	5.29E-07)	17.43	(16.23	18.63)
ANZ	4.12E-03	(3.03E-03	5.57E-03)	1.25E-05	(1.03E-05	1.51E-05)	18.18	(17.14	19.21)
EEU	3.90E-03	(2.81E-03	5.38E-03)	3.13E-05	(2.56E-05	3.83E-05)	11.17	(10.49	11.85)
FSU	8.87E-03	(7.49E-03	1.05E-02)	8.51E-05	(7.65E-05	9.46E-05)	10.21	(9.89	10.52)
MDE	6.32E-03	(4.86E-03	8.19E-03)	1.26E-05	(1.07E-05	1.49E-05)	22.38	(21.29	23.47)
CAM	3.65E-03	(2.87E-03	4.62E-03)	1.30E-05	(1.12E-05	1.51E-05)	16.77	(16.03	17.52)
SAM	2.75E-02	(1.81E-02	4.14E-02)	4.07E-06	(3.14E-06	5.27E-06)	82.24	(75.89	88.58)
SAS	3.16E-02	(2.43E-02	4.08E-02)	2.51E-05	(2.13E-05	2.95E-05)	35.45	(33.74	37.16)
SEA	1.43E-02	(1.06E-02	1.91E-02)	1.94E-05	(1.62E-05	2.33E-05)	27.15	(25.66	28.65)
CHI	1.26E-02	(9.50E-03	1.67E-02)	3.18E-05	(2.67E-05	3.80E-05)	19.93	(18.88	20.97)
MAF	1.43E-02	(1.06E-02	1.91E-02)	1.94E-05	(1.62E-05	2.33E-05)	27.15	(25.66	28.65)
SSA	1.43E-02	(1.06E-02	1.91E-02)	1.94E-05	(1.62E-05	2.33E-05)	27.15	(25.66	28.65)
SIS	1.43E-02	(1.06E-02	1.91E-02)	1.94E-05	(1.62E-05	2.33E-05)	27.15	(25.66	28.65)

Table 3. Parameters of the nitrous oxide emission reduction cost curve.

	Quadratic	Exponential - constant	Exponential - exponent
USA	2.14E-05 (1.91E-05 2.39E-05)	1.36E-08 (1.29E-08 1.45E-08)	39.61 (38.56 40.65)
CAN	6.92E-05 (6.29E-05 7.60E-05)	1.62E-08 (1.54E-08 1.70E-08)	65.33 (63.88 66.78)
WEU	7.26E-06 (6.60E-06 7.98E-06)	1.97E-08 (1.88E-08 2.08E-08)	19.18 (18.75 19.60)
JPK	5.32E-07 (3.21E-07 8.57E-07)	9.54E-09 (7.38E-09 1.23E-08)	7.46 (6.60 8.33)
ANZ	2.08E-04 (1.89E-04 2.29E-04)	4.62E-09 (4.39E-09 4.86E-09)	212.40 (207.68 217.11)
EEU	9.39E-05 (8.89E-05 9.93E-05)	8.35E-08 (7.91E-08 8.83E-08)	33.53 (33.53 33.53)
FSU	1.05E-05 (1.00E-05 1.10E-05)	1.94E-08 (1.91E-08 1.98E-08)	23.25 (22.91 23.60)
MDE	1.05E-05 (1.00E-05 1.10E-05)	1.94E-08 (1.91E-08 1.98E-08)	23.25 (22.91 23.60)
CAM	2.35E-04 (2.19E-04 2.53E-04)	2.00E-08 (1.89E-08 2.13E-08)	108.39 (107.83 108.95)
SAM	1.05E-05 (1.00E-05 1.10E-05)	1.94E-08 (1.91E-08 1.98E-08)	23.25 (22.91 23.60)
SAS	5.64E-04 (5.29E-04 6.01E-04)	1.71E-07 (1.62E-07 1.80E-07)	57.44 (57.14 57.74)
SEA	2.55E-15 (2.16E-15 3.01E-15)	4.72E-18 (4.12E-18 5.40E-18)	23.25 (22.91 23.60)
CHI	2.16E-05 (2.02E-05 2.30E-05)	1.42E-07 (1.35E-07 1.50E-07)	12.32 (12.26 12.39)
MAF	1.05E-05 (1.00E-05 1.10E-05)	1.94E-08 (1.91E-08 1.98E-08)	23.25 (22.91 23.60)
SSA	1.05E-05 (1.00E-05 1.10E-05)	1.94E-08 (1.91E-08 1.98E-08)	23.25 (22.91 23.60)
SIS	1.05E-05 (1.00E-05 1.10E-05)	1.94E-08 (1.91E-08 1.98E-08)	23.25 (22.91 23.60)

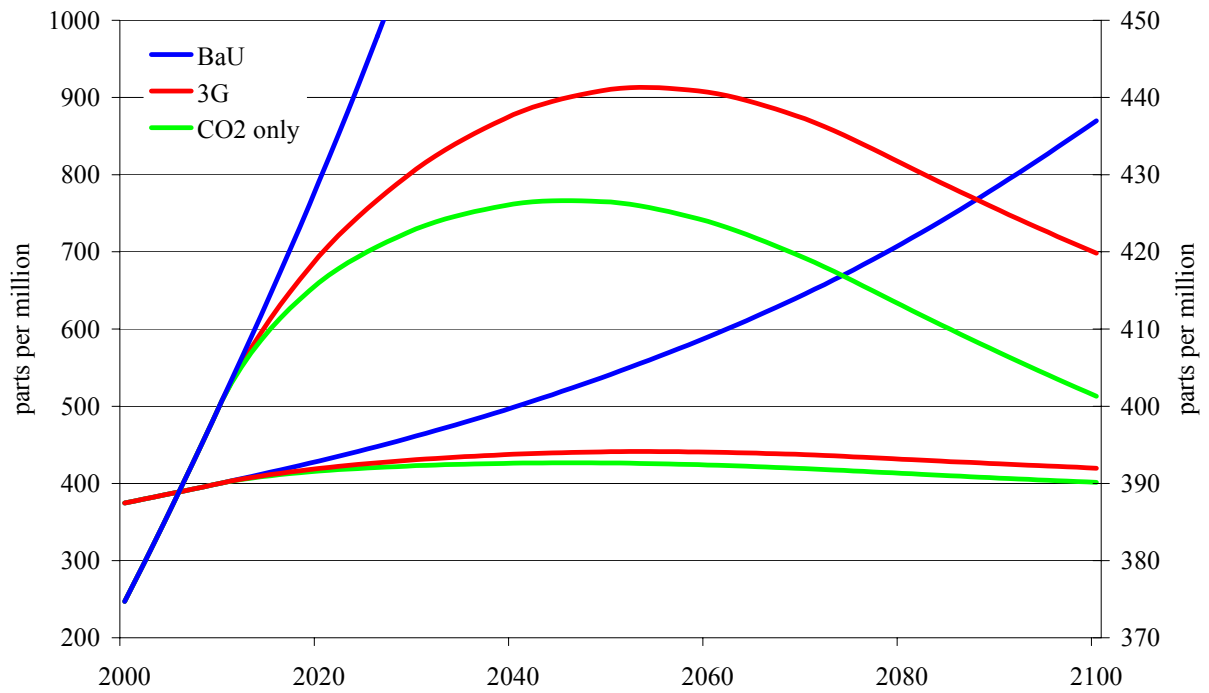


Figure 1. The atmospheric concentration of carbon dioxide for the business as usual scenario and two scenarios keeping anthropogenic radiative forcing below 4.5 Wm^{-2} , one with only CO₂ emission reduction, and one with CO₂, CH₄ and N₂O emission reduction (3G). The scenario on the left and right axis are identical, but displayed at a different scale.

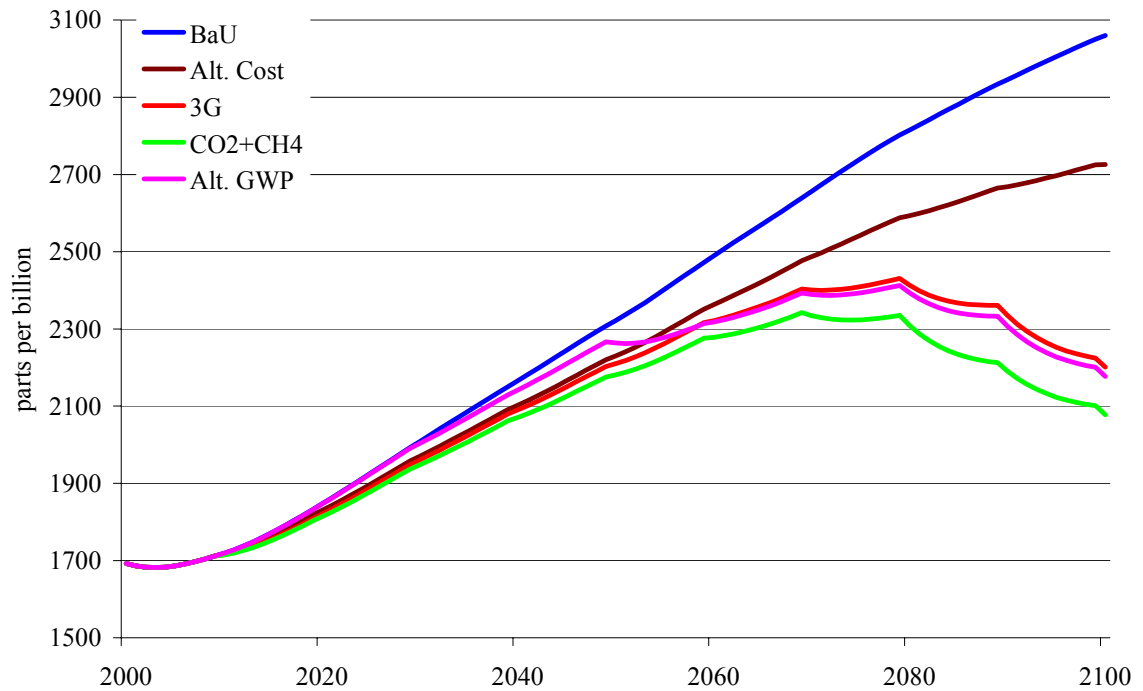


Figure 2. The atmospheric concentration of methane for the business as usual scenario and four scenarios keeping anthropogenic radiative forcing below 4.5 Wm^{-2} ; one with only CO₂ and CH₄ emission reduction, and three with CO₂, CH₄ and N₂O emission reduction (3G, Alt. Cost, Alt. GWP). The “Alt. Cost” scenario uses exponential cost curves for methane and nitrous oxide rather than quadratic ones; the “Alt. GWP” scenario uses the actual contribution to radiative forcing in 2070 rather than the IPCC 100-year GWPs.

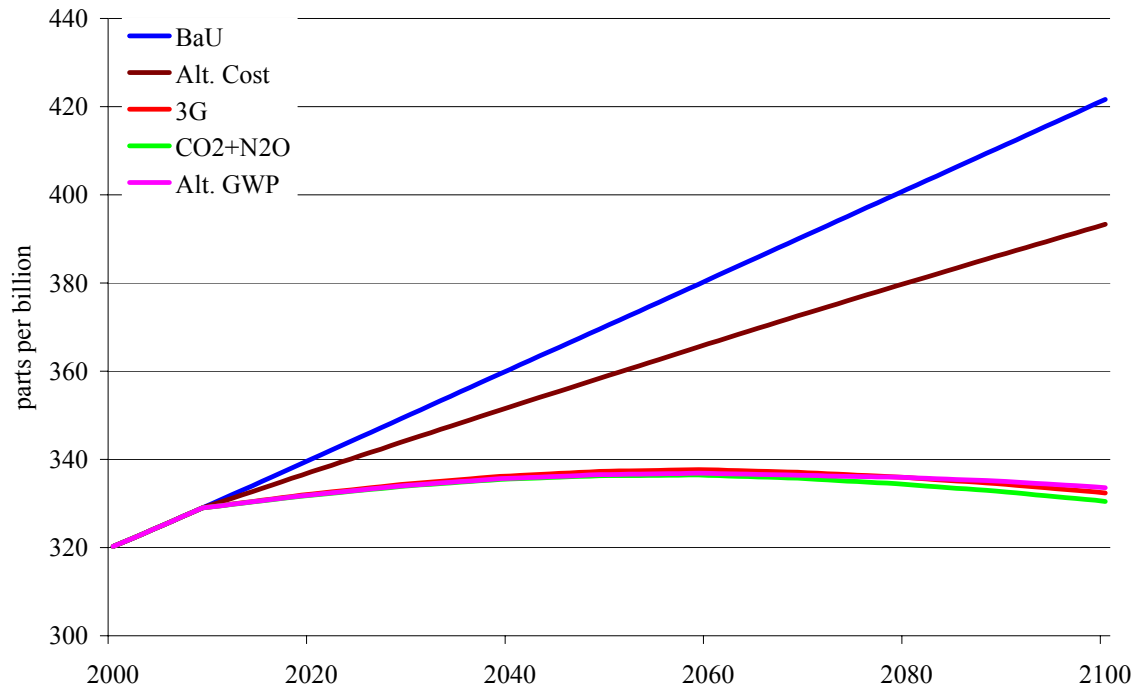


Figure 3. The atmospheric concentration of nitrous oxide for the business as usual scenario and four scenarios keeping anthropogenic radiative forcing below 4.5 Wm^{-2} ; one with only CO₂ and N₂O emission reduction, and three with CO₂, CH₄ and N₂O emission reduction (3G, Alt. Cost, Alt. GWP). The “Alt. Cost” scenario uses exponential cost curves for methane and nitrous oxide rather than quadratic ones; the “Alt. GWP” scenario uses the actual contribution to radiative forcing in 2070 rather than the IPCC 100-year GWPs.

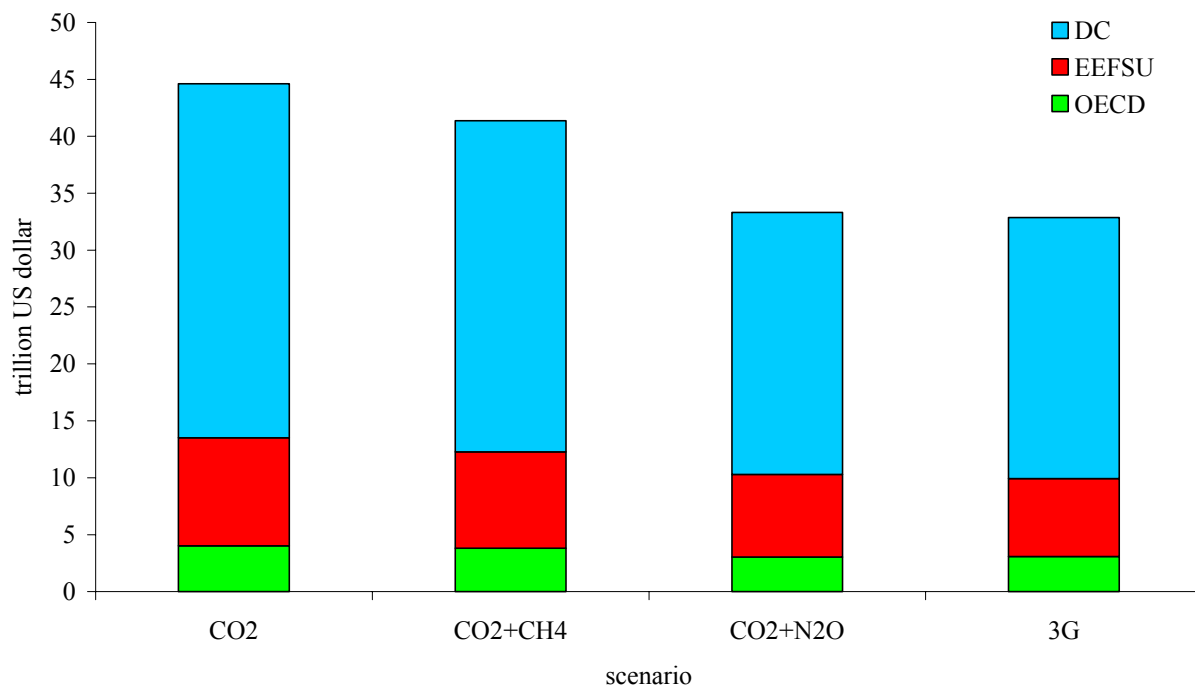


Figure 4. The net present value of consumption losses due to alternative policies to keep anthropogenic radiative forcing below 4.5 Wm^{-2} , viz. only CO₂ emission reduction, CO₂ and CH₄ emission reduction, CO₂ and N₂O emission reduction, and emission reduction with all three gases (3G).

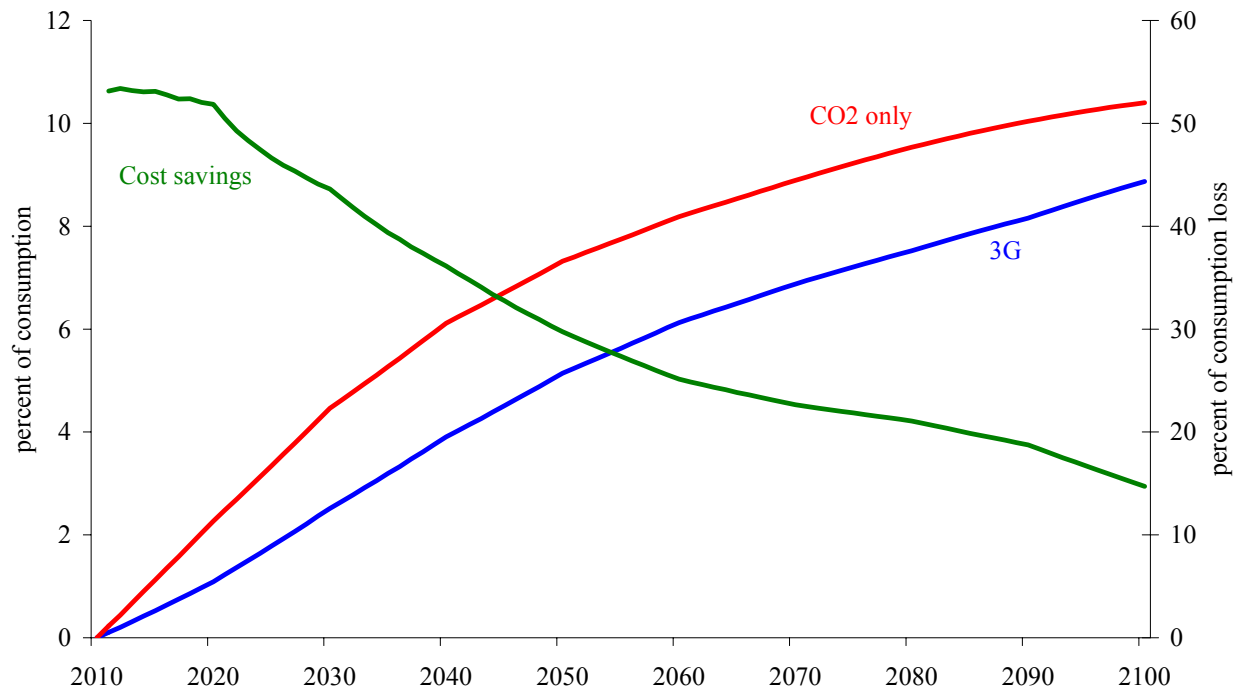


Figure 5. Annual world consumption losses (left axis) due to alternative policies (3G: three gases; CO₂ only) to keep anthropogenic radiative forcing below 4.5 Wm⁻²; the cost savings due to the other gases is shown on the right axis.

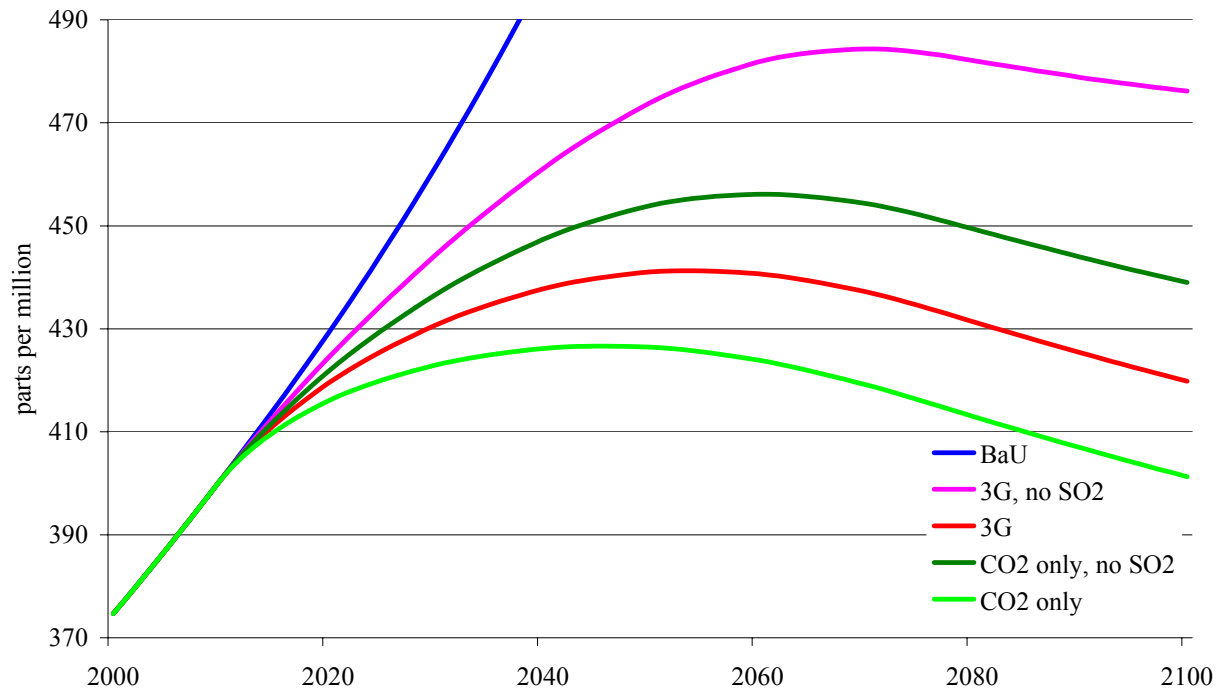


Figure 6. The atmospheric concentration of carbon dioxide for the business as usual scenario and four scenarios keeping anthropogenic radiative forcing below 4.5 Wm^{-2} , two with only CO_2 emission reduction, and two with CO_2 , CH_4 and N_2O emission reduction (3G). A further distinction between the scenarios is whether or not SO_2 is included.

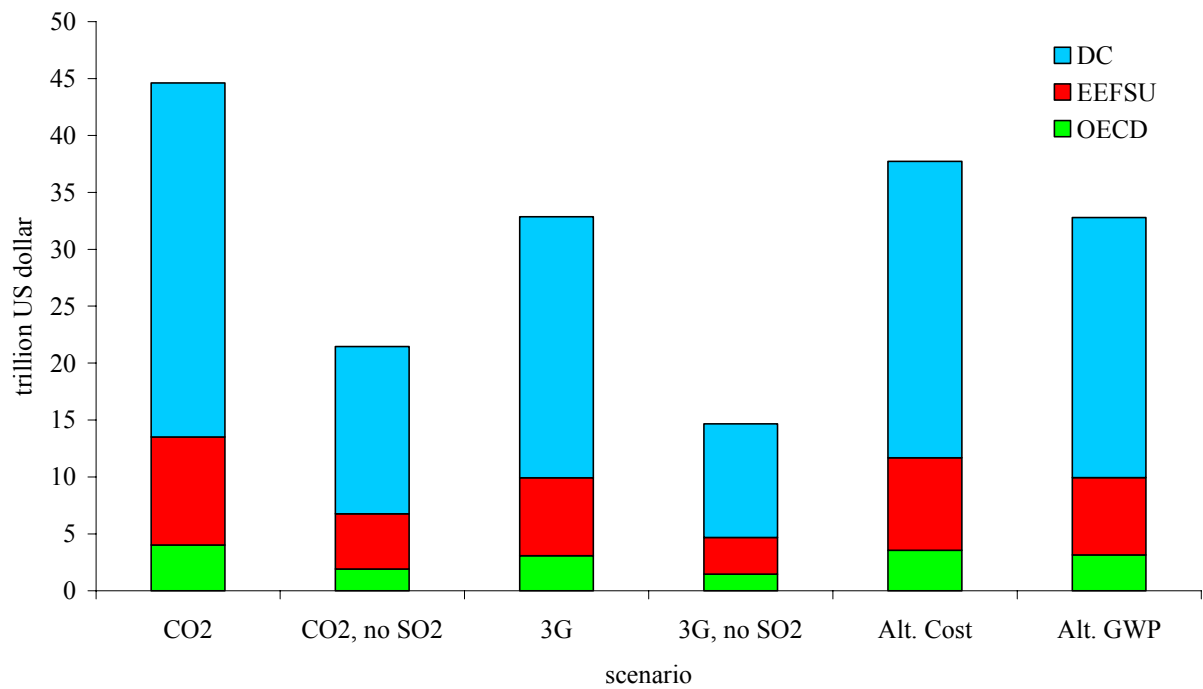


Figure 7. The net present value of consumption losses due to alternative policies to keep anthropogenic radiative forcing below 4.5 Wm^{-2} , viz. only CO_2 emission reduction (with and without SO_2), emission reduction with all three gases (3G, with and without SO_2), emission reduction with all three gases with exponential rather than quadratic cost function (Alt. Cost), and emission reduction with all three gases with contributions to 2070 radiative forcing rather than IPCC GWP (Alt. GWP).

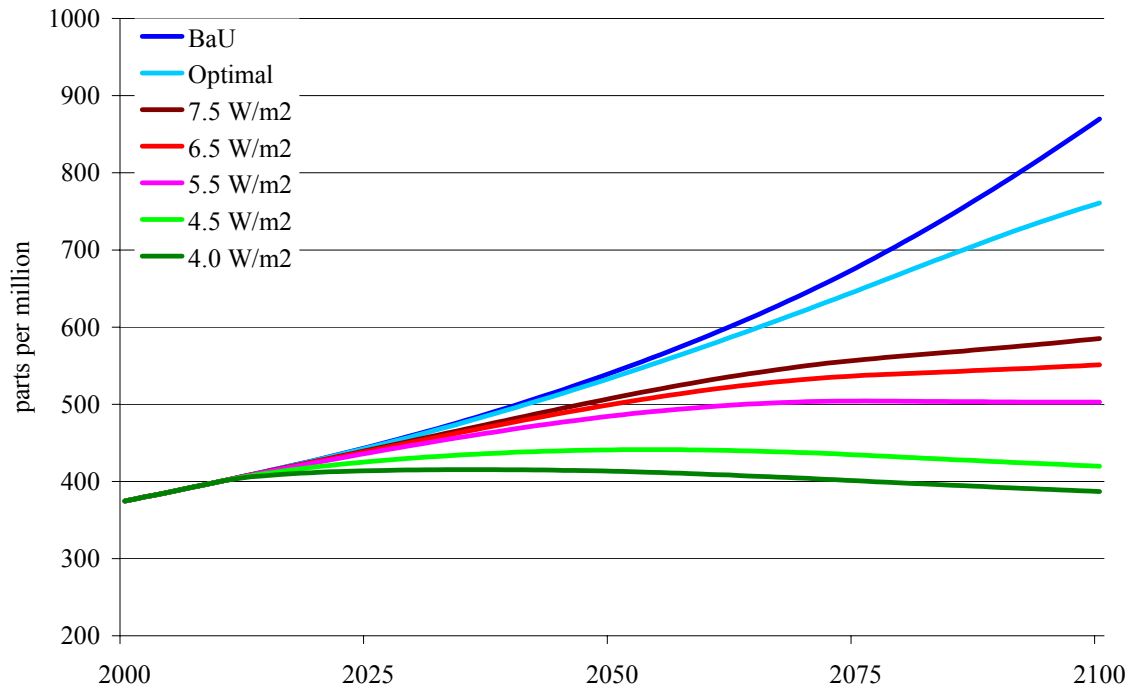


Figure 8. The atmospheric concentration of carbon dioxide for the business as usual scenario and five scenarios keeping anthropogenic radiative forcing below 4.0, 4.5, 5.5, 6.5 and 7.5 Wm^{-2} , respectively. Also shown is the scenario in which marginal emission reduction costs are set equal to the marginal damage costs in 2005 (\$7/tC), rising with the discount rate (Optimal).

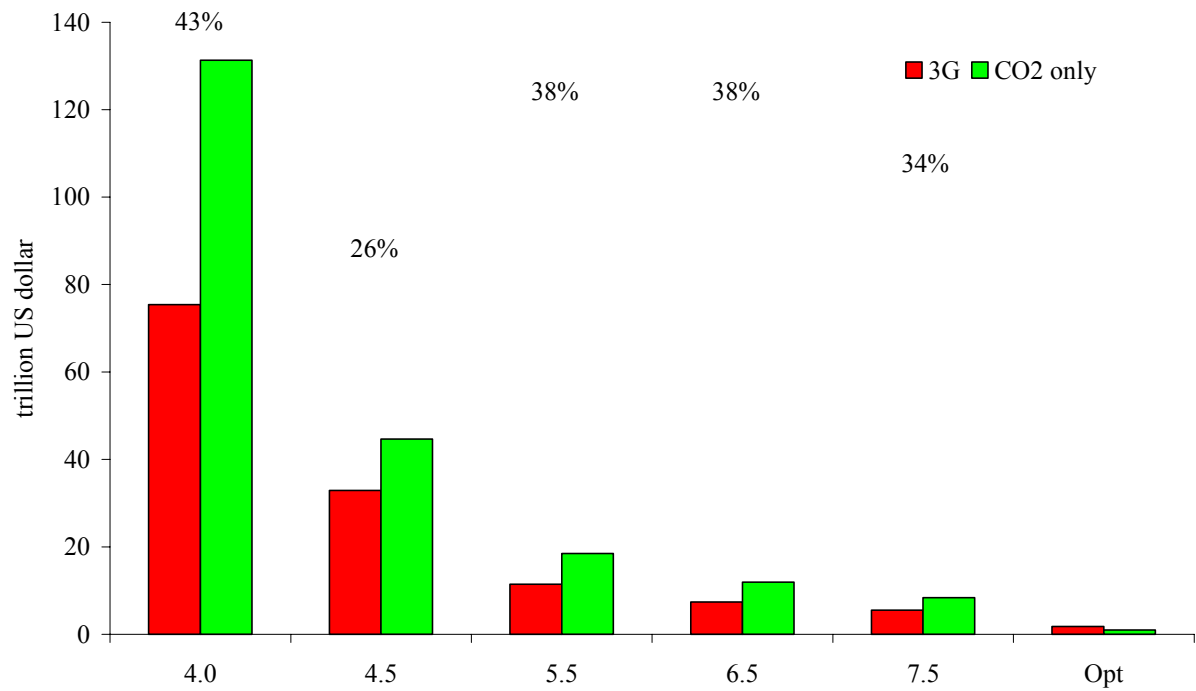


Figure 9. The net present value of consumption losses due to alternative policies to keep anthropogenic radiative forcing below 4.0, 4.5, 5.5, 6.5 and 7.5 Wm^{-2} , respectively, with carbon dioxide, methane and nitrous oxide emission reduction (3G) and with only carbon dioxide. Also shown are the costs of the scenario in which marginal emission reduction costs are set equal to the marginal damage costs in 2005 (\$7/tC), rising with the discount rate (Opt). The percentages are the costs savings due to include methane and nitrous oxide emission abatement.

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

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Abstract: The Version 5 of the POLES model has been developed for the assessment of multi-gas emission reduction strategies. Abatement options have been introduced for all non-CO₂ GHGs in the Kyoto Basket and, for the agricultural sector, Marginal Abatement Cost curves have been derived from the new AGRIPOL model. Combined with an international emission permit scheme that is based on the Soft Landing approach, an emission profile respecting climate targets of 550 ppmv provides a relatively soft constraint case for developing countries. The multi-gas analyses first of all demonstrate the relevance of the approach as changing from a CO₂-only 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. Not surprisingly however, the impacts on world demand and primary fuel mix are less pronounced in the multi-gas case. This is easily understandable as a counterpart for introducing more margins of freedom in the abatement effort.

1 INTRODUCTION

The mitigation of climate change and of its adverse effects will require significant reductions in greenhouse gas (GHG) 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 GHGs, 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:

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- 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 (CO₂ 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 corresponding 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, in particular the AGRIPOL model for agriculture. The corresponding reference projection scenario, as well as the marginal abatement cost curves for other GHGs are presented and analysed in Section 3. Section 4 provides a description of the global emission profiles and underlying hypotheses for the abatement scenarios to 2030 that are assessed in Section 5. Finally, the key conclusions of the study are given in Section 6.

2 THE POLES MODEL AND THE OTHER GREENHOUSE GAS MODULES

2.1 A brief introduction to the POLES modelling system

POLES (Prospective Outlook for the Long-term Energy System, 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, the model provides endogenous international energy prices and detailed information on energy balances for each of the model's country or region (European Commission, 2003). 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 e.g. 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 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 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 world integration is ensured through the energy markets module. Only one world market is considered for oil (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 the existing or potential export routes.

2.2 The modelling framework for the Other Greenhouse Gas

The OGHG module simulates and projects emissions of carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), perfluorocarbons (PFC), hydrofluorocarbons (HFC), and sulphur hexafluoride (SF₆) gas, i.e. the 5 GHGs identified in the Kyoto Protocol on top of energy-related CO₂. All GHGs are connected to an activity (production or consumption) and, when possible, the activity level is taken from a 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 the multi-gas approach, the abatement options for the OGHGs 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, N₂O, ...).
- 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 emissions⁴.

CO₂ and N₂O from fuel combustion

CO₂ emissions from energy combustion and N₂O emissions from some activities (transport, power generation) are directly derived from the POLES energy demand modules. The reductions result directly from changes in the fuel-mix structure and energy consumption from the energy model functions at each carbon tax level.

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

Non CO₂ gas from energy and industry GHGs

For the other non-CO₂ 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 POLES activity variables 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, which 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: AGRIPOL

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 usually tackled with two alternative 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 an individual sector, is included with its emissions coefficients (Kemfert, 2001); biosphere-climate process-oriented models, such as Image⁵ (Alcamo et al., 1998), which consider the impacts on production and on climate of expected trends of population and economic growth, as well as changes in production and consumption patterns, the demand for agricultural products and the feedback of agriculture on climate.

⁵ www.rivm.nl/image

- At the plot level in bottom-up crop growth models, such as Cropsyst, Epic or Stics⁶, 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 GHG emissions reduction options provided by agricultural practices, through a representation of production and technological choices, as influenced by carbon penalties. Such models provide a consistency framework for developing Marginal Abatement Costs curves from agriculture. Their development requires: the processing of data collected or simulated at 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 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 University⁷, 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: in order to allow the simulation of the responses to carbon prices this model maintains a behavioural approach while using a single framework worldwide, exploiting available data, and incorporating the risk-factor associated with changes in agricultural practices.

AGRIPOL, modelling 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 sector's 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 ensuring a consistent treatment across world regions and activities, in order to allow for comparisons of abatement potentials with other sectors.

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

AGRIPOL is a static economic optimisation model that runs for a set 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 regional level.

In its present version, AGRIPOL accounts for 8 major non-CO₂ GHG emitting activities⁸, 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 choice of practices of a representative⁹ agent is modelled, representing the “regional commodity producers” that maximise their net revenues from the agricultural activities and minimise the risk associated, 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. The equations concerning other resources are used for a metering of the quantity of resources required, in order to eventually check the consistency with other models' results.

Data on average GHG emissions by activity have been 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 group¹⁰, the non-CO₂ GHG network¹¹, and to a lesser extent, the OECD group on soil carbon indicators and FAO initiatives (experts' consultation, forum) on carbon sequestration¹². For each activity, energy consumption is also considered, as an indirect CO₂ source, so as to properly deal with energy-intensive processes. Extrapolation was performed from data available in published and discussed reports or recomputed from own local sources. Economic data are composed of

⁷ <http://agecon.tamu.edu/faculty/mccarl>

⁸ Dairy livestock producing milk and emitting CH₄ and N₂O, non-dairy livestock producing beef and emitting CH₄ and N₂O, rice production as a source of CH₄, three N₂O 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 Modeling Forum website: <http://www.stanford.edu/group/EMF> .

¹² Respectively, <http://www.oecd.org/agr/env/indicators.htm> and

operational costs and structural costs, prices that multiply yields (with corresponding yields and income variances) and additional revenues and subsidies from agricultural policies.

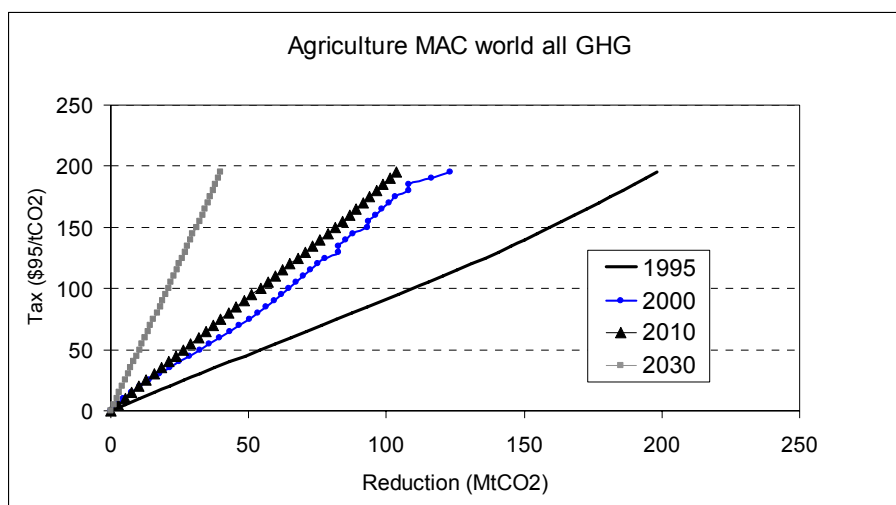
The simulation is based on the representative agent's responses to the carbon price. This price directly affects the variable costs, thus modifying net economic margins. It also affects indirectly fixed costs, when lower emission practices require capital investments. When the carbon price changes, substitutions 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 considered yet.

Results: the 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 \$/tCO₂e. For the BAU scenario in 1995, the level of emissions estimated by the model for the 8 agricultural activities considered correspond to 4.0 GtCO₂. Five regions account for about 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 \$/tCO₂e simulation case the economic abatement potential corresponds to 5 MtCO₂e in 1995 and 1.5 MtCO₂e in 2030. Potentials are more deeply exploited when applying a price of 50 \$/tCO₂e: 1.2% (12.8 MtCO₂e) in 1995, 0.2% (2.6 MtCO₂e) in 2030.

Figure 1: Global marginal abatement Cost Curves in agriculture



The Marginal Abatement Cost curves (see Figure 1) shows a lower response to carbon price in the long term, which is due to the increasing pressure of demand on production that already limits the potentials for technological progress and the limitation of land availability.

While the AGRIPOL model provides a consistent assessment framework, two pending issues still limit the relevance of the 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 and do not transfer it to the consumers. Second, agricultural carbon sinks are not considered, especially concerning the soils where carbon could be stocked with adequate production practices. Indeed further research is still needed, on the one hand to introduce possible impacts on the demand for agricultural products while maintaining the coherence with the BAU scenario results provided by IMAGE, and on the other hand for a thorough representation of the sink capabilities provided by agriculture.

3 THE POLES 5 REFERENCE CASE AND THE ASSOCIATED MAC CURVES

3.1 The multi-gas 2030 Reference projection

The following section provides the aggregate results of the POLES 5 model under the set of hypotheses and parameters that have been developed under the Reference case for GDP growth, economic structure, population growth and urbanisation.

The detailed analysis of emissions, 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 slower increase. Although broad generalisations should be avoided, the key outcomes of the Reference multi-gas projections can be stated as follows:

- CO₂ emissions are expected to increase substantially in the Reference, at a rate of 2.1 %/year, reaching 46.2 GtCO₂e in 2030. Most of the increase comes from China (10 GtCO₂e in 2030, from 3.2 GtCO₂e in 1995) and from other Asian regions, due to rapid increases in energy consumption. The CO₂ emissions in the Economies In Transition are projected to recover their 1995 level by 2010 and to increase slowly afterwards.
- CH₄ emissions in Industrialised Countries are practically stable, while they are expected to increase significantly in Developing Countries, mostly in relation with the expansion of agricultural activities (livestock, manure, waste management) and fossil fuel consumption. In the case of the Economies In Transition the increase in emissions is mostly due to fossil fuel production and transport. Total CH₄ emissions is expected to reach 8.4 GtCO₂e in 2030 up from 6.3 GtCO₂e in 1995, if no policy action is taken.
- The growth in nitrous oxide emissions is substantially lower than for the other GHGs. N₂O emissions are even projected to decline in Western Europe and stabilise in North America. As in the case of methane emissions, Developing Countries represent the largest increase in N₂O emissions from agricultural activities such as fertiliser utilisation and animal waste, and from

industrial activities such as nitric and adipic acid production. N₂O emissions from transport represent less than 2% of total N₂O emissions (2.4 GtCO₂e in 2030, compared with a total of 40 Mt CO₂ in 1995).

- Concerning the High Global Warming Potential gas (HFC, PFC, and SF₆), the rapid growth of industry growth in Developing Countries lead to an exceptional increase in emissions over the projection period. The developing countries become the largest source of those emissions by the year 2030. Altogether, these three HGWP gas reach the level of 2 GtCO₂e in 2030 compared with 355 MtCO₂e in 1995.

These analyses by emission category shouldn't give birth to a false appreciation of the relative impacts of the different gas on climate change. CO₂ emissions are, and will remain, by far the dominant source and in spite of the rapid growth in non-CO₂ emissions, the weight of CO₂ 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. Methane emissions will remain the second one with a slightly decreasing share, representing 14 % of total emissions in 2030

Table 1: The POLES 5 world GHG Reference projection

	MtCO ₂					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%
ch4w st	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%

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

In order to assess the global impacts of multi-gas abatement policies, 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 allows to identify important differences among the 17 activities and across regions. These can be described as follows:

- Some activities – such as CO₂ from cement industry or CH₄ and N₂O from agriculture – are highly inelastic to the introduction of a carbon value, and this for all regions, with reductions of about one or two percentage points even for high carbon values. While this weak sensitivity is easily understandable in the case of cement, the interpretation for agricultural activities involves much more complex considerations. In this latter case the results to some extent depend on the treatment of technologies in the agriculture and on the limitations imposed to the preliminary agriculture model (e.g. the fixed demand and regional production hypotheses described in previous section).
- Conversely, a set of activities show a very high sensitivity to the carbon value, with reductions beyond 50 % when it is sufficiently high (50 \$/tCO₂, all carbon values here are expressed in 1995 dollars). This is the case for CH₄ from gas transport and from coal mines (surface and underground), also for N₂O from chemical industry and for PFC, both from aluminium and semi-conductor industry. An extreme case is the one of SF₆ from industry, where a 100 % reduction is obtained with a 20 \$/tCO₂e carbon value.
- Most other activities show an intermediate sensitivity level, with reductions in the range of 15 to 30 % for a 50 \$/tCO₂e carbon value. This is in particular the case for the largest activity in terms of emissions, i.e. CO₂ from the burning of fossil fuel. CH₄ from oil and from gas production, CH₄ from waste and landfills, SF₆ 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 \$/tCO₂e and a hypothetical full emission trading at world level, world 2010 GHG emissions would be reduced by 7.8 GtCO₂e, from a total of 40 GtCO₂e 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 in terms of GHG abatement. They illustrate 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

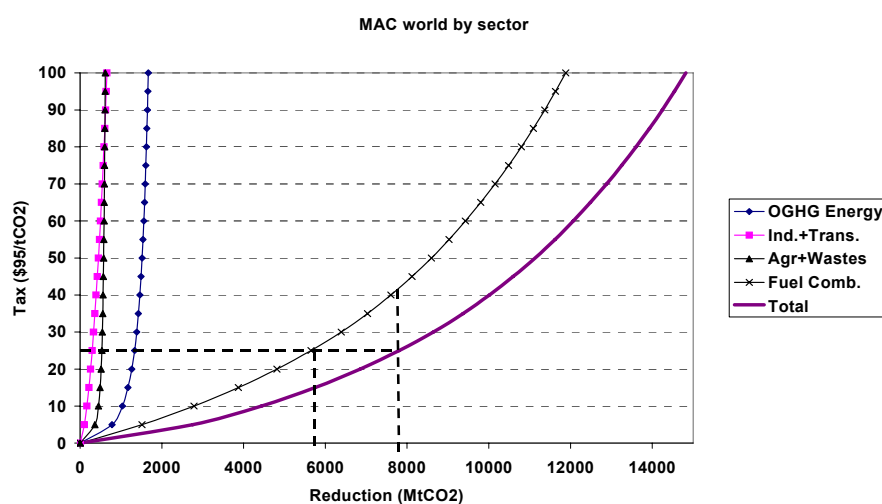


Figure 3: Global 2010 MAC curves, by gas categories, 2010

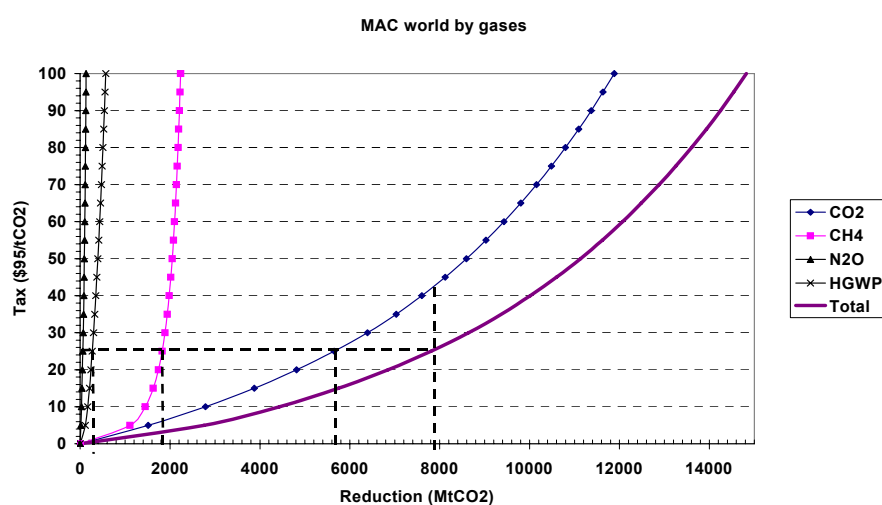
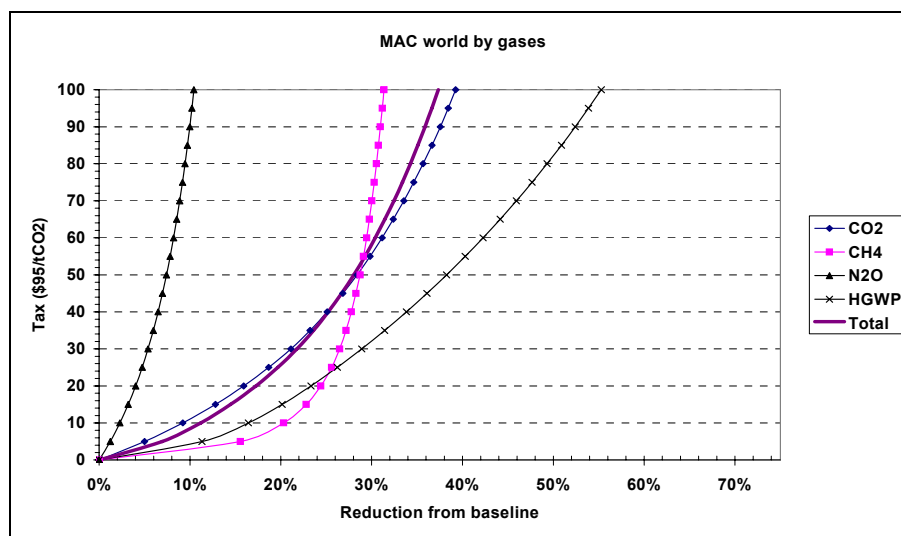


Figure 3 illustrates the contribution of each type of GHG and it appears that CO₂ is, not surprisingly, the main contributor to total abatement, in quantities (5.6 GtCO₂) and proportion (72%). Its contribution is indeed almost equal to the one of the “fossil fuel burning” activity, as the contribution 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 N₂O, only 1 %. However, the predominance of CO₂ from fossil fuels in total 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 \$/tCO₂e carbon value supposed here – corresponding to an ambitious abatement program for the 2010 horizon – the inclusion of other gas would allow to increase total reductions by 38 % (from 5650 tCO₂e to 7800 tCO₂e)
- in another perspective, reaching the same total reduction in a “CO₂ only strategy” would imply a carbon value slightly superior to 40 \$/tCO₂e and thus cost approximately 60 % more – both in terms of marginal and total cost – than a multi-gas approach.

These gains in total abatement for a given carbon value or in marginal and total costs 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 CO₂ only or for the 6 GHGs. Surprisingly enough, the two MACs are very close to each other, as illustrated in Figure 4. This is because the lower abatement costs for CH₄ and HGWP gas are compensated by the steeper MAC curve for N₂O, 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 CO₂ from Land Use are not modelled and accounted for in this exercise, these first analyses are largely consistent with the corresponding results from the existing 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 deemed useful 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, in order to provide a consistent basis for the comparison of the different scenarios.

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 in a long term perspective. 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 CO₂ 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 2050 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 corresponding emission paths allow a stabilisation around 550 ppm for CO₂ implying early action to curb current emission trends. As the time horizon of the POLES 5 model is 2030, the use of the B1 emission profile appears 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

While the global emission profile is thus been taken from the B1 scenario, the international emission endowment 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). The framework for the development of the full multi-gas scenarios has thus been based on a three stages process:

- 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, in addition to the multi-gas (MG) case, of two different “CO₂-only” variants, the “CO₂-only only” (COO) and the “CO₂-only proportional” case (COP)¹³.

¹³ The original GECS study (Criqui, 2002) encompasses four scenarios, two-multi-gas with differentiated endowment schemes and two CO₂-only. For simplicity's sake, only the Soft Landing – Multi-Gas case is described here.

The Soft Landing scenario (SL)

In the “Soft Landing – Multi-Gas” scenario (SL-MG), 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) the emissions in 2030 should be 15% lower than the corresponding level in 2010; and that for the Eastern Europe and Former Soviet Union 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 indeed reflects the Soft Landing approach used in Blanchard et al., 2002¹⁴: It results in three additional country categories with the “Emerging Countries” (per capita GDP above 60% of the 2010 OECD level, Category 2), “Developing Countries” (per capita GDP 15 to 60% of the 2010 OECD level, Category 3) and “Least Advanced Countries” (per capita GDP under 15% of the 2010 OECD level, Category 4), which have to stabilise their emissions respectively in 2015, 2030 and 2045.

The analyses concerning the two “CO₂-only” cases are carried out simply by:

- applying the whole volume of reductions from the Soft Landing – multi-gas (SL-MG) scenario to the energy related CO₂ emissions for the SL CO₂-only “only” scenario (COO);
- while applying the same percentage reduction to CO₂ than to all gas in the SL CO₂-only “proportional” scenario (COP).

4.2 Resulting endowments by main regions

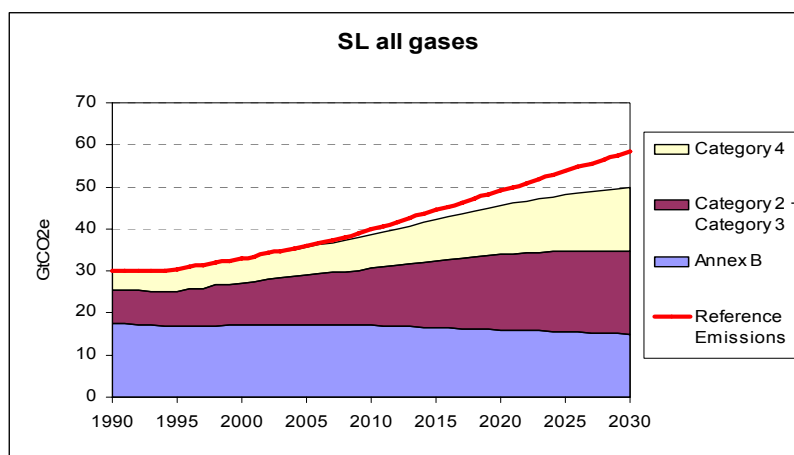
In all scenarios and up to 2010 all constrained Annex B countries - with the exception of the USA - follow their Kyoto targets (reached in 2010), while non-Annex B countries follow their baselines. The USA follows a path that is close to the so-called “Bush plan¹⁵”. It is assumed that, from 2011 onwards, all countries participate to the global allocation schemes described above. This constitutes only a rough estimation of the possible emission trajectories as it corresponds to a “linearisation” of the more

¹⁴ The “soft landing” approach has also been used in other studies. See Criqui et al., 2003, Russ and Criqui, 2004.

¹⁵ This plan calls for a -18% of reduction of the emissions intensity in the USA over the 2002-2012 period.

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 Europe countries and the Former Soviet Union, follow their baseline emissions and do not use the “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 GtCO₂e), while Annex B and the Least Advanced Countries each benefit from similar total endowments (15 GtCO₂e). In terms of energy-CO₂ emissions, the 2030 global endowment is of course lower in the COO case than in the COP case: 35 vs.. 37 GtCO₂, while the Reference energy-CO₂ emissions is of 44 GtCO₂ in 2030. In both cases, Developing Countries are allocated the largest share (14.5 GtCO₂ for COO and 14.8 GtCO₂ for COP). Least Developed Countries get the same allocation in the two cases (10 GtCO₂), while Annex B gets slightly more in the COP case: 11.6 GtCO₂ vs. 10 GtCO₂.

5 ASSESSMENT OF THE MULTI-GAS ABATEMENT STRATEGY

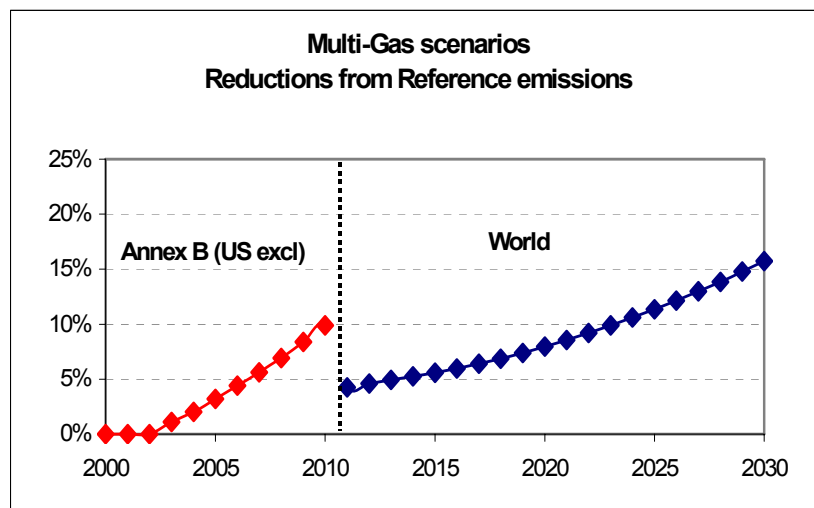
Once the international endowments corresponding to the three above-described scenarios have been calculated, the multi-gas assessment studies have been performed with the POLES 5 model in a two stages approach:

- 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 the Reference case.

Figure 6: Emission reduction from Reference



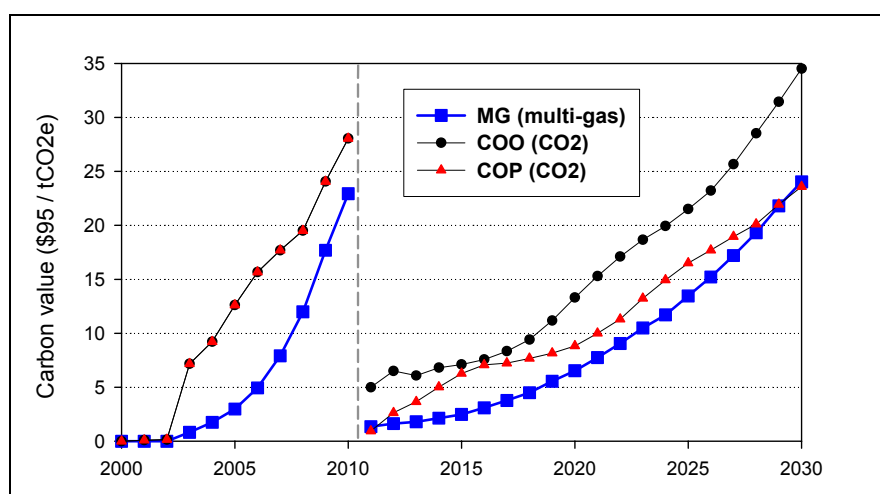
5.1 The time-path of the Carbon Value

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 $\$/tCO_2e$, equivalent to $\text{€}_{99}/tCO_2e$) 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)

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 \$/tCO₂e in 2010, when Annex B countries (except the US) reach their Kyoto targets. After 2010, the entry of all non-Annex B countries in the bubble of constrained countries entails a sharp decrease in the CO₂e value that drops to 1.3\$/tCO₂e, before it rises again and reaches 24 \$/tCO₂e in 2030 (Figure 7).

Figure 7: CO₂e values for the multi-gas and CO₂ reduction cases



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 simplicity's sake, no hypothesis have been made for CDM reductions in the Kyoto time-frame.

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

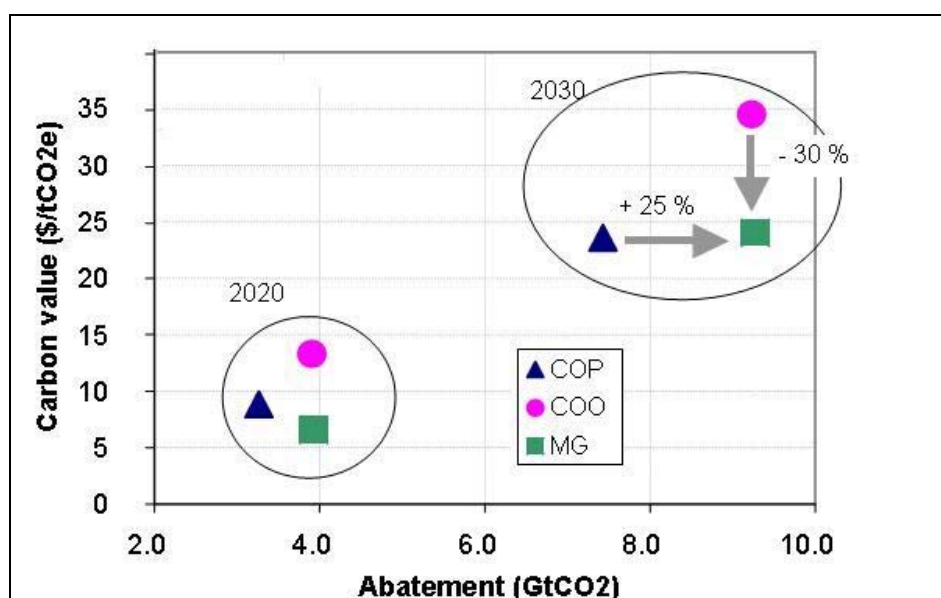
In these two scenarios it is hypothesised that “cap and trade” emission reduction policies are applied exclusively to CO₂ reductions. Up to 2010 both CO₂-only “only” and CO₂-only “proportional” scenarios correspond to the Kyoto reduction target from base-year, supposing that the same percentage reduction 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 \$/tCO₂. 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 CO₂ 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 \$/tCO₂e in the COP case and 34 \$/tCO₂e in the COO case (Figure 7).

Finally, the key advantages of Multi-Gas strategies relatively to CO₂-only approaches are clearly illustrated in Figure 8, which clearly illustrates how going from CO₂-only to multi-gas strategies either allows:

- to significantly increase the total abatement for the same carbon value, ie 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 8: MAC vs. total abatement in 2020 and 2030, MG, COO and COP scenarios



5.2 Impacts on the World Energy Balances

The scenarios can also be analysed in terms of impacts on the world energy balance. In the following section, the balances of the different emission reduction scenarios are compared with the one of the

POLES model Reference projection. Table 2 presents the key results of the Reference scenario, while Table 3 and 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 to 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. In all scenarios, the reduction in primary energy consumption is mostly due to the sharp decrease in the use of solid fossil fuels (coal, lignite). In 2030 and compared to the reference scenario, the solid fossil fuel consumption is 27 to 37 % lower. The use of oil and gas are also affected, although in very low proportions for natural gas: minus 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 minus 6 to 9 % in 2030.

These lower levels of fossil fuel consumption are partly 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 new 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, than in the Multi-Gas cases. This is an unavoidable effect of any Multi-Gas strategy: while relaxing the pressure that is imposed on the energy sector, they do create a context of relatively lower 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 Version 5 of the POLES model has been developed and applied in the perspective of the assessment of multi-gas emission reduction strategies. Abatement options have been introduced for all non-CO₂ GHGs in the Kyoto Basket. For the agricultural sector, Marginal Abatement Cost curves have been derived from the new 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, aiming at a stabilisation in the emissions of all countries before 2050. 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 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.

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 energies 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 CO₂-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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Multigas Mitigation: An Economic Analysis Using GRAPE Model

Atsushi Kurosawa

Future global warming may depend strongly on the potential for abating emissions of greenhouse gases (GHGs). Flexibility in implementing climate change mitigation policies can significantly reduce mitigation costs and has three dimensions; space, time and gas species. Therefore, multiple greenhouse gas reduction flexibility should be considered. The emission and reduction potential of CO₂ and non-CO₂ GHGs are assessed here using an integrated assessment model under climate change targets. The implications on gas life as well as abatement timing uncertainty on costs, technological availability, etc. are discussed. The introduction of additional multigas reductions will cut the economic burden of achieving a given climate change target. The conclusions are threefold; (1) Multigas mitigation is a cost effective strategy compared to CO₂-only mitigation under the same climate target, (2) CO₂ mitigation is expected to lead to ancillary reductions in CH₄, N₂O and SO_x emissions, and (3) There is great uncertainty in the assessment of non-CO₂ GHG mitigation opportunities.

1. INTRODUCTION

Kyoto protocol (KP) (UNFCCC, 1997) defines six types of greenhouse gases (GHGs) for future emission control. They are carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF₆). HFCs, PFCs and SF₆ are often called fluorinated greenhouse gases (F-gases). These non-CO₂ GHGs can be converted CO₂-equivalent amount by multiplying global warming potential (GWP) numbers. 100-year GWP weighted sum of above GHGs should be reduced to

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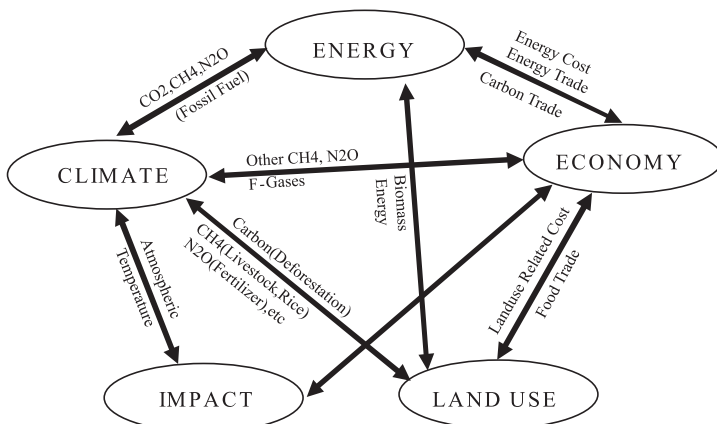
the level specified in the ANNEX B of KP if the parties ratify KP. Although a large number of studies have been made on fossil fuel CO₂ reduction potential, there is little agreement as to non-CO₂ gases emissions and reduction potential. The purpose here is to explore further into the explicit assessment of multiple gas emissions scenario based on the comprehensive assessment using emission factors and activity data. In the previous works, I dealt with CO₂, CH₄ and N₂O in the multiple gas reduction analysis (Kurosawa, 2002), and non-CO₂ Kyoto GHG assessment without climate policy (Kurosawa, 2003). I will develop the assessment more fully to include all KP GHGs above in the following analysis to conduct comprehensive and endogenous reduction potential assessment.

The flexibility of climate change mitigation policy is composed of three characteristics; space, time and gas species. Emission certificate trade, joint implementation and clean development mechanism (i.e. Kyoto mechanism) depend on spatial flexibility (Kurosawa, 1999). Intertemporal flexibility could mitigate drastic shock if banking and/or borrowing of GHG quota would be available (Kurosawa, 2000). In addition, the diversity of target GHGs will enhance the choices of climate change mitigation measures and enable more flexible policy options.

2. MODELING FRAMEWORK

GRAPE (Global Relationship Assessment to Protect the Environment) model consists of five modules dealing with issues on energy, climate, land use, macroeconomics and environmental impacts (Figure 1). Global disaggregation covers ten regions. They are North America (NAMR), Western Europe (WEUR), Japan (JAPN), Oceania (OCEA), China (CPAS), Southeastern Asia and other Asia (SEAS), Middle East and North Africa (MENA), Sub-Sahara Africa (SSAF), Latin America (LAMR), and Former Soviet Union and Eastern Europe (FSEE). To include long-term climate change dynamics, the base year and time horizon of

Figure 1. Model Framework



the model are 2000 and 2100 respectively. The model depends on economic utility maximization methodology with consideration of global trade balance (Kurosawa, 1999). The utility function defined by intertemporal discounted regional sum of product, which contains population, logarithm of per capita consumption and regional Negishi weight adjustment factors. I modified macroscopic base data such as population, GDP, and final energy demand data followed by United Nations (UN, 2004) and International Energy Agency estimates (IEA, 2002). Forest, geological and ocean CO₂ sequestration assessment methodology follows previous work (Kurosawa, 2004)

Sources, emission activity indexes and emission factor improvement rates are summarized in Table 1. The emission of non-CO₂ gases from specific source is calculated by multiplying the emission factor and the activity index within the model. Base year emission data are reconstructed to match with GRAPE regional disaggregation using Energy Modeling Forum 21 (EMF21) data assessment (DeAngelo, 2005, Scheehle, 2005, Ottinger, 2005 and Sohngen, 2005). Emission factors of non-CO₂ sources vary depending on regional conditions and technological progresses. I divided base year sector emission data by activity indexes such as production, consumption, GDP and population to obtain the emission factors, and reduced future CH₄ and N₂O emission factors considering improvement of productivity and other technology progress. F-gases emission factors are assumed to decrease by alternatives and self-regulation of industries in the long run.

There are a lot of F-gas chemical species. F-gas emissions are aggregated to four representative gases followed by EMF21 data (Ottinger, 2005) for the convenience of analysis. HFC23, HFC134a, CF₄ and SF₆ are selected based on the emissions and concentrations in recent years. The emissions of gas species other than representative ones are converted to representative gas emissions using IPCC WGI SAR 100-year GWPs (IPCC, 1995). In this sense, four-representative-gas concept is virtual one. Concentration decay of these gases is assumed to behave one-box model using representative gas lifetime listed in IPCC WGI TAR (IPCC, 2001).

Additional non-CO₂ GHG abatement with the payment to abatement technologies is assumed in the sectors shown in Table 2. Marginal abatement cost (MAC) curves of non-CO₂ GHGs abatement are defined by initial cost, maximum cost and maximum reduction rate compared to the base year emissions. In most of these sectors, regional maximum reduction potential will expand based on the technological progress estimate and it is assumed that the same amount of abatement will be possible with relatively low cost. Initial cost is set to 10US\$/TCE (ton carbon equivalent) and long-term regional maximum reduction ratio convergence by technology diffusion is assumed.

Atmospheric concentration of each GHG is obtained using four-box model for CO₂ and one-box model for non-CO₂ GHGs. Radiative forcing values of forcing agents including CO₂, other GHGs and SO_x aerosol etc. are estimated by the functions of atmospheric concentration level in IPCC WGI TAR (IPCC, 2001) and the relationship between SO_x emissions and radiative forcing by Andronova, et.al. (2001). Summing up these values provides global mean radiative forcing.

Table 1. Non-CO₂ GHG Sources, Activity Indexes and Emission Factor Improvement Rates

Gases	Emission sources	Activity indexes	Emission Factor Improvement Rates
CH ₄	Fossil fuel production (Coal, oil and natural gas)	Fuel production	Developed Regions: 0.3%/year Developing Regions: 0.5%/year
	Fossil fuel combustion (Coal, oil and natural gas)	Fuel consumption	Same as AEEI(#)
	Livestock (Enteric fermentation etc.)	Meat production	Same as Meat Productivity
	Rice paddy	Cereal production	Same as Cereal Yield
	Landfill	GDP	All regions: 2%/year
	Wastewater, etc.	GDP	All regions: 2%/year
	Biomass Combustion, etc	Exogenous	No Improvement
	Fertilized soils	Cereal production	All regions: 1%/year
N ₂ O	Fossil fuel combustion (Coal, oil and natural gas)	Fuel consumption	Same as AEEI(#)
	Livestock Manure	Meat Production	Same as Meat Productivity
	Chemical industry	GDP	All regions 2%/year
	Human Sewage	GDP	All regions 2%/year
	Biomass Fuel, etc.	Exogenous	No Improvement
	HFC23 for HCFC22 production	GDP	All regions: 1.5%/year
	ODS substitute (HFC134a, etc.)	Population	All regions: 1.5%/year
	PFCs	GDP	All regions: 1.5%/year
F-Gases	SF ₆	GDP	All regions: 1.5%/year

(#) Autonomous Energy Efficiency Improvement Rate

Table 2. MAC Upper Bound (Base Year) and Maximum Abatement Ratio

Gases	Emission sources	MAC Upper Bound	
		(\$/TCE)	Maximum Abatement Ratio
CH ₄	Fossil fuel production (coal)	20	All regions: 90%
	Fossil fuel production (oil and gas)	200	All regions: 60%
	Livestock	30	NAMR: 30%, Others 20%
	Rice paddy	200	JAPN: 20%, CPAS&SEAS: 50%, Other regions: 0%
	Landfill	200	All regions: 90%
N ₂ O	Fertilized soils	200	NAMR 70% , JAPN 20%, CPAS&SEAS 50%, Other regions 20%
	Chemical industry	200	All regions: 95%
F-Gases	HFC23 for HCFC22 production	20	All regions: 70%
	ODS substitute (HFC134a, etc.)	200	All regions: 70%
	PFCs	200	All regions: 90%
	SF ₆	20	All regions: 90%

Temperature increase from pre-industrial level is calculated by the ACCC model impulse response function (IRF) (den Elzen, et.al, 2003) with 2.5 degC climate sensitivity. I changed the time constants of ACCC CO₂ box model to tune the model behavior while box model distribution fraction remains the same as that of original values.

3. RESULTS

Radiative forcing with relative to pre-industrial is adopted as representative integrative climate change parameter including the non-CO₂ forcing effect. Rate of change in global mean atmospheric surface temperature is an additional constraint to evaluate its sensitivity. Existence of forest CO₂ sequestration is another choice of climate mitigation policy. Taking these factors into considerations, I analyzed five simulation cases below.

REF: Reference case and there is no climate policy constraint.

CO₂-ONLY: Radiative forcing limit (4.5 W/m²) with no additional non-CO₂ GHG reduction.

CO₂-SINK: CO₂-ONLY plus forest CO₂ sequestration.

MG: Radiative forcing limit, additional non-CO₂ GHG reduction is assumed.

MG-CMB: MG plus rate of temperature change limit (0.2 degC per decade after 2030).

MG-SINK: MG plus forest CO₂ sequestration.

I will use the terms “MG-cases” to refer to MG, MG-CMB and MG-SINK cases, and “CO₂-cases” to explain CO₂ and CO₂-SINK cases. Two kinds of actions are possible to reduce non-CO₂ GHGs. One is activity level change, which affects production or consumption of the sector directly. The other is additional reduction with abatement cost mentioned above without sector activity change. MG-cases include both actions while CO₂-cases assume only activity level change. In the CO₂-ONLY, MG and MG-CMB cases, forest area of each global region is fixed to the REF case values to exclude the forest CO₂ sequestration effect.

3.1 GHG Emissions

Global CO₂ emissions in simulation cases are shown in Figure 2. REF case emission gradually increases and reaches approximately 21.6 PgC in 2100. On the other hand, MG-cases emissions decrease to approximately 5 PgC by energy conservation, energy supply structure change, CO₂ capture and storage and afforestation (Figure 3 and Figure 4). In general, MG-cases emissions are relatively higher than those of CO₂-cases since additional non-CO₂ reduction is balanced with CO₂ emission increase under the same constraint after 2050.

Figure 5 illustrates global anthropogenic CH₄ emissions in REF case by sources. The ratio of emissions from fossil fuel production, consumption as well as livestock is continuously high during the 21st century. Except MG-CMB case, CO₂-cases and MG-cases CH₄ emissions increase initial decades before changing to the decreasing trend around 2050 (Figure 6). Main reason of short-term consistency

Figure 2. Global CO₂ Emissions

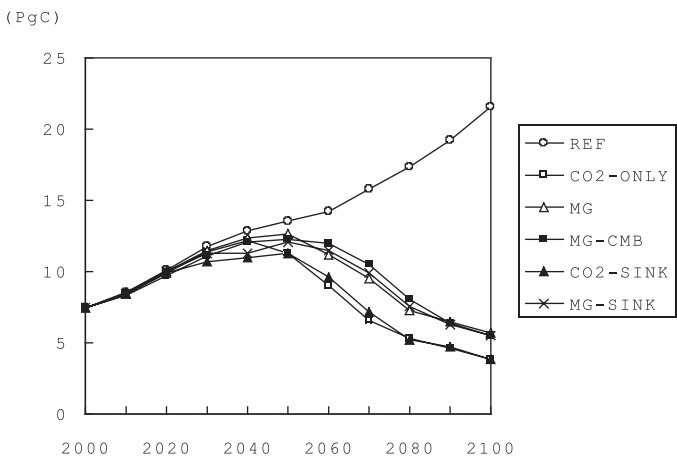


Figure 3. Global Carbon Balance (MG case)

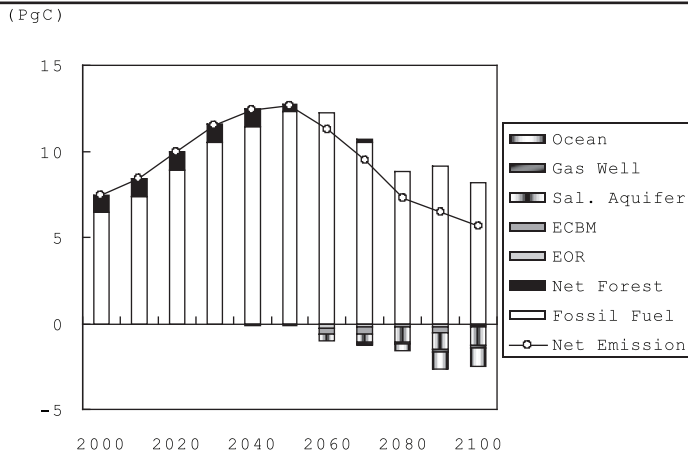
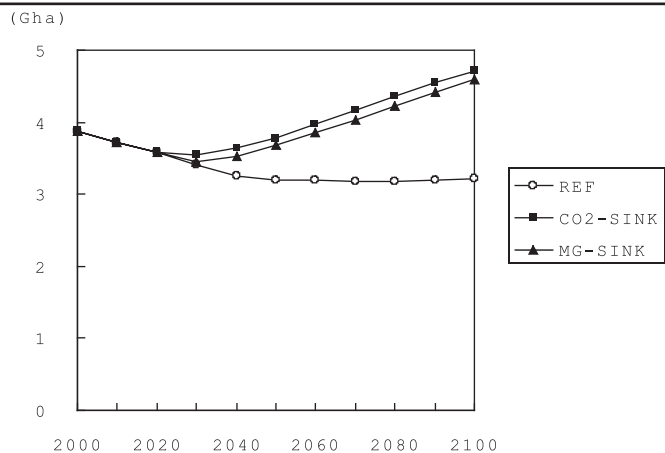


Figure 4. Global Forest Area



of the emissions paths is short gas lifetime. CH_4 lifetime is set to 12 years (IPCC, 2001) and it is relatively short compared to long-term target assumed. Drastic reduction is observed in MG and MG-SINK after 2060 to meet with the target. On the other hand, MG-CMB case emission is decreasing after 2030 to adapt the rate of temperature change constraint. Total emissions in 2100 for REF, CO_2 -cases and MG-cases are approximately 540, 300 and 200 Tg- CH_4 respectively.

Fertilized soil is the dominant source in N_2O emissions at present and during the 21st century in REF case (Figure 7). The MG-cases N_2O emissions from fertilized soil decrease by around a half compared to those of REF case. Transaction cost of agricultural soil mitigation measure is not included in the analysis. The unit reduction cost would be higher than that of large scale point

Figure 5. Global CH₄ Emissions by Sources (REF case)

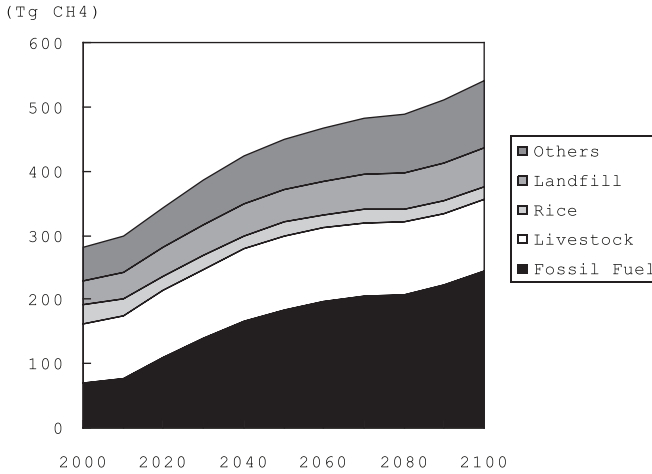
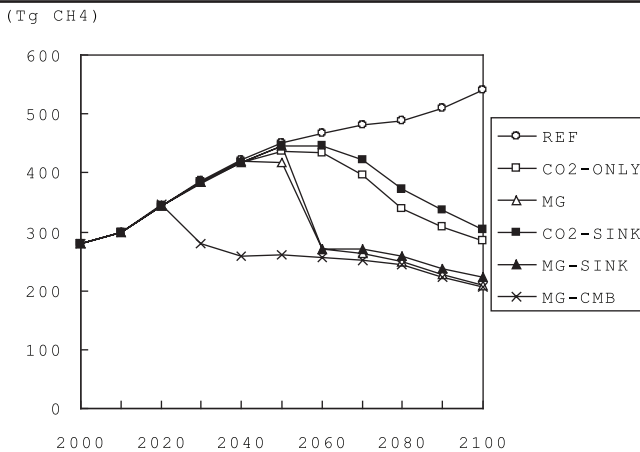


Figure 6. Global CH₄ Emissions



sources since agricultural soil is one of distributed emission sources. Figure 8 suggests that the fertilized soil emission can be abated if the pure cost without transaction follows the abatement cost estimate. We have to pay attention to early emission reduction of MG-CMB case in 2020. This response occurs to prepare the rate of temperature change constraint after one decade. Because N₂O lifetime is set to 114 years (IPCC, 2001) and it is longer compared to that of CH₄. Total emissions in 2100 for REF, CO₂-cases and MG-cases are approximately 16, 10 and 9 Tg-N₂O respectively.

The global reduction ratio of GWP weighted sum of F-gases in MG case vs. REF case reaches approximately 70% in the long run, in spite of the fact that

Figure 7. Global N₂O Emissions by Sources (REF case)

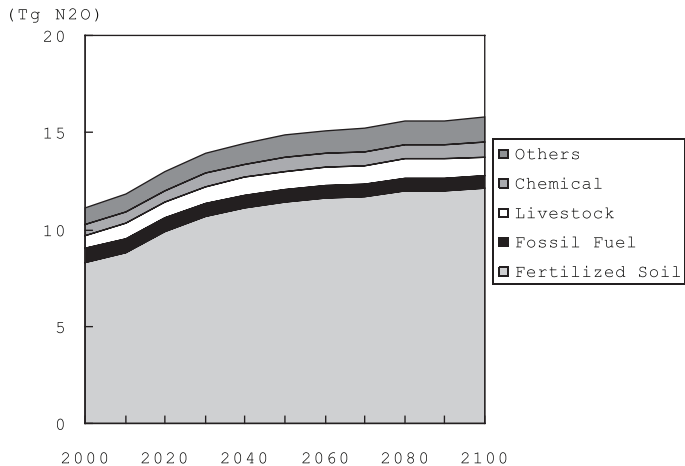
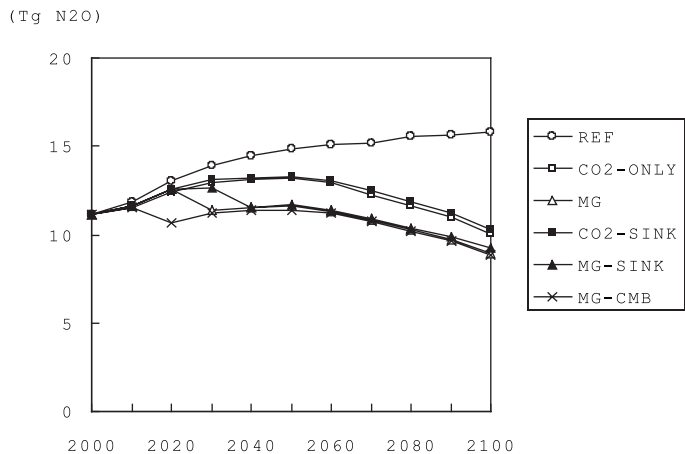


Figure 8. Global N₂O Emissions



the impact of climate policies for each virtual F-gas is different. Each virtual F-gases emission reduction rates are summarized in Figure 9.

3.2 Radiative Forcing and Temperature Rise

Radiative forcing in 2100 with relative to pre-industrial for REF case is 5.9(W/m²), while the other cases values reach upper bound (i.e. 4.5 W/m²). Temperature increase from pre-industrial level is 3.0 (degC) for REF, and 2.5 (degC) for other cases. MG case SO_x aerosol forcing is increasing according to fossil fuel consumption decline, and its value is higher than that of REF case

Figure 9. Reduction Rate of F-gases (MG case vs. REF case)

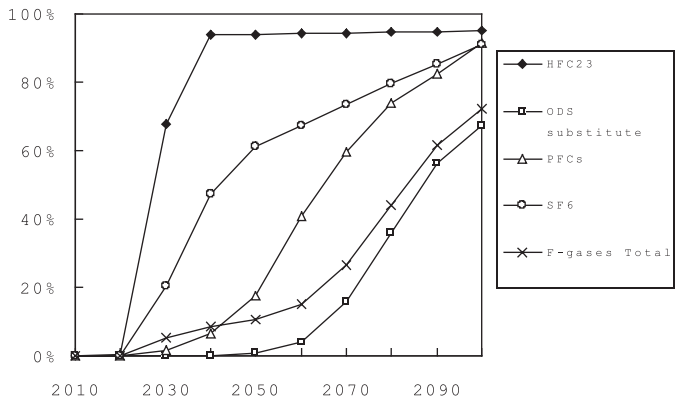
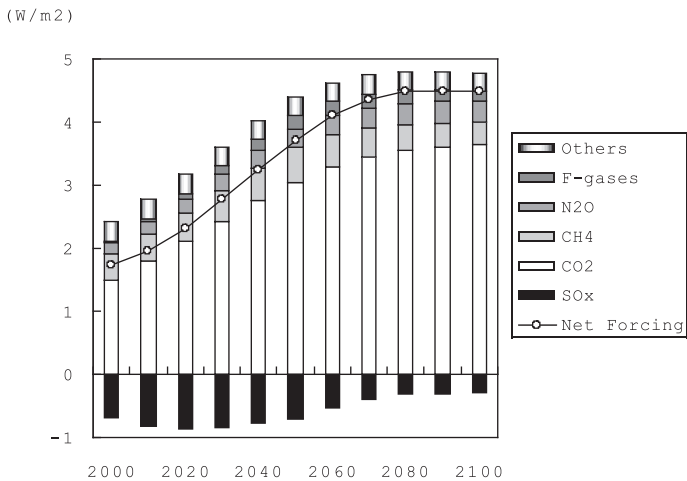


Figure 10. Radiative Forcing (MG case)



(Figure 10). This tendency suggests that the forcing-decreasing effect of CO₂, CH₄ and N₂O by abatement exceeds forcing-increasing effect by SO_x aerosol under the prerequisite adopted in the simulation.

3.3 Economic Effects

I show the GDP losses of CO₂-cases and MG-cases vs. REF case in Figure 11. The combination of multiple GHG mitigation and afforestation in MG-sink case is the most cost-effective measure under the same long-term climate target. Adding the short-term rate of temperature change target in MG-CMB case

leads to different macroeconomic activity because we require early actions to control the speed of climate change. CO₂-cases and MG-cases GDP changes are less than 1% before 2050, but it is increasing exponentially afterwards to the range between 3.8% and 8.6% in 2100.

4. DISCUSSIONS

Declining the dependency on fossil fuel in global energy system is effective to reduce greenhouse effects from CO₂ as well as CH₄ and N₂O. I evaluate non-CO₂ GHG contribution with relative to CO₂ using IPCC WGI TAR 100-year GWPs. CH₄ plus N₂O contribution ratio range among three types of GHG emissions from fossil fuel during 21st century is stable and it is approximately from 7% to 9% in the REF case. Reduction efforts in fossil fuel production and consumption lead to CH₄ and N₂O reduction. CO₂-ONLY case results reveal this effect correctly by the following ancillary benefit index (ABI);

$$ABI = \frac{GWP_{100,CH_4} \cdot \Delta E_{CH_4} + GWP_{100,N_2O} \cdot \Delta E_{N_2O}}{\Delta E_{CO_2}} \quad (1)$$

where

ABI: ancillary benefit index

$GWP_{100,i}$: 100-year global warming potential value of GHG species *i*

ΔE_i : fossil fuel related emission reduction of GHG species *i*

Global ABI value is negative in initial few decades since CH₄ emissions slightly increase by the fuel shift to natural gas, but the ratio will gradually increases to approximately 8% in the long run (Figure 12). It means that the reduction ratio of CO₂ versus aggregated other two GHGs converges to the same degree to match with the radiative forcing target. Climate mitigation measures of CO₂ abatement policy will relax the climate impacts more effectively.

Further non-CO₂ GHG abatement efforts are required in agriculture sector. In energy sector climate policy, there are alternatives to satisfy demand although some options are costly. On the contrary, in the agriculture sector, we can hardly imagine food substitutes or conservations. Therefore, additional non-CO₂ GHG abatement in the agricultural sector is vital under the possibly high transaction cost. If we take measures in the fertilizing activity, which is most dominant in the anthropogenic N₂O emissions, we have to pay attention to the uncertainty in crop yield in the long run. The yield could rise by additional nitrogen fertilizer application but it will raise N₂O emissions. Technologies including agricultural management and gene technology etc. could enhance the productivity.

In general, determinant factors affecting GHG mitigation option introduction are economics, technologies, and benefit of mitigation actions. It is obvious that economic factors include pure cost, which relates to mitigation action itself. Transaction cost of distributed sources such as transportation or agriculture would be high. This obstacle should be overcome by providing

Figure 11. Global GDP Losses (vs. REF case)

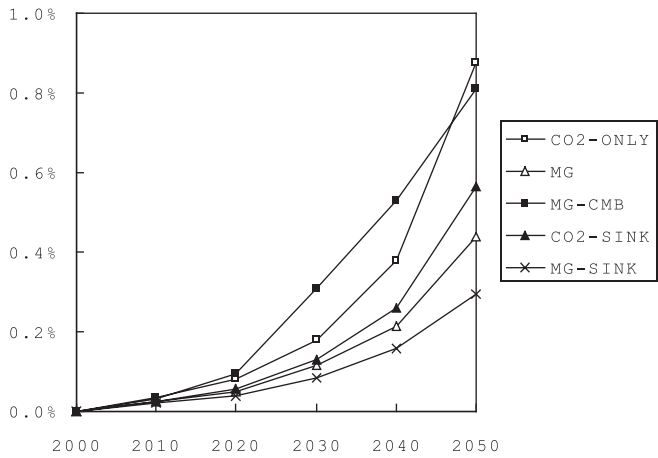
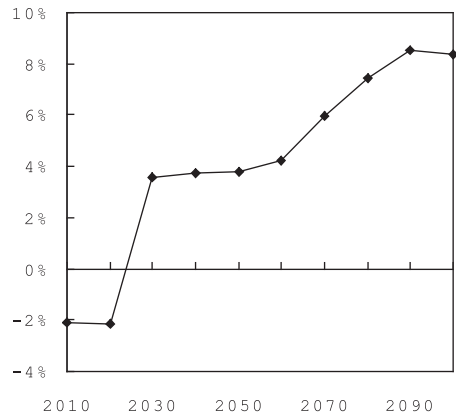


Figure 12. Global Non-CO₂ Ancillary Benefit Index by Fossil Fuel Reduction (CO₂-ONLY case)



economic incentive and/or public outreach. Technology is the vital factor but the existence of GHG mitigation option itself is not enough to activate actions. It will not be used without utilization know-how and local management which is suitable for regional conditions. The co-benefit of GHG mitigation can be driving element of mitigation policy. Energy recovery in the carbon sequestration would produce additional gas and oil production by EOR (Enhanced Oil Recovery) and ECBM (Enhanced Coal Bed Methane). In addition, fossil fuel saving actions improves the local air quality indicators, such as SO_x and NO_x.

The simulation result suggests that relative importance of long-lived GHG action in a short period. But short-lived GHGs mitigation actions are also

important since some GHGs' concentration and radiative forcing have been already much higher than those of pre-industrial and their warming effect cannot be neglected.

5. CONCLUSIONS

Multi-gas mitigation should be included in the mitigation actions to realize comprehensive climate policy in spite of the uncertainty in technologies, climate dynamics, and socioeconomic conditions. The conclusions are threefold; (1) *Multi-gas mitigation is a cost effective strategy compared to CO₂- only mitigation under the same climate target*, (2) *CO₂ mitigation is expected to lead to ancillary reductions in CH₄, N₂O and SO_x emissions*, and (3) *There is great uncertainty in the assessment of non-CO₂ GHG mitigation opportunities*.

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Burden Sharing Within a Multi-Gas Strategy

Alain Bernard, Marc Vielle** and Laurent Viguiet****

The purpose of this paper is to assess and compare regional welfare costs associated with alternative multi-gas strategies for a stabilization of global greenhouse gases (GHG) emissions in the long run. Mitigation costs of non-CO₂ greenhouse gases are integrated into a multi-region multi-country CGE model of the world economy. Calibrations are based on GHG emissions projections from, and marginal abatement cost curves provided by, the EMF21 working group for the six greenhouse gases. We find that the introduction of non-CO₂ GHGs in the mitigation strategy reduces significantly the welfare cost of a long term emissions stabilization policy but that benefits vary across regions. We also find that the various possible rules of emission quotas allocation may have large effects on the burden sharing among regions.

1. INTRODUCTION

To be consistent with a long term objective of concentration stabilization, future agreements on climate change need to be global, to deal with all greenhouse gases (GHGs), and to address equity and cost-efficiency concerns. A large number of studies have explored the question whether a global agreement on climate change is likely to emerge (Barrett (1990)), and the way it might bring incentives for developing countries to participate through direct side payments (Germain et al. (1998), Germain and van Ypersele (1999)) or issue linkages (Barrett (1997), Carraro and Siniscalco (1996), Tol et al. (2000), Viguiet (2004)). Other contributions in the literature have shown that the incorporation of non-CO₂ GHGs in climate policies could substantially reduce the cost of meeting an emissions target (Manne and Richels (2001), Reilly et al. (1999)), though the

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contribution may greatly vary from one country to another and depend on the stringency of the emissions constraint (Hyman et al. (2003)). A growing body of literature has also analyzed equity issues regarding the allocation of emission allowances and the way abatement costs might be shared across countries (Bohringer and Loschel (2003), Babiker and Eckaus (2002), Blanchard et al. (2003), Grubb (1995)). Other have assessed the efficiency gains from introducing international emissions trading and CDM (Babiker et al. (2000), Bernard and Vielle (1999), Criqui et al. (1999)).

This paper is an attempt to put these different issues together. It explores alternative multi-gas strategies to stabilize global GHG emissions in the long term. We show that political decisions on initial allocation of emissions quotas across countries are still a major concern when all the GHGs are constrained and when countries can freely trade emission permits. Even in this cost-effective framework, decisions on the choice of the allocation rule affect significantly the burden sharing across countries. Our estimates are based on regional baseline emissions projections for the period 1990 to 2020 and on cost estimates for mitigation provided by the EMF21 working group for the six greenhouse gases (Delhotal et al. (2007), De Angelo et al. (2007), Ottinger et al. (2007), Scheehle and Kruger (2007)) and for forest sequestration (Sohngen and Sedjo (2007)).

In section 2, we briefly present the GEMINI-E3 model, along with the methodology implemented for estimating welfare costs of climate policies. In section 3, we describe the approach for incorporating non-CO₂ GHGs emissions and abatement costs in GEMINI-E3. In Section 4, we present numerical results showing the economic gains from a multi-gas strategy to stabilize GHG emissions in the long run. In section 5, we consider different rules that might be used to allocate emission allowances across countries, and assess these rules in a multi-gas approach with international emission trading. Section 6 concludes.

2. THE MODEL

We assess the economic impacts of implementing multi-gas strategies using the GEMINI-E3 model. GEMINI-E3 is a multi-country, multi-sector, dynamic computable general equilibrium model incorporating a highly detailed representation of indirect taxation¹. The new version of GEMINI-E3 used in this paper is built on a comprehensive energy-economy data set, the GTAP-5 database (Hertel (1997)), that models both energy markets in physical units and macroeconomic relations and constraints through a detailed Social Accounting Matrix (SAM), for a large set of countries or regions, and bilateral trade flows. The reference case for each country/region has been closely calibrated onto a mix of projections of CO₂ emissions, energy consumption, GDP, and population, provided by the U.S. Department of Energy (Energy Information Administration

1. This version of GEMINI-E3 is formulated as a mixed complementarity problem using GAMS with the PATH solver (see Ferris and Munson (2000), Ferris and Pang (1997)).

Table 1. Dimensions of the GEMINI-E3 Model

Countries or Regions		Sectors
Annex B		Energy
Germany	DEU	01 Coal
France	FRA	02 Crude Oil
United Kingdom	GBR	03 Natural Gas
Italy	ITA	04 Refined Petroleum
Spain	ESP	05 Electricity
Netherlands	NLD	Non-Energy
Belgium	BEL	06 Agriculture
Rest of EU-15	OEU	07 Mineral products
Switzerland	CHE	08 Chemical Rubber Plastic
United States	USA	09 Metal and metal products
Japan	JAP	10 Paper Products Publishing
Eastern Europe ^a	CEA	11 Transport n.e.c.
Canada, Australia, and New Zealand	CAZ	12 Sea Transport
Former Soviet Union	FSU	13 Air Transport
Non-Annex B		14 Other Goods and services
China	CHI	
Brazil	BRA	Household Sector
India IND		
Middle East and Turkey	MID	Primary Factors
Asia	ASI	Labor
Latin America and Mexico	LAT	Capital
Rest of World ^b	ROW	Energy
		Fixed factor (sector 01-03)
		Other inputs

a. Includes Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovakia, and Slovenia.

b. All countries not included elsewhere (mostly Africa).

(2003)), the International Energy Agency (International Energy Agency (2002a), International Energy Agency (2002b)), the World Bank and the United Nations.

The original version of GEMINI is fully described in Bernard and Vielle (1998)². Updated versions of the model have been recently used to analyze the implementation of economic instruments for GHG emissions in a second-best setting (Bernard and Vielle (1999)), to assess the economic impact of US withdrawal from the Kyoto Protocol (Bernard and Vielle (2002)), the market power of Russia in the carbon market (Bernard et al. (2003)), and to assess the EU-wide carbon emission trading scheme implemented by the European Union (Viguier et al. (2006)).

Table 1 gives an overall description and the main characteristics of the present version of the model. Beside a comprehensive description of indirect taxation, the main feature of the model is to simulate all relevant markets: markets for commodities (through relative prices), for labor (through wages), for domestic

2. For a complete description of the model see our web site and the technical document downloadable at: <http://gemini-e3.epfl.ch/>

and international savings (through rates of interest and exchange rates). Terms of trade, i.e. transfers of real income between countries resulting from variations of relative prices of imports and exports, and then “real” exchange rates, are also closely coped with.³

The welfare cost of energy and environment policies is measured comprehensively by the households’ surplus since final demand by other institutional sectors is supposed constant in the scenarios⁴. It is then the sum of the change in income and of the “Equivalent Variation of Income” (*EVI*) measured from the change in prices according to the classical formula. In the case of a STONE-GEARY utility function, the Equivalent Variation of Income for a change of the price system from the initial situation ($\overline{PC}_i$) to the final situation (PC_i) is such as:

$$\frac{\overline{HCT} - \sum_i \overline{PC}_i \cdot \phi_i}{\Pi_i (\overline{PC}_i)^{\beta_i}} = \frac{\overline{HCT} + EVI - \sum_i \overline{PC}_i \cdot \phi_i}{\Pi_i (PC_i)^{\beta_i}} \quad (1)$$

where ϕ_i is the minimum consumption and β_i the marginal budget share of good i in the demand function, and $\overline{HCT}$ is the total household consumption. The households’ surplus is then:

$$S = \left(HCT - \sum_i PC_i \cdot \phi_i \right) - \Pi_i \left(\frac{PC_i}{\overline{PC}_i} \right)^{\beta_i} \left(\overline{HCT} - \sum_i \overline{PC}_i \cdot \phi_i \right) \quad (2)$$

In a closed economy, the households’ surplus reflects the pure substitution effect of taxation, i. e. the Deadweight Loss of Taxation (*DWL*). In an open economy, income effects are added to the pure substitution effect through the change in the relative prices of foreign trade. The associated gains or losses from “terms of trade”, as they are known in the foreign trade literature, may be an important and even in some cases a major part of the total welfare gain or loss for a given country (though of course, they are transfers from one country to the other and sum to zero at the world level) (Babiker et al. (2004)).

The way it works in the model is that, from the numerical results the households’ surplus (*S*) and the gains from terms of trade (*G*) are directly computed, and then the *DWL* -that represents the “domestic cost” of the policy- is obtained by subtracting the latter to the former:

$$G = \sum_i (PX_i - \overline{PX}_i) EX_i - \sum_i (PI_i - \overline{PI}_i) M_i \quad (3)$$

3. The real exchange rate between two countries is the relative price of the numéraires chosen in each country (and usually based on a basket of goods representative of GDP). It is not identical to the monetary exchange rate of the currencies of the two countries: in particular, the real exchange rate can evolve between countries belonging to a same monetary union.

4. Total investment by firms is constant, but not its allocation among sectors.

$$DWL = S - G \quad (4)$$

where PI_i , PX_i , M_i and EX_i represent respectively the prices of imports and exports and the quantities of imports and exports.

3. INTRODUCING NON-CO₂ GREENHOUSE GASES

For non CO₂ GHG, all the data on emissions and abatement costs were provided by the EMF21 Working Group⁵ on Multi-Gas Mitigation and Climate Change.

3.1 Modeling Non-CO₂ Greenhouse Gases Emissions

We take into account 12 sources of CH₄ emissions and 9 sources of N₂O emissions on the basis of the EMF21 database (Scheehle and Kruger (2007)). Four types of fluorinated gases are also introduced in the model: PFCs, SF₆, HFC-23, other HFCs (Ottinger et al. (2007)). PFCs include all high-GWP gases emitted from aluminum and semiconductor manufacturing, including CF₄, C₂F₆ and C₃F₈. SF₆ includes all high-GWP emissions from the production and processing of magnesium and from the use of electrical equipment. HFC-23 represents all high-GWP emission from the production of HCFC-22. Other HFCs include all high-GWP gases emitted during their use as substitutes to ozone-depleting substances, including emissions from air conditioning and refrigeration equipment, foams, solvents, MDI and non MDI aerosol, and fire extinguishing equipment. This includes primarily HFCs with lifetimes under 100 years.

The emissions of each source, GHG_i , are linked to an activity level (or an economic driver):

$$GHG_i = \frac{v_i}{\theta_i} \cdot ED_i \quad (5)$$

where ED_i is the economic driver, v_i stands for a coefficient representing the amount of source i emitted by the economic driver and θ_i is an exogenous technical progress on the coefficient v_i . v_i is calibrated on the basis of the emission inventories provided by the EMF21 for the 1990-2020 period. After 2020 we suppose that the technical progress associated with v_i is equal to 2% per year for CH₄ and N₂O emissions and 1.5% for fluorinated gases.

In Appendix 1, we depict the correspondence between the sources and the sectors/products in GEMINI-E3, the variables of the model representing the economic drivers, and the availability of marginal abatement cost curves in the EMF21 database.

5. For information on the Energy Modeling Forum: <http://www.stanford.edu/group/EMF/home/index.htm>

3.2 Modeling Abatement Costs for Non-CO₂ Greenhouse Gases Emissions

Abatement is computed on the basis of the EMF21 abatement curves (see Delhotal et al. (2007), De Angelo et al. (2007), Ottinger et al. (2007)). There are different ways to introduce abatement cost function in a CGE model. As in Hyman et al. (2003), one can model GHGs directly as an input into the production function. In this approach, a new CES is introduced, generally at the top of the nested CES structure, between these GHGs and the other standard inputs. This new CES is calibrated through the elasticity of substitution. The substitution parameter is estimated in such a way that the CES matches marginal abatement costs derived from bottom-up data. This approach is well-adapted to a CGE framework and permits to represent abatement costs for non-CO₂ gases. However, the estimated CES do not always give an accurate approximation of the discontinuous marginal abatement cost curves from the EMF21. This is why we decided to introduce directly the MACs in the model. From the 15 break even carbon prices given by the EMF21, we derive a curve by doing a linear interpolation between each price. Then we can compute the level of emissions, GHG_i , on the basis of a GHG tax using the following equation:

$$GHG_i = \frac{v_i}{\theta_i^a} \cdot [1 - f_i^{a,b}(TGHG)] \cdot ED_i \quad (6)$$

with $a \leq TGHG \leq b$

where $f_i^{a,b}(TGHG)$ is a linear approximation of the abatement curve between the two break even prices of carbon corresponding to the tax, $TGHG$. We do not incorporate any technical progress in the MAC curve after 2020.

The total cost of abatement is approximated by the integral of the marginal abatement cost on the interval $[0, TGHG]$. In order to avoid non-constant returns to scale in production functions, we suppose that the operational cost of abatement is bounded by the government and consists of government consumption.

Government consumption is then the sum of two terms: a “final” good, which is representative of various services for households and the economy as a whole; and “intermediate” good which is the abatement cost corresponding to the integral of the MAC curve.

This distinction is important in GEMINI-E3 since climate change scenarios are implemented, as previously mentioned, at constant final demand (except obviously households’ final consumption and imports, and in particular at constant government final consumption) in order to get relevant yearly measures of welfare costs.

Finally the taxes on non-CO₂ greenhouse gases are included into the base price of the sector that emits the pollutant.

4. CARBON STRATEGY VERSUS MULTI-GAS STRATEGY

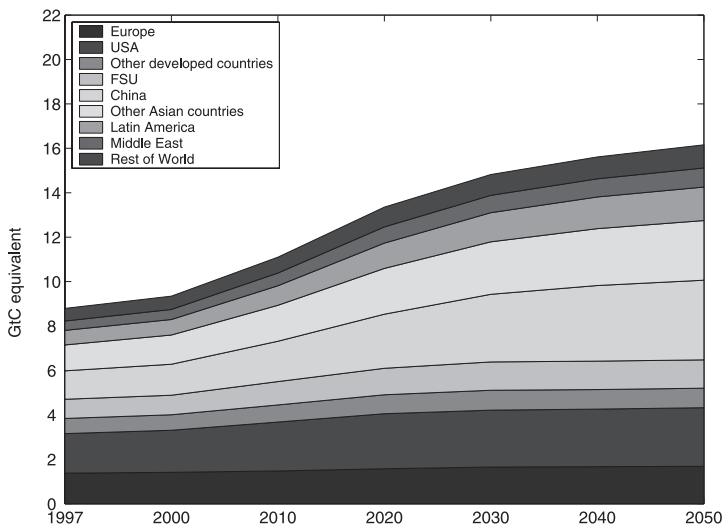
4.1 Reference Case

The reference case for the different regions is closely calibrated onto the projections of CO₂ emissions, energy consumption, GDP, and population provided by the U.S. Department of Energy (Energy Information Administration (2003)) for the years 2000 to 2025. After 2025, we assume a convergence of GDP growth rates to 2% per year for developed regions and 2.5% per year for developing regions that are reached at the end of the baseline projection. Greenhouse gases emissions are projected to reach 13 Gt of carbon equivalent in 2020 and 16 GtC equivalent in 2050. Figure 1 details the regional GHG emissions in the reference case. The share of developing countries in global GHG emissions is projected to increase from 48% in 2000 to around 60% in 2050. At the world level, the contribution of carbon emissions remains stable at around 72% of total GHG emissions.

4.2 Policy Scenarios

We run two types of policy scenarios with GEMINI-E3: (i) A *CO₂-only scenario* where only carbon dioxide emissions are taxed and (ii) a *multi-gas scenario* in which all GHG emissions are taxed using a 100-yr GWPs equivalent between gases. In the two cases we use the optimal trajectory for worldwide GHG emissions provided by the MiniCAM model and based respectively on the *Long-term CO₂-only Stabilization Scenario* and on the *Long-term Multigas Stabilization Scenario* as defined by the EMF21 working group.

Figure 1. Regional Greenhouse Gas Emissions – Reference Case



In the two scenarios the emissions constraint is assumed to be reached through the implementation of a worldwide uniform tax, expressed in US dollars, without emission trading. The opportunity of introducing international emission trading is discussed in section 5. Finally the scenarios presented hereafter do not include any sinks contribution.

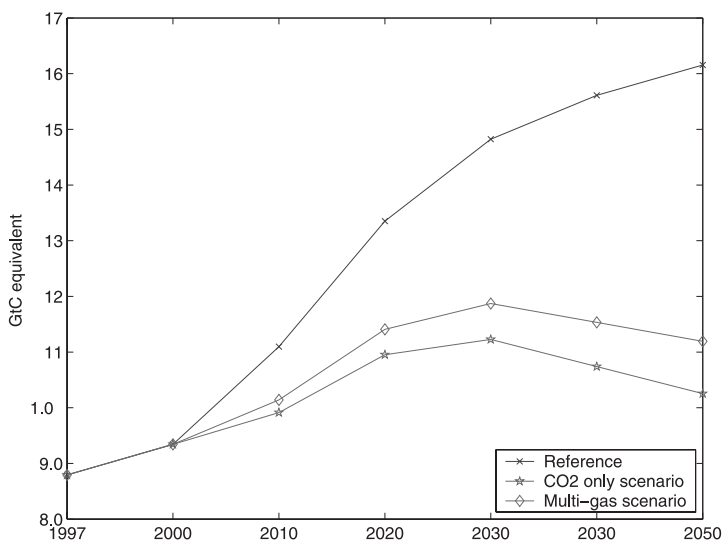
As shown in Figure 2, the constraint on worldwide GHG emissions is reduced when non-CO₂ gases are included in the climate policy. In the multi-gas scenario, GHG emissions are projected to decrease by 30% in 2050 compared to the reference case. In the CO₂-only scenario GHG emissions are supposed to go 36% below the baseline scenario.

4.3 The Gains from Multi-Gas Policies

When a multi-gas strategy is implemented, the cost of abatement can be significantly lower (Hyman et al. (2003), Reilly et al. (1999)). The carbon tax is reduced by a factor greater than 2. The CO₂ tax rises from 30 US dollars per ton of carbon equivalent (USD/tC-Eq.) in 2010 to 302 USD/tC-Eq. in 2050 in the CO₂ only scenario. In the multi-gas scenario, the GHG tax goes from 10 USD/tC-Eq. in 2010 to 113 USD/tC-Eq. in 2050.

Globally, the welfare cost of the CO₂-only policy is evaluated to be around 820 billions of 2000 US dollars. This global welfare cost is reduced to 300 billions of US dollars when all the greenhouse gases are taxed. As shown in Figure 3, the welfare effects might greatly differ from one country to another, and three types of countries or regions may be distinguished:

Figure 2. Global Greenhouse Gas Emissions – Reference Case and the Global Constraints



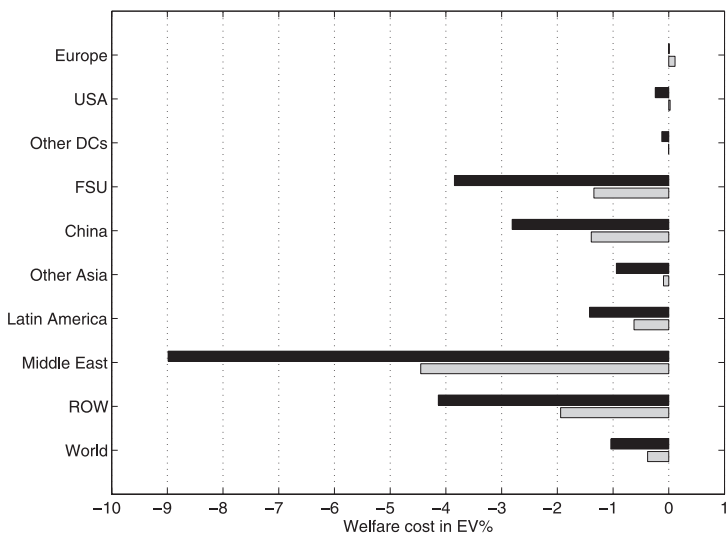
- Low-cost regions; i.e. industrialized countries that are the least affected by the implementation of a uniform GHG tax. These countries, in particular those of the European Union, benefit from gains in the terms of trade. Moreover the incremental taxation on GHG emissions induces a smaller relative increase of energy prices than in developing countries because of their high initial taxation (Babiker et al. (2003), Bernard et al. (2003)). Thus, the contribution to GHG emissions abatement is relatively lower in these regions;
- Medium-cost regions; i.e. developing countries which face an important increase in energy prices that are not outweighed by gains from terms of trade;
- High-cost regions; i.e. energy exporting countries (Middle East and Former Soviet Union) where the constraint on GHG emissions implies deadweight losses, negative terms of trade effects, and a decline of revenues from fossil energy exports (Babiker et al. (2000), Bernard et al. (2003)).

Finally, the introduction of a multi-gas strategy is profitable for all countries and reduce significantly the cost of the greenhouse gas constraint.

4.4 Contribution of Various GHGs

At the world level, the contribution of non-CO₂ GHGs to total abatement in a multi-gas strategy is 20% in 2050; 13% of the abatement comes from a reduction of methane, 4.2% from fluorinated gas, and 3.2% from nitrous oxide. Non-CO₂ GHG emissions are lower in the CO₂-only scenario than in the reference case. Effectively, non-CO₂ emissions are reduced in the energy sector as a result of the abatement of CO₂ emissions. This is in particular the case for methane emissions

Figure 3. Welfare Costs -CO₂ vs. Multi-Gas Policy



linked to coal mining and natural gas system (production, processing, transmission and distribution), other methane emissions linked to the use of fossil fuel energy, and nitrous oxide emissions resulting from fossil energy combustion. The contribution of non-CO₂ gases is estimated to be around 3.6% of total GHG emissions reduction in the *CO₂ only scenario* (3.3% for methane and 0.3% for N₂O).

At a regional level, the results are more contrasted and depend mainly on the shares of the different gases in the reference scenario. For example in the countries or regions where electricity is mainly generated from non carbon sources (i.e. hydraulic and/or nuclear), the share of CO₂ reduction is relatively small (i.e. 44% in France or Switzerland). In other countries, the share of CO₂ reduction may also be small because of the high contribution of agriculture (i.e. 36% in Brazil where emissions from animals and their waste are large) and consequently the multi-gas strategy is then particularly efficient. When on the opposite the fuel mix is dominated by fossil fuels, the contribution of CO₂ in total abatement tends to be higher (i.e. 81% in the US and 86% in China), and the gains from a multi-gas strategy are more limited.

5. ALLOCATION REGIMES WITHIN THE MULTI-GAS STRATEGY

In this section, we assess and compare a set of proposals for allocating quotas in a global agreement on climate change. The scenarios are defined in such a way that the long-term multi-gas stabilization target as defined by EMF21 working group is reached.

5.1 Alternative Rules for Allocating Emission Quotas

Different options have been proposed for designing a global agreement on climate change (Baumert et al. (2002)). As noted in Blanchard et al. (2003), one cannot expect to identify just one fair solution for allocating quotas and then sharing the economic burden between countries. Experience shows that negotiators do not put forward a single allocation rule based on a clearly identified value judgment on equity but a mix that takes into account their own features and situation. Among the great numbers that have been put forward, seven options are considered here:

1. Allocation of quotas that equalizes marginal abatement costs across countries (TAX);
2. Allocation of quotas according to ability to pay, represented by GDP (ABILITY);
3. Allocation of quotas proportional to population (POP);
4. Allocation of quotas proportional to GHG emissions per dollar of GDP (GDP);
5. Allocation of quotas proportional to emissions in the reference case (SOV);

6. Allocation of quotas that equalizes welfare costs as a percentage of GDP (WELF);
7. Allocation of quotas that equalizes welfare costs per capita (WPOP).

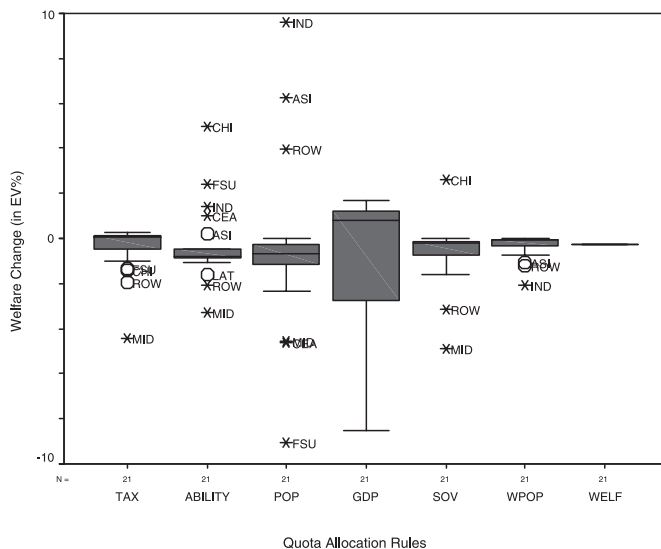
These allocations covering all GHG emissions are assessed and compared, assuming they can be freely traded in a competitive world carbon market.

5.2 Comparison and Assessment of the Different Rules

Figure 4 shows a Tukey's box & whiskers plot for the distribution of welfare costs in equivalent variation under the different allocation rules for GHG emissions quotas across the 21 GEMINI-E3 regions by 2050. It appears that the *ABILITY* and *POP* scenarios give a large number of extreme data points. In the *ABILITY* scenario, five regions are above the whisker -Asia (0.2%), Eastern Europe (0.98%), India (1.4%), FSU (2.4%), and China (5%) -and three are below -Latin America, (-1.6%), the rest of world (-2.1%) and Middle East (-3.3%). The *POP* scenario presents very extreme data points. The Middle East (-4.5%), Eastern Europe (-4.6%) and particularly FSU (-9.1%) would support a very high burden whereas the rest of world (3.9%), Asia (6.2%) and India (9.6%) would largely benefit from climate protection.

The *GDP* scenario does not have extreme points but the distribution is highly asymmetric. The box representing the interquartile range is large compared to other allocation rules, and the whisker is asymmetric. In this approach, welfare

Figure 4. Welfare Change Under Alternative Allocation Rules



costs are distributed in the range of -8.5% in FSU and the Middle East to +1.4% and +1.7% in Switzerland and France, respectively.

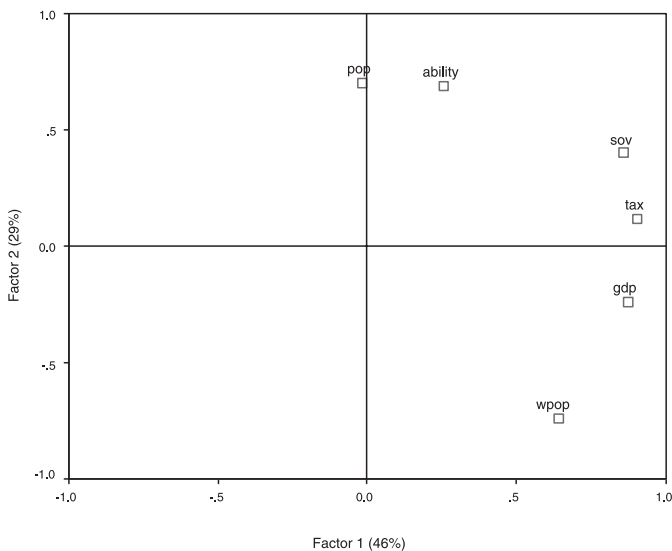
In the *TAX* and *SOV* scenarios, the distribution is also asymmetrical but it is relatively concentrated: 50% of the countries would have a welfare cost in the range of -0.7% to +0.1% in the *TAX* scenario, and -0.7% to -0.1% in the *SOV* scenario. The whispers are also relatively small and the number of data outside the whispers is limited. The two allocation schemes are costly for the Middle East which supports a welfare cost estimated at around -4.5% in 2050.

The *WPOP* scenario has by far the lowest variance, except the *WELF* case which gives, by definition, the same welfare costs across the different regions. This allocation rule that equalizes per capita welfare costs gives almost the same welfare costs across developed countries but would impose a higher burden on high population-growth developing countries such as India, Asia, and China.

In order to identify patterns in data, and expressing the data in such a way as to highlight their similarities and differences, one can perform a principal component analysis. Figure 5 shows a projection of the initial variables in a two-factors space⁶. The two factors bear 75% of the initial variance of the data. The six variables are far from the center, which means that they are significantly correlated.

The horizontal axis (factor 2) is linked to the shape of the cloud of data. Closed to zero, the *POP* and *ABILITY* scenarios are well approximated through a

Figure 5. Principal Component Analysis of the Allocation Rules



6. Note that the *WELF* case is not relevant in this analysis since all the observations are reduced to one data point.

third degree polynomial interpolation. These allocation rules correspond to “win-loose” situations where (i) a large set of countries support low welfare costs, (ii) some regions are largely better off with the agreement on climate change, and (iii) some other regions are worse off. The winners and losers are not necessarily the same countries in the two scenarios. For example, FSU would be favored in the *ABILITY* scenario but disadvantaged in the *POP* scenario.

On the right of the graph, one can find scenarios characterized by logarithmic distributions (i.e. *TAX*, *SOV* and *GDP*). Thus, in the *TAX* and *SOV* scenarios, the welfare costs range from around -5% to zero. These scenarios may be defined as “loose-loose” situations. Nobody gains from the new constraint on GHG emissions.

The vertical axis is linked with the ranking of countries and regions in the different scenarios. On the bottom of the graph, the *WPOP* scenario is costly for high-population low-income countries (i.e. India, China, and Asia). On the top, the *POP* and *ABILITY* scenarios are generally in favor of large developing countries like Asia or India.

This analysis shows that the implementation of simple abstract principles of distributive justice to the difficult problem of quota allocation is not trivial. Even if one assumes a multi-gas policy with full emission trading, the initial GHG emission quotas across countries is likely to have large distributive effects. From the point of view of developing countries, the political acceptability of these rules decreases when one shift down and drag right on figure 5. It is the reverse from the developed countries point of view. Equalize welfare costs across countries (*WELF*) is an elegant solution to avoid these distributive impacts of the climate change policy. But this approach is built on model-based results and creates few incentives for developing countries to participate.

6. CONCLUSION

In accordance with previous studies, we find that the introduction of non-CO₂ GHGs in the mitigation strategy may reduce significantly the economic cost of long term emissions stabilization. If all regions benefit from a multi-gas strategy, the gains vary across regions depending on (i) the different contribution of GHGs due to economic structures (i.e. share and characteristics of agriculture), fuel mix in the electricity sector, and pre-existing energy taxation, and (ii) differences in mitigation costs.

We also find that the process of allocating initial emission quotas may have large effects on regional costs, even if emissions permits can be traded internationally. The choice of the allocation rule may largely change the distribution of the economic costs. It comes from our numerical simulations that the allocation schemes based on ability and population criteria would create different categories of players. Since “winners” and “losers” are likely to be developing countries, it is difficult to expect a global agreement based on these rules. One could use equality in welfare costs as the benchmark. However, the

weakness of any welfare-based rule is in the disagreements that would inevitably arise over the choice of the welfare function (Babiker and Eckaus (2002)). The allocation that would result from harmonized carbon tax also raises a number of problems. In particular, it appears that welfare costs would be low -or even negative -in developed countries whereas developing countries would support high costs -in particular the Middle East.

One can then conclude that incorporation of non-CO₂ GHGs and emissions trading would hardly create enough incentive for developing countries to participate to a global agreement on climate change. Whatever the proposed allocation rule, the post-Kyoto climate change policy architecture will have to consider innovative mechanisms that would be able to create incentives for international cooperation.

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APPENDIX

Appendix 1. Methane, Nitrous Oxide, and Fluorinated Gases in GEMINI-E3

Source	Economic Drivers	Sector/ Product	MAC
CH ₄			
Biofuel Combustion	Households' Consumption	14	
Biomass Burning	Households' Consumption	14	
Coal Mining	Production	1	Yes
Enteric Fermentation	Production	6	Yes
Fuel stat. + mobile sources	Domestic Production	4	
Manure Management	Production	6	Yes
Natural Gas System	Domestic consumption	6	Yes
Oil System Domestic	Production	4	Yes
Rice production	Production	6	Yes
Solid Waste	Households' Consumption	14	Yes
Wastewater	Households' Consumption	14	
Other Sources	Households' Consumption	14	
N ₂ O			
Agri. Soil Management	Production	6	Yes
Other Agri. Sources	Production	6	
Biomass Fuel	Households' Consumption	14	
Fossil Fuel Combustion	Fossil Fuel Consumption	1,3,4	
Manure Management	Production	6	
Other Non Agri. Sources	Households' Consumption	14	
Adipic Acid Production	Production	8	Yes
Nitric Acid Production	Production	8	Yes
Human Sewage	Households' Consumption	14	
Fluorinated Gases			
PFCs	Households' Consumption	14	Yes
SF ₆	Households' Consumption	14	Yes
HFC-23	Households' Consumption	14	Yes
other HFCs	Households' Consumption	14	Yes



Non-CO₂ Greenhouse Gases in the Second Generation Model

Allen A. Fawcett* and Ronald D. Sands**

The Second Generation Model (SGM) was developed to analyze policies designed to reduce greenhouse gas emissions. This paper documents how greenhouse gas emissions are calculated in the SGM, and provides an application to several Energy Modeling Forum scenarios that stabilize radiative forcing by using policies that either exclusively limit CO₂ emissions or include both CO₂ and non-CO₂ greenhouse gases. Additionally, this paper discusses an extension which includes advanced fossil generating technologies with CO₂ capture and storage in the USA region of the SGM.

1. INTRODUCTION

There is likely no silver bullet that will solve the global climate change problem. Instead, a whole range of different mitigation options should be examined in order to achieve any climate policy goal. Limiting the focus of a climate policy to any particular subset of options has the potential to greatly increase the cost of achieving any particular target. This paper examines the cost reductions that can be achieved by including non-CO₂ greenhouse gases in a climate policy, compared to a policy focusing solely on CO₂ emissions from the combustion of fossil fuels. The paper also looks at several other emissions mitigation options and their potential roles in addressing climate change, including biofuel offsets, afforestation, sequestration in agricultural soils, and geologic sequestration.

The first section of this paper gives some background information about the extent and structure of the SGM, while the second section describes in some detail the emissions calculations in the SGM for both CO₂ and non-CO₂

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greenhouse gases. The third section shows the importance of including non-CO₂ greenhouse gases in a climate policy and analyzes the scenarios designed by the Energy Modeling Forum (EMF-21). The final section of the paper examines biofuel offsets, afforestation, sequestration in agricultural soils, CO₂ capture and storage, how these additional options can be incorporated into the SGM, and what role these options can play in greenhouse gas emissions abatement.

2. SGM BACKGROUND

The Second Generation Model (SGM) is a collection of 14 regional computable-general-equilibrium (CGE) models with an emphasis on energy transformation, energy consumption, and greenhouse gas emissions. Regional models may be run independently or as a system with international trade in carbon emissions rights. The SGM is maintained at the Joint Global Change Research Institute, operated by Pacific Northwest National Laboratory and the University of Maryland. The original SGM technical presentation is provided by Edmonds, *et al.* (1991). More recent documentation includes model theory (Fawcett and Sands, 2005) and an overview of model data and parameters (Sands and Fawcett, 2005).

The SGM projects economic activity, energy consumption, and greenhouse gas emissions for each region in five-year time steps from 1990 through 2050. It is designed specifically to address the following issues associated with global change: (1) projecting baseline carbon emissions over time for a country or group of countries; (2) determining the least-cost method to meet any particular emissions constraint; (3) providing a measure of the carbon price, in dollars per metric ton; and (4) providing a measure of the overall cost of meeting an emissions target.

The SGM contains some interesting model features: many of the regional models are developed jointly with analysts from that region; capital stock is segmented into five-year vintages by sector; capital stock is industry-specific; the elasticity of substitution between inputs is greater for new capital than for old capital vintages; and input-output tables are calibrated for consistency with base-year energy balances in order to maintain energy balance throughout the model time horizon.

A large set of parameters simulate technical change over time for any given production process. These parameters influence the rate of change in efficiency of all inputs to any particular production sector in the model. Separate parameters are available for each input to each production process. Furthermore, these rates of change in input efficiency can be varied at each five-year time step and are particularly useful for baseline calibration.

Each production process is represented by either a constant-elasticity-of-substitution (CES) or a fixed-coefficient (Leontief) production function. Most production sectors use a single production function for each capital vintage, but electricity is an important exception. The electricity sector is divided into

Table 1. Production Sectors and Subsectors in the SGM

	Sector #	Production Sector	Subsectors
Services	1	Everything else	
Energy Production	2	Crude oil production	
	3	Natural gas production	
	4	Coal Production	
Energy Transformation	5*	Coke production	
			Oil
			Gas
	6	Electricity generation	Coal
			Nuclear
	7	Oil Refining	Hydro
	8	Distributed gas	
Manufacturing	9*	Paper and Pulp	
	10*	Chemicals	
	11*	Cement	
	12*	Primary metals	
	13*	Non-ferrous metals	
	14*	Other industry and construction	
Transportation	15*	Passenger transport	
	16*	Freight transport	
Agriculture	17*	Grains and oil crops	
	18*	Animal Products	
	19*	Forestry	
	20*	Food processing	
	21	Other agriculture	

Sectors labeled with an asterisk are only included in the extended set of production sectors.

subsectors that represent alternative processes for generating electricity such as gas-turbine, coal-steam, nuclear, or hydro. Each electricity subsector has a separate production function, with its own heat rate and cost parameters. The original SGM production sectors covered three types of energy production, three types of energy transformation, one sector for primary agriculture, and an “everything else” sector. Some regional models have been extended to include additional production sectors to provide added coverage of energy intensive industries and transportation. The extended production sectors introduce two transportation sectors and six manufacturing sectors, disaggregate the agricultural sector into five separate sectors, and include an additional energy transformation sector. The electricity generation sector differs from the other production sectors: it has at least five subsectors or ways to generate electricity.

Many of the 14 regional models, including Canada, Western Europe, Japan, former Soviet Union, China, India, Mexico, Brazil, and South Korea were developed along with local institutions using local data. The models are then available to those institutions for their own analysis. For example, SGM-Japan has

Table 2. Regions in the SGM

Annex I	Non-Annex I
United States*	China*
Canada	India*
Western Europe	Mexico
Japan*	South Korea*
Australia and New Zealand	Middle East
former Soviet Union	Brazil*
Eastern Europe	Rest of World

Regions labeled with an asterisk have the extended set of production sectors listed in Table 1.

been used within Japan in a model comparison exercise of the cost of reducing greenhouse gas emissions. Currently, the base year for all SGM regions is 1990, and we have extended the number of production sectors in six of the SGM regions: United States, Japan, China, India, South Korea, and Brazil. Development efforts continue with data collection to bring all SGM regions to the full set of production sectors. Local data will be used where possible; otherwise global data sets will be used for economic input-output tables (Global Trade Analysis Project) and energy balances (International Energy Agency).

Output from SGM is often summarized as a set of marginal abatement cost curves that show the relationship between a carbon price and the quantity of emissions reduced relative to baseline emissions. The marginal abatement cost curves generally shift outward over time because of an expanding economy and the time required for capital stock turnover. These dynamics of carbon mitigation result partly from the vintage production structure of SGM. Model results have been used in several studies conducted by the Stanford Energy Modeling Forum (e.g., MacCracken *et al.*, 1999) and in various U.S. Government studies. Other applications include Sands *et al.* (1998) and Sands (2004).

3. SGM GREENHOUSE GAS EMISSIONS

Emissions of the following suite of gases are currently tracked in SGM:

- CO₂ emissions from fossil fuel combustion processes.
- CH₄ emissions which emanate from the production and distribution of natural gas, mining of coal, from the raising of ruminant animals, the growing of rice, from sanitary landfills, and from combustion processes (principally biomass burning).
- N₂O emissions from combustion processes, fertilizer use, and selected natural sources.
- HFC-23 emissions from the production of HCFC-22.
- Short lived HFC emissions from various uses as substitutes for ozone-depleting substances, including losses from refrigeration

Table 3. Greenhouse Gas Emissions Sources in the SGM

Gas	Source #	Emissions Source	Associated Production Sector
CO ₂	1	Oil Combustion	2 - Crude oil production
	2	Gas Combustion	3 - Natural gas production
	3	Coal Combustion	4 - Coal Production
CH ₄	4	Coal Production	4 - Coal Production
	5	Enteric	21 - Other agriculture
	6	Natural Gas Systems	10 - Distributed gas
	7	Oil Systems	2 - Crude oil production
	8	Landfills	1 - Everything else
	9	Manure	21 - Other agriculture
	10	Other Agricultural Methane	21 - Other agriculture
	11	Other Non-Agricultural Methane	1 - Everything else
	12	Wastewater	1 - Everything else
HFC-23	13	HFC-23	1 - Everything else
HFCs	14	Ozone Depleting Substances Substitutes	1 - Everything else
N ₂ O	15	Industrial Processes	1 - Everything else
	16	Manure	21 - Other agriculture
	17	Mobile Source	1 - Everything else
	18	Soil	21 - Other agriculture
	19	Stationary Source	1 - Everything else
PFCs	20	Aluminum	1 - Everything else
	21	Semiconductor	1 - Everything else
SF ₆	22	Electricity Distribution	6 - Electricity generation
	23	Magnesium	1 - Everything else

and air-conditioning equipment, foam blowing, aerosol propellants, cleaning solvents, and fire extinguishers.

- PFC emissions from aluminum and semiconductor production.
- SF₆ emissions from use in electrical switch gear and as a cover gas in magnesium smelting.

In the absence of a carbon policy, emissions are released costlessly into the atmosphere, and thus have no effect on either the cost of production or the demand for investment goods. In general, the release of CO₂ into the atmosphere is considered to be proportional to the energy content of the specific fuel by a fixed ratio and therefore largely independent of the sector or subsector in which the fossil fuel form is combusted. In contrast, since emissions of the non-CO₂ greenhouse gases are not limited to fuel use activities, a different procedure is required for tracking these emissions.

While greenhouse gas emissions in SGM are calculated in different ways for CO₂ and non-CO₂ gases, the same general strategy is used for all emissions. Emissions are assumed to be proportional to the scale of input utilization. The SGM uses a set of emissions sources that are each associated with the release of a particular greenhouse gas in the model. Each source is also associated with the production sector in the model that is most closely related to the actual emissions

activity. An emissions factor for each source links the quantity of output in the associated production sector with actual emissions. Table 3 shows the emissions sources in SGM along with their associated gases and sectors.

Note that since SGM contains a large amount of detail on energy production and transformation, and since CO₂ emissions are linked to fuel use activities, CO₂ emissions sources are closely related to their associated SGM production sectors. Emissions of the non-CO₂ gases originate from a much broader set of sources, therefore the SGM production sectors they are associated with are not as closely related to the source. The specifics of calculating emissions in SGM will be discussed in sections below.

3.1 CO₂ Emissions in the SGM

The combustion of fossil fuels drives CO₂ emissions in SGM. Essentially, SGM tracks the domestic demand for fossil fuels in energy units and converts this to emissions using an emissions factor that relates the energy content of the fuel to the carbon content. The following equation is used to find the carbon equivalent emissions of CO₂ from oil combustion in a particular region:

$$Emissions_{OilCmb} = EMC_{OilCmb} \cdot ((1 - \alpha_{OilPrd}) \cdot QDem_{OilPrd} - Trade_{RefOil}) \quad (1)$$

where: $Emissions_{OilCmb}$ is the carbon equivalent emissions of CO₂ from oil combustion, measured in millions of metric tons of carbon equivalent emissions (MtCe); EMC_{OilCmb} is the emissions factor for oil combustion, or the oil-specific carbon content in MtCe per exajoule (EJ) of the energy source;¹ $QDem_{OilPrd}$ is a quantity measure of the total domestic demand for goods from the oil production sector, measured in exajoules; α_{OilPrd} is the percentage of output from the oil production sector that goes to non-energy uses, which accounts for the fact that not all oil products are combusted; and $Trade_{RefOil}$ accounts for the trade of refined oil products measured in exajoules, ensuring that emissions from the combustion of refined oil products are attributed to the country where they are combusted. The entire term in parentheses represents the amount of oil that is combusted domestically in exajoules, so that emissions are ascertained by multiplying this term by the emissions factor.

Emissions from the natural gas combustion and coal combustion sources are similarly calculated. Carbon equivalent CO₂ emissions from natural gas combustion are found in a particular region using the equation below:

$$Emissions_{GasCmb} = EMC_{GasCmb} \cdot ((1 - \alpha_{GasPrd}) \cdot QDem_{GasPrd} - Trade_{DistNatGas}) \quad (2)$$

1. Millions of metric tons carbon equivalent per exajoule (MtCe/EJ) is equivalent to kilograms carbon equivalent per gigajoule (kgCe/GJ).

where: $Emissions_{GasCmb}$ is the carbon equivalent emissions of CO₂ (MtCe) from natural gas combustion; EMC_{GasCmb} is the emissions factor (MtCe/EJ) for natural gas combustion; $QDem_{GasPrd}$ is the total domestic demand (EJ) for goods from the natural gas production sector; α_{GasPrd} is the percentage of output from the gas production sector that goes to non-energy uses; and $Trade_{DistNatGas}$ accounts for the trade (EJ) of distributed natural gas.

Finally, the carbon equivalent CO₂ emissions from coal combustion are given by the following equation:

$$Emissions_{CoalCmb} = EMC_{CoalCmb} \cdot ((1 - \alpha_{CoalPrd}) \cdot QDem_{CoalPrd}) \quad (3)$$

where: $Emissions_{CoalCmb}$ is the carbon equivalent emissions of CO₂ (MtCe) from coal combustion; $EMC_{CoalCmb}$ is the emissions factor (MtCe/EJ) for coal combustion; $QDem_{CoalPrd}$ is the total demand (EJ) for goods from the coal production sector; and $\alpha_{CoalPrd}$ is the percentage of output from the coal production sector that goes to non-energy uses.

In the presence of a carbon policy, reductions in CO₂ emissions require reductions in the amount of fossil fuel combusted. In the model this means reducing the emissions activities associated with the release of CO₂, which requires reducing the domestic demand for coal, oil, and natural gas production.²

3.2 Non-CO₂ Emissions in the SGM

For non-CO₂ greenhouse gases, emissions factors do not represent a stoichiometric relationship between the output and actual emissions. In some cases this is because the relationship between emissions and the actual emissions activity is not stoichiometric, in others it is because the actual emissions activity is much more narrowly defined than the SGM production sector the emissions are associated with. Instead, base year emissions for each source, $Emissions_{i,1990}$ measured in MtCe,³ are used as an input, and the emissions factors, EMC_i measured in MtCe per dollar of output, are calculated by dividing base year emissions by the total demand from the associated production sector:

$$EMC_i = \frac{Emissions_{i,1990}}{TotDem_{j,1990}} \quad (4)$$

where $TotDem_{j,1990}$ is the base year domestic demand, measured in dollars, for the production sector j , which is the production sector associated with emissions source i . Emissions in future time periods, t , are calculated as follows:

2. Another option for reducing CO₂ emissions is capture and storage. Adding this option to SGM will be discussed later in this paper.

3. Emissions of non-CO₂ gases are converted to carbon equivalent emissions using global warming potentials from the 1996 IPCC Second Assessment Report.

$$Emissions_{i,t} = EMC_i \cdot (1 + EMCADJ_{i,t}) \cdot TotDem_{j,t} \quad (5)$$

where $EMCADJ_{i,t}$ is a time dependent adjustment parameter for the emissions factor for source i . This is used to tune emissions to an exogenous emissions forecast.

For the EMF-21 exercise, the EPA provided, through the Stanford Energy Modeling Forum, a set of emissions projections through the year 2020. These projections are detailed in Ottinger *et al.* (2006), and Scheehle and Kruger (2006). Emissions of the non-CO₂ greenhouse gases in SGM were tuned to these projections through 2020 using the $EMCADJ_{i,t}$ time dependent adjustment parameter. After 2020 there are two options for determining emissions in SGM. The first option is to simply hold the post 2020 time dependent adjustment parameters, $EMCADJ_{i,t}$, constant at their 2020 levels. With this option, changes in emissions of non-CO₂ gases after 2020 are solely driven by changes in the demand for goods from the associated production sectors. One problem with this approach is that it tends to overestimate the growth in emissions after 2020, since the growth rate of non-CO₂ emissions tends to be smaller than the growth rate of the production sectors they are associated with in SGM. For example, emissions of CH₄ from landfills in the US have a downward trend from 1990 to 2020, but since the associated production sector for this source is the service sector, holding the emissions factor constant after 2020 results in a reversal of this downward trend. Another option is to extrapolate the reference case emissions projections and use the time dependent adjustment parameters, $EMCADJ_{i,t}$, to adjust reference case emissions after 2020 to the extrapolated projections. This is the strategy used for the EMF-21 scenarios presented in this paper.

Emissions reductions for non-CO₂ gases are accomplished in two ways in the model. As is the case with CO₂ emissions, emissions of non-CO₂ gases can be reduced by lowering output from the associated production sectors. The second mechanism for non-CO₂ emissions reductions are exogenous marginal abatement cost curves. EPA provided, through the Stanford Energy Modeling Forum, a set of marginal abatement cost curves for various emissions activities, which are described in DeAngelo *et al.* (2006), DelHotal *et al.* (2006), and Ottinger *et al.* (2006). The following equation shows how emissions of non-CO₂ gases are calculated when using a marginal abatement cost curve.

$$Emissions_{i,t} = EMC_i \cdot (1 + EMCADJ_{i,t}) \cdot (1 - MAC_{i,t}) \cdot TotDem_{j,t} \quad (6)$$

where $MAC_{i,t}$ is the percentage reduction in emissions that can be achieved, given a particular carbon price, for emissions from source i in time period t . In the presence of a carbon policy that applies to non-CO₂ greenhouse gases, emissions from any particular source will be reduced as output from the associated sector falls, and emissions will be further reduced by an amount indicated by the marginal abatement cost curve for that source at the prevailing carbon price.

4. EXAMPLES FROM EMF-21 SCENARIOS

A number of scenarios were run by the modeling groups participating in EMF-21. The main purpose of these scenarios was to show the effect of including non-CO₂ greenhouse gases in a climate stabilization policy. Three primary scenarios using SGM were reported to EMF-21: (1) SGM reference case; (2) long-term, CO₂ only stabilization; (3) long-term, multigas stabilization. The two stabilization scenarios are both designed to stabilize radiative forcing at 4.5 Wm² relative to pre-Industrial times by 2150. This corresponds to an equilibrium temperature increase of 3.0°C, for a 2.5°C per CO₂ doubling in climate sensitivity. In the CO₂ only stabilization scenario, non-CO₂ greenhouse gases are excluded from the carbon policy, while in the multigas stabilization scenario, the entire suite of greenhouse gases is covered by the carbon policy.

Since SGM does not consider the extent of the effect various gases have on radiative forcing, an alternative method for running the scenarios was required. For short term models, global total emissions for all greenhouse gases (based on 100-yr GWPs) were provided by PNNL using the MiniCAM model that matched the stabilization target. The stabilization scenarios were implemented in SGM using full ‘when’ and ‘where’ flexibility. ‘When’ flexibility was achieved by allowing emissions banking. To meet the stabilization target with emissions banking, the carbon price path was set by allowing the carbon price to be a Hotelling price growing at a 3% interest rate, and the initial carbon price was set so that cumulative global CO₂ equivalent emissions from 2015 to 2050 were equal to the emissions total provided from the MiniCAM model over the same time

Figure 1. Global Reference Case Emissions

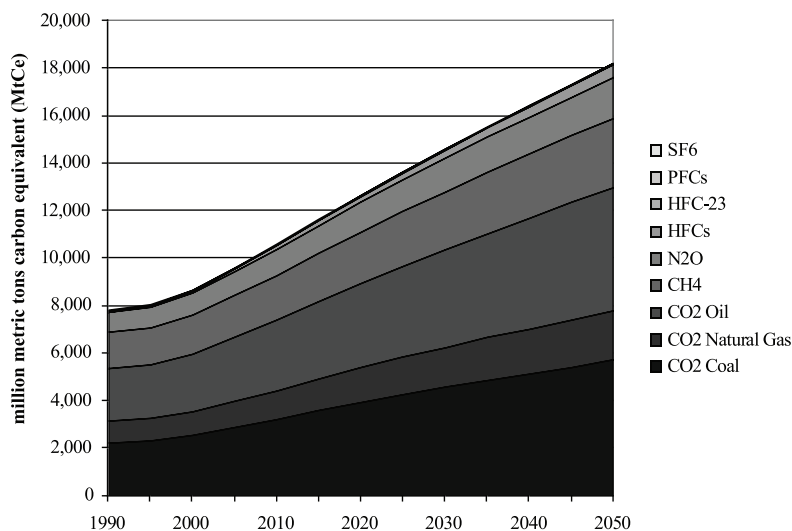
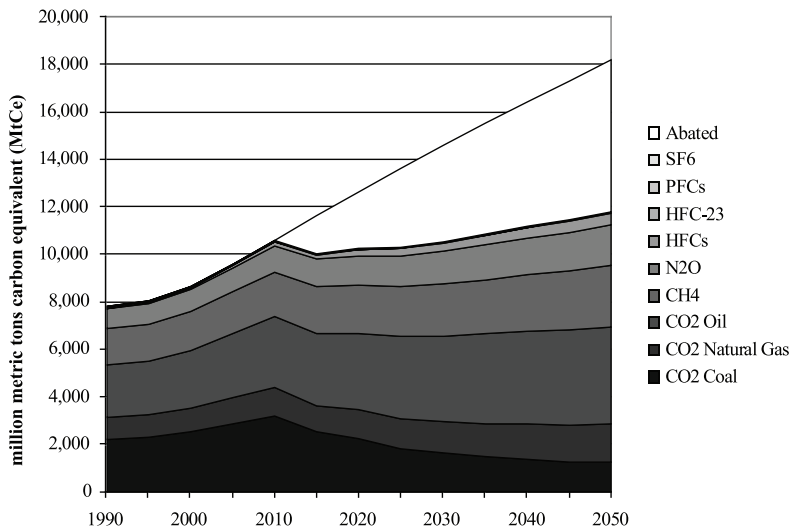


Figure 2. Global CO₂ Only Policy Emissions

period. The policy was implemented as a global carbon price, which equates the marginal cost of abatement across all countries in the model, and gives the model ‘where’ flexibility. Allowing the entire suite of greenhouse gases to be covered by the policy can be thought of as allowing ‘what’ flexibility to the model.

Global carbon equivalent emissions are broken out by greenhouse gas in Figure 1. Emissions of non-CO₂ greenhouse gases make up approximately 29% of the cumulative global total from 2010 to 2050. Emissions of CO₂ from coal combustion accounts for 31% of the total, and CO₂ from crude oil combustion makes up 28% of the total.

Figure 2 shows the global carbon equivalent emissions by greenhouse gas in the long-term, CO₂ only stabilization scenario. To achieve the targeted emissions reductions with a CO₂ only policy requires a 34% reduction in cumulative global CO₂ emissions from 2010 to 2050, while un-priced non-CO₂ emissions fall by only 6%. The majority of the CO₂ emissions reductions come from decreases in coal combustion which makes up only 18% of total emissions in the presence of the CO₂ only policy. This is primarily accomplished by fuel switching in the electricity sector.

In Figure 3 we see that in the long-term, multigas stabilization scenario, the targeted emissions reductions are achieved without the sharp reductions in CO₂ emissions from coal combustion seen in the previous scenario. Cumulative global CO₂ emissions from 2010 to 2050 are only reduced by 19%, while non-CO₂ emissions now fall by 43%.

To see how the carbon price differs under a CO₂ only policy versus a multigas policy, we can look the cumulative abatement curves presented in Figure

Figure 3. Global Multigas Policy Emissions

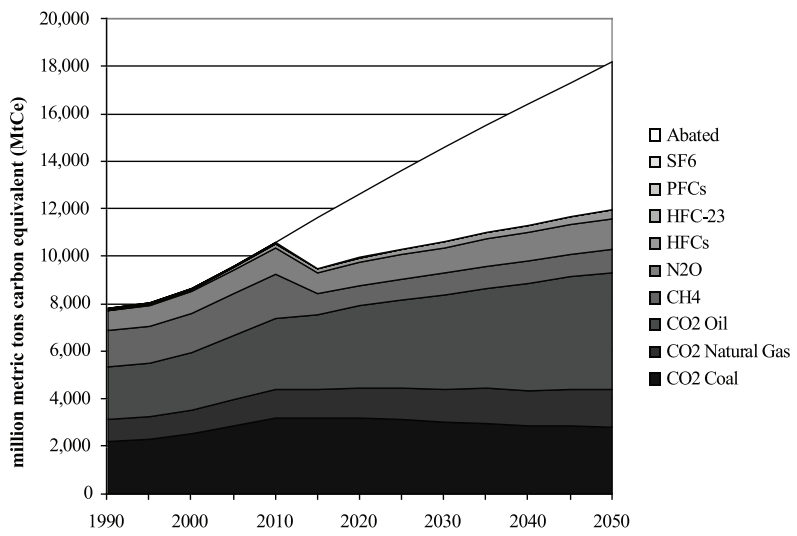
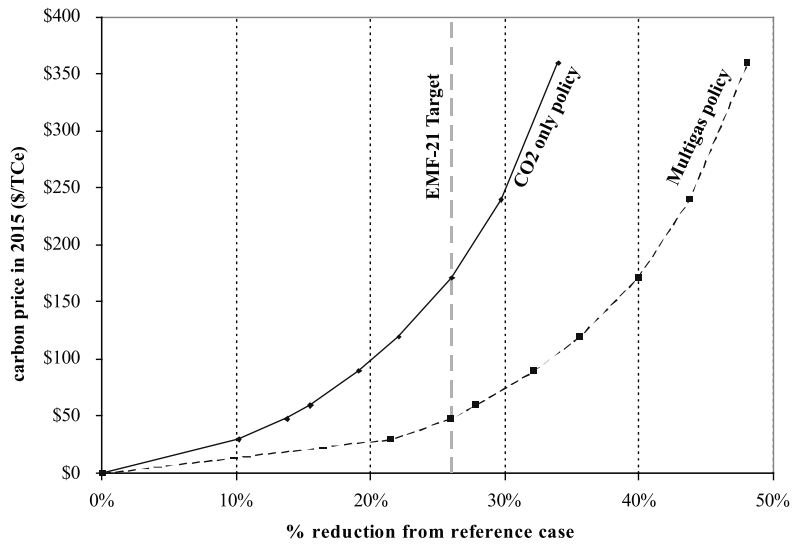


Figure 4. Global Cumulative Emissions Reductions (2013–2050 with Hotelling Price and 3% Interest Rate)



4. These curves were generated from a series of model runs with different starting values for the carbon price. The x-axis shows the percentage reduction in the cumulative global total carbon equivalent emissions from 2010 to 2050. The emissions targets in the EMF-21 scenarios correspond to a 26% reduction, which

can be achieved under a CO₂ only policy with an initial carbon price of \$143 in 2015, or by an initial carbon price of \$40 in 2015 under a multigas policy.

The emissions target in the EMF-21 scenarios is rather expensive to achieve with a CO₂ only policy. Under the long-term, CO₂ only stabilization scenario, reducing CO₂ emissions from the energy system is the only option for reducing emissions in the model. Within the energy system, the cheapest emissions reductions come from fuel switching in the electricity generation sector. More costly emissions reductions include reducing the use of refined oil in the transportation sectors, and reducing the demand for energy-intensive goods. In this scenario, most of the fuel switching options in the electricity sector are used, and further costly emissions reductions are required, resulting in a high carbon price. In the long-term, multigas stabilization scenario, much of the costly emissions reductions from reducing the use of refined oil in the transportation sectors and reducing the demand for energy intensive goods, are replaced by relatively inexpensive reductions of non-CO₂ greenhouse gases. This results in a much lower carbon price.

While the version of the model used in the above analysis represents the core of SGM, development of the model is an ongoing effort, and additional features continue to be added. One area of development is the inclusion of several additional emissions abatement options including renewable energy sources, soil carbon sequestration, and advanced fossil electricity generation technologies with CO₂ capture and storage. Including some of these additional abatement options should shift out the cumulative emissions reduction supply curve, and allow tighter emissions targets to be achieved at a lower cost in the model. The next section will discuss the development efforts aimed at including some of these additional emissions abatement options in SGM.

5. ADDITIONAL ABATEMENT OPTIONS IN SGM-USA

Previous sections of this paper provide a global analysis of the opportunities for reducing greenhouse gas emissions with full “where” flexibility along with mitigation options that include increased efficiency in energy combustion and reductions in emissions of non-CO₂ greenhouse gases. These methods are defined as:

Energy Combustion: Reduction in carbon emissions through reduced combustion of fossil fuels. This is modeled within a CGE framework as a response to a uniform carbon price. Carbon emissions respond to changes in the carbon price in three ways: shift in output among producing sectors, substitution of other inputs for energy within producing sectors, and shifts among electricity generating technologies.

Non-CO₂ Gases: Reduction in emissions of methane, nitrous oxide, and F-gases. Guidance from EMF-21 was used to establish a baseline for

these gases and the marginal abatement cost curves. However, EMF-21 provided baseline estimates through year 2020 only; modeler's judgment was used to extend the baseline through 2050.

A full analysis of greenhouse gas mitigation options should include all activities that reduce net emissions of CO₂ and other greenhouse gases, along with activities that store carbon. This section expands the set of mitigation options to include those from the terrestrial ecosystem and CO₂ capture and storage (CCS), defined as:

Terrestrial Options: Biofuel offsets, afforestation, and sequestration in agricultural soils. These options are simulated using exogenous marginal abatement cost curves based on McCarl and Schneider (2001) and Sands *et al.* (2002).

CCS: CO₂ capture from electricity generation and storage in geologic formations. Simulation of this option is accomplished by expanding the set of electricity generation technologies in SGM-USA to include CO₂ capture from pulverized coal, integrated gasification combined cycle (IGCC), and natural gas combined cycle (NGCC) generating plants. A constant cost per metric ton of storage is assumed for each of the capture and storage technologies. The methodology is described further in Sands (2004).

These additional mitigation options are considered for the United States, but are not operational at a global level in the SGM. Therefore, analysis in this section covers all of the above mitigation options for only the United States. This exercise is useful to understand the interaction among these options and to get an idea of the relative contributions of each to overall reductions in net greenhouse gas emissions.

5.1 Methodology

For energy combustion and non-CO₂ gases, mitigation potential is sensitive to assumptions about baseline emissions from the present to 2050. All of the greenhouse gas mitigation options require that a baseline be established as well as the cost of reducing emissions from the baseline. Figure 5 displays baseline emissions from energy combustion and the non-CO₂ gases. The energy baseline is from SGM-USA; the non-CO₂ baseline is from EMF-21.⁴

All of the mitigation options in this section are simulated as a response

4. Beyond 2020, non-CO₂ greenhouse gas emissions are linearly extrapolated based on the trend from year 2000 to 2020.

to an exogenous carbon price. An exogenous carbon price time path is particularly useful for combining results from a CGE model and various marginal abatement cost curves derived from other models or outside analysis. Hypothetical carbon policies are represented by a set of time paths of carbon prices. For tractability, we consider either carbon prices that increase at a fixed percentage rate per year (Hotelling rate) or remain constant. Constant carbon prices can be considered a special case of a Hotelling rate where the rate of increase is zero. Hotelling carbon prices are convenient to approximate the dynamics of greenhouse gas mitigation when the emissions constraint is cumulative over time and banking is allowed between time periods.

No single model can adequately simulate all the activities and processes that might contribute to reductions in net greenhouse gas emissions. We rely here on exogenous marginal abatement cost curves provided by EMF-21 and from the U.S. Agricultural Sector Model (ASMGHG). Marginal abatement cost curves from ASMGHG were created from a series of constant-carbon-price experiments. For consistency between SGM and ASMGHG, we use constant carbon prices for the results in this section that cover only the United States.

Terrestrial options are considered as offsets to what would have occurred in the absence of a carbon policy. All of these options interact through competition for land and are best handled within a framework that simulates land allocation in response to market conditions, such as in ASMGHG. The three major mitigation options in ASMGHG are soil sequestration, afforestation, and biofuel offsets, defined as:

Soil sequestration: carbon stored in agricultural soils related to cropping and tillage practices

Afforestation: expanded forest land area relative to 1990 base

Biofuel offsets: net reduction in carbon emissions by using biomass-based fuels instead of fossil fuels

The potential for CCS is sensitive to the amount of electricity produced by technology in a baseline scenario. The U.S. electricity baseline for this study is shown in Figure 6. This baseline is similar to projections by the U.S. Energy Information Administration, EIA (2003), with one major exception: we include IGCC in the baseline projection to provide an option for IGCC+CCS in a policy scenario.

5.2 U.S. Emissions Reductions

For consistency across models, all of the mitigation options were simulated with a series of constant-carbon-price experiments. Results are shown in Figure 7 for a carbon price of \$200 per metric ton beginning in year 2015. Emissions reductions relative to baseline are shown for four classes of mitigation options: reduction in carbon dioxide emissions from the energy

Figure 5. U.S. Baseline Emissions from Energy Combustion and Non-CO₂ Greenhouse Gases

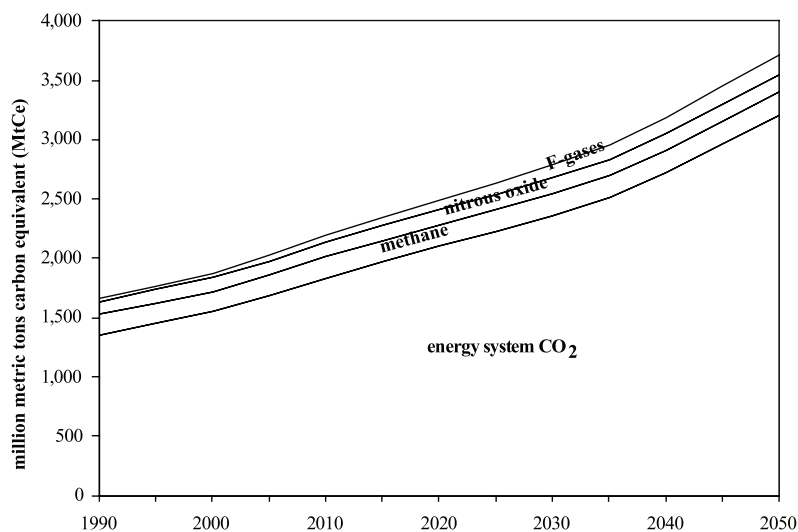
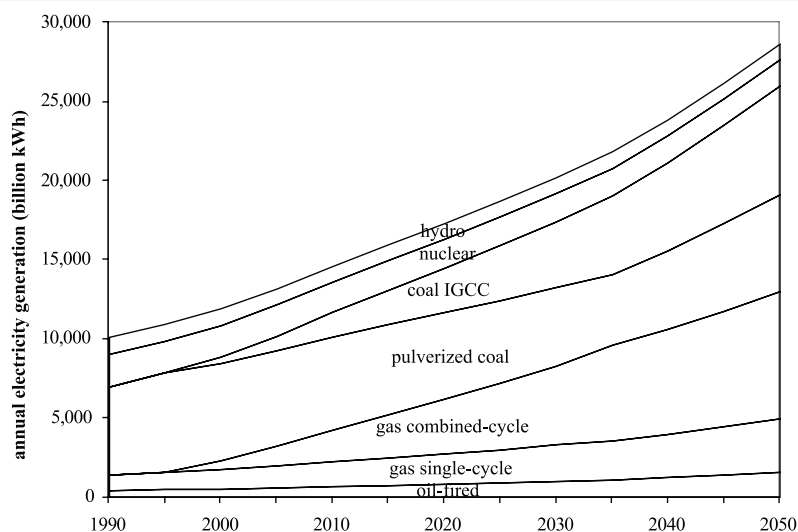
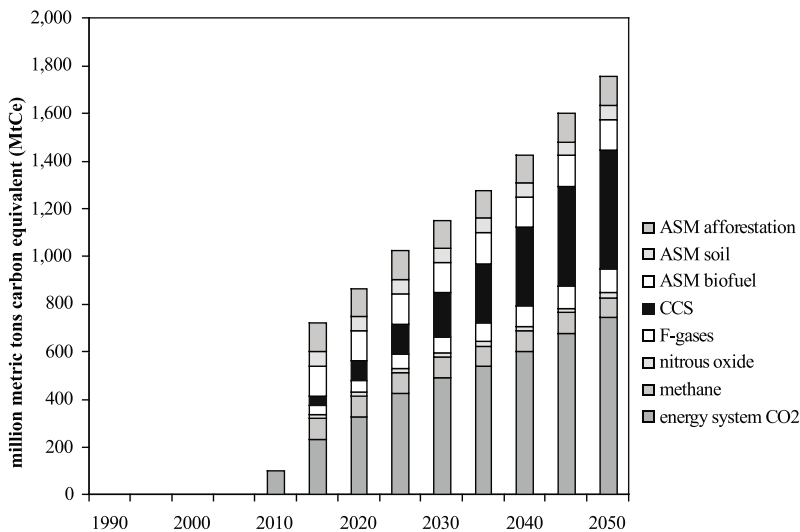


Figure 6. U.S. Electricity Baseline



system; reductions in emissions of non-CO₂ greenhouse gases; CO₂ capture and storage (CCS) from electricity generation; and mitigation options in agriculture and forestry. Reductions in emissions of non-CO₂ greenhouse gases in Figure 7 respond immediately to the carbon price in year 2015 and remain roughly the

Figure 7. U.S. Annual Emissions Reductions with a Carbon Price Held Constant at \$200 per TCe Beginning in 2015

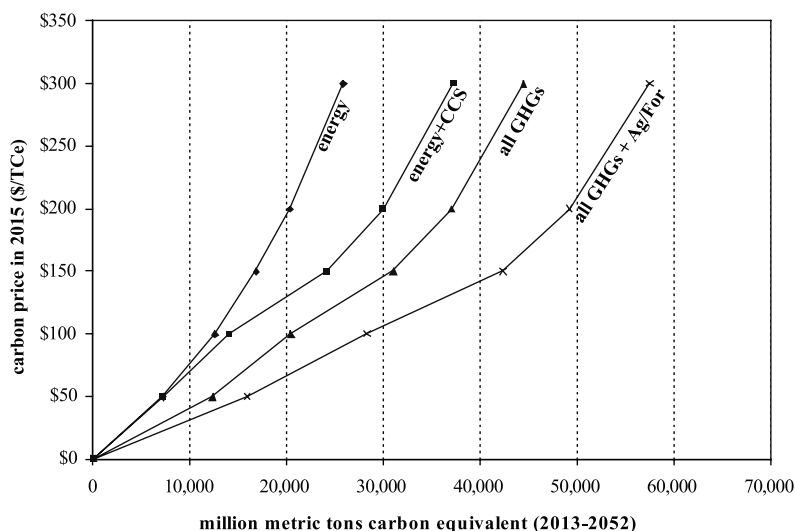


same throughout the model time horizon. This is also true of the agriculture and forestry options.

One of the limitations of this analysis is that the exogenous marginal abatement cost curves for the non-CO₂ gases and the terrestrial options are static. Marginal abatement curves for the non-CO₂ greenhouse gases assume that the full economic potential can be achieved immediately in the presence of a carbon price – there are no limitations due to capital stock turnover. The marginal abatement cost curves for carbon storage in agricultural soils and forests are an annualized representation that cannot capture all of the dynamics of carbon accumulation and saturation.

Figure 8 provides another view of these four classes of greenhouse gas mitigation options in a set of cumulative supply curves. These supply curves are particularly useful for policies that have a cumulative emissions constraint or allow banking of greenhouse gas emissions rights over time. Cumulative supply curves, as in Figure 8, are particularly useful for determining the approximate carbon price needed for carbon policies with various cumulative emissions constraints and varying sets of mitigation options. For example, if the cumulative emissions target is 20,000 million tCe over 40 years, a carbon price of \$200 per tCe is needed if the only allowable policy option is reductions in carbon emissions from the energy system. If CCS and reductions in other greenhouse gas emissions are included as policy options, the necessary carbon price is about \$100. The carbon price can be reduced even further if agriculture and forestry options are included. Stricter cumulative targets and limited policy options can result in the carbon price becoming very high. These results demonstrate that mitigation options beyond

Figure 8. U.S. Cumulative Emissions Reductions Over 40 Years at Alternative Constant Carbon Prices



reducing carbon emissions from the energy system are needed to prevent very high carbon prices with aggressive emissions targets. Reductions in emissions of the non-CO₂ greenhouse gases provide an important class of mitigation options, along with CCS and the agriculture and forestry system.

6. CONCLUDING REMARKS

Results presented here are sensitive to a number of assumptions. For non-CO₂ greenhouse gases, the quantity of emissions reductions depends directly on estimates of baseline emissions over the model time horizon. We used a linear extrapolation rule to extend the EMF-21 baseline from year 2020 to 2050 for all of the non-CO₂ greenhouse gases. For the US, baseline CO₂ emissions in the SGM closely track the forecasted emissions in the Annual Energy Outlook. The quantity of emissions reductions required to achieve the targets in the EMF-21 scenarios, and thus the carbon price required, are directly dependent on these assumptions about baseline emissions. The quantity of emissions reductions obtainable from CCS depends on baseline assumptions on IGCC plants and the rate of capital stock turnover in electricity generation. Results on agricultural and forestry options are an annualized approximation to a dynamic process which will change along with our ability to better capture the dynamics of agricultural and forestry options in the SGM.

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Benefits of Multi-Gas Mitigation: An Application of the Global Trade and Environment Model (GTEM)

Guy Jakeman* and Brian S. Fisher*†

To address the problem of human induced climate change effectively, climate policy must embody the principles of economic efficiency, environmental effectiveness and equity. In this paper it is shown that such a climate change policy should include a broad coverage of major greenhouse gases and sources. ABARE's Global Trade and Environment Model (GTEM) is used to analyse the economic impact of meeting a radiative forcing target using policies that focus on carbon dioxide emissions only and policies that focus on all major greenhouse gases and sources, including land use change and forestry emissions. It is projected that incorporating non-carbon dioxide gases into climate change policy reduces the economic adjustment cost significantly. Broadening the sources of carbon dioxide to include land use change and forestry emissions further reduces the economic adjustment costs.

1. INTRODUCTION

Under the United Nations Framework Convention on Climate Change, the international community has been responding to the possible threat of human induced climate change. The Kyoto Protocol has been one of the most obvious and ambitious examples of the response to date.

Until a few years ago, much of the debate in the international community focused on policies to monitor and address the growth and environmental impact of carbon dioxide emissions. The international community has recognised however, that, although the physical quantity of non-carbon dioxide gases emitted each year from anthropogenic sources is less than five per cent of total greenhouse gas emissions, their radiative forcing effects are significant and have contributed

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substantially to the problem of human induced climate change (approximately 30 per cent of total positive radiative forcing since 1750 is due to non-carbon dioxide greenhouse gases (IPCC 2001)). Hence, any international greenhouse gas mitigation policy that is to be both economically efficient and environmentally effective must focus on all major greenhouse gases.

Until recently, detailed estimates on the available technologies and associated costs of mitigating non-carbon dioxide emissions by region have not been available. ABARE has previously undertaken analysis of the potential benefit of abatement policies that account for a range of greenhouse gases rather than carbon dioxide alone (see Brown et al. 1999). This analysis focused on the Kyoto Protocol emission targets and was conducted using earlier estimates of the cost of non-carbon dioxide abatement opportunities. For the study in this paper, all emissions data and abatement opportunities and costs in GTEM have been reviewed and revised to incorporate the work undertaken by the contributors to the Energy Modeling Forum (EMF) 21 modeling exercise.

The purpose in this paper is to examine the economic impact of emissions abatement policies designed to stabilise the increase in radiative forcing from pre-industrial times at 4.45 W/m^2 by 2150 (corresponding approximately to a 3°C temperature increase). Three policy scenarios with different coverage of greenhouse gases and sources are examined: when carbon dioxide emissions alone are constrained (excluding land use change and forestry emissions); when multiple greenhouse gases are constrained; and when multiple greenhouse gases are constrained including emissions from land use change and forestry.

It is shown that incorporating the abatement opportunities of non-carbon dioxide emissions into climate change policies can significantly reduce the cost of meeting a given radiative forcing target. It is also shown that policies that incorporate land use change and forestry emissions can further reduce the economic cost of meeting a given target.

2. ANALYTICAL FRAMEWORK

The analysis of the economic impacts of climate change policies in this paper is based on simulation results from ABARE's general equilibrium model of the world economy, GTEM. Anthropogenic greenhouse gas emissions arise from many activities throughout the economy and therefore policies designed to constrain emissions will influence almost every part of the economy. Models such as GTEM are able to capture the impacts of policy changes on large numbers of economic variables such as prices, output and trade and investment flows between regions.

GTEM is a recursively dynamic general equilibrium model developed at ABARE to address policy issues with long term, global dimensions, such as climate change. It is derived from the MEGABARE model (ABARE 1996) and the static GTAP model (Hertel 1997). A detailed description of the theoretical structure of GTEM can be found in Pant (2002); the document, together with some working papers that illustrate further model developments, can be found

on ABARE's web site (www.abareconomics.com). The key structural features of GTEM are also documented in Pezzey and Lambie (2001).

The GTEM database (based on the GTAP 5.4 database, Dimaranan and McDougall 2002; http://www.gtap.agecon.purdue.edu/databases/v54/v54_doco.asp), corresponds to the year 1997 and contains 68 regions, 62 commodities and five primary factors. For this study, the database is aggregated to the 16 regions, 18 tradable commodities and four primary factors shown in Table 1. Each tradable commodity is produced by a single industry.

Capital, land, labor and natural resources are the four primary factors of production. The capital stock in each region accumulates by net investment in each period. Both capital and labor are mobile between industries within regions and, to a lesser extent, across regions through international capital flows and labor migration. Land is used only in agriculture and is fixed in each region. The natural resource is a factor used solely in the production of resource based commodities (coal mining, oil and gas extraction, other mining, forestry and fishing) and is not mobile between sectors or regions. With the exception of regions that are known to have little or no deposits, returns to the natural resource in the reference case are assumed to move with the regional numeraire, which allows for changes in the level of economic reserves.

The labor supply for each region is determined endogenously over time as a function of the working age population and age specific participation rates. The underlying population dynamics in the GTEM population module capture the

Table 1. Regional and Commodity Coverage

Region		Commodity		Primary factors	
1	United States	1	Brown coal	1	Land
2	European Union (15)	2	Coking coal	2	Labor
3	Canada	3	Steaming coal	3	Capital
4	Australia	4	Oil	4	Natural
5	New Zealand	5	Natural gas		Resource
6	Japan	6	Petroleum products		
7	EFTA ^a	7	Electricity		
8	Eastern Europe	8	Iron and steel		
9	Russian Federation	9	Nonferrous metals		
10	Other CIS ^b	10	Chemicals, rubber, plastics		
11	China	11	Other mining		
12	Brazil	12	Nonmetallic minerals		
13	India	13	Manufacturing		
14	Mexico	14	Transport		
15	OPEC	15	Agriculture		
16	Rest of world	16	Forestry and fishing		
		17	Processed food and beverages		
		18	Services		

a. European Free Trade Area: comprises Switzerland, Norway and Iceland.

b. Other Commonwealth of Independent States: comprises Azerbaijan, Armenia, Belarus, Georgia, Kazakhstan, Kyrgyz, Moldova, Tajikistan, Turkmenistan, Uzbekistan and Ukraine.

idea that as countries move along the economic development path, with increasing per person incomes, changes in fertility and mortality rates follow a well defined pattern. The model uses estimates of the dependence of fertility and mortality rates on income and an exogenously imposed migratory pattern to predict age and gender specific population changes.

In GTEM, electricity and iron and steel production are modeled using a ‘technology bundle’ approach. With this approach, different known production techniques are used to generate a homogeneous output from each industry. Electricity can be generated from brown coal, steaming coal, petroleum, gas, nuclear, hydro or renewable based technologies, while iron and steel can be produced using blast furnace or electric arc technologies. Each production technique is represented by a Leontief production function. To achieve a given level of industry output, outputs from each of the production techniques are chosen so as to minimise the production costs — using a CRESH (constant ratios of elasticities of substitution, homothetic) aggregator function of the techniques. By modeling energy intensive industries in this way, GTEM rules out technically infeasible combinations of inputs being chosen as model solutions while allowing for input substitution within each industry in response to price changes.

A key assumption made when modeling emission abatement scenarios is that the amounts of electricity generated by hydro power in OECD countries remain at reference case levels over the simulation period. This assumption reflects the increasing difficulty of locating sites for large-scale hydroelectric projects in OECD countries (IEA 2002).

Industries other than electricity and iron and steel combine fixed proportions of intermediate inputs, with the exception of primary factors and energy inputs, to produce a single good each. Non technology bundle industries obtain a least cost combination of six energy commodities (brown, coking and steaming coal, natural gas, petroleum and coal products and electricity) to produce an energy composite and a least cost combination of the four primary factors to produce a primary factor composite. The industry then forms a least cost combination of these two composites to obtain an energy–factor composite. The interfuel and interfactor substitutions and substitution between fuels and primary factors occur via a nested CES (constant elasticity of substitution) approach (Pant 2002). This means that industries can alter their fuel mix and reliance on fossil fuels in response to price changes.

In the standard GTEM framework, technological change in all policy simulations is assumed to occur at the same rate as in the reference case¹. As discussed in Jakeman et al. (2004) this assumption is likely to overestimate the costs of policies that result in large price changes across the economy, since it is likely

1. Note, changes in input ratios related to the technology bundle, fuel-fuel, fuel-factor and factor-factor switching mechanisms, represent changes in the *mix* of (or average) technologies used by industries (ie movement along the technology frontier). The modeling of the induced innovations hypothesis allows changes in the *available* technologies relative to the reference case (ie movement of the technology frontier itself).

that firms will change the focus of their research and development expenditure in order to develop new processes and products that reduce their dependence on any input whose relative cost rises substantially. The endogenous induced innovations methodology developed in Jakeman et al. (2004) is incorporated into the version of GTEM used in this analysis. In this methodology, it is assumed that there is a fixed amount of technical change (or efficiency improvements) available in each region in each time period. The economy allocates the innovation across all inputs and industries to minimise the net present value of input costs.

In GTEM, a single representative household in each region owns all factors of production, receives all payments made to the factors, all tax revenues and all net interregional income transfers. In the standard model closure, the representative household takes prices as given. The household allocates its net income to private and public consumption and savings. National savings are assumed to move in line with national income.

In a given period, consumption expenditure of the representative household is calculated as the difference between current household income and savings. Taking this expenditure level as given, the representative household maximises its current period utility function by choosing consumption levels for the 18 goods (specified in Table 1) from domestic and imported sources.

GTEM assumes a global financial centre that pools regional savings and allocates the investment fund to individual regions. Global savings always equal global investment. For a given region, the excess of investment over domestic savings represents an increase in net debt.

At a regional level, rates of return in GTEM may differ, reflecting the region specific risk characteristics. Investment demands are determined by changes in regional growth and regional expected rates of return relative to the expected global rate of return. It is assumed in GTEM that regional investors (that is, regional borrowers) issue bonds to global savers at a risk free global average rate of return.

A key feature of GTEM is that it takes account of and models the impacts of policies on trade flows between regions. In equilibrium, the exports of a given good from one region to the rest of the world are equal to the demand for the good produced in that region from the remaining 15 regions. Goods are transported between regions by an international transport industry. This industry takes prices as given and minimises the cost of obtaining transport services from each region subject to a Cobb–Douglas function. The cost of international transport is added to the cost of imports to each country.

For each good and primary factor, taxes on production, sales, exports and imports are accounted for separately. As a result, for a given good, the supply price, market price, domestic user's price and *fob* price of a commodity in the producing region and the *cif* price, duty paid market price and user prices in the importing region are clearly distinguished.

In the standard model closure used in this analysis, prices adjust fully to equate the supplies of and demands for all factors and goods from each region in each period. Among other things, this implies that any unemployment generated

as a result of policy changes is eliminated instantaneously through adjustments in the real wage. GTEM specifies the exchange rate of a region as the price of the global currency in terms of local currency. The model maintains the average unit of global investment as a global numeraire and the bundle of consumer goods within a region as a regional numeraire. It is assumed that monetary policy in each region targets the price of its regional numeraire (that is, the consumer price index) and that the supply of global currency is targeted to the price of the global numeraire (ie the price of global bonds). The exchange rate for a region can then be interpreted as a measure of the barter terms of trade between the global numeraire and the regional numeraire in question.

There are a number of simplified models that project the change in atmospheric concentrations of different greenhouse gases for given future emission paths. For the GTEM climate module, the MERGE 4.5 climate module equations have been used to estimate the changes in the atmospheric concentrations of carbon dioxide, methane and nitrous oxide (go to <http://www.stanford.edu/group/MERGE> to contact the authors). Estimates of the change in radiative forcing due to the concentrations of these gases relative to pre-industrial times are obtained from the equations in chapter 6 of the IPCC Third Assessment Report (IPCC 2001, p. 358).

2.1 Emissions Modeling in GTEM

The GTEM emissions database includes combustion and noncombustion carbon dioxide, methane and nitrous oxide emissions, which account for around 98 per cent of global anthropogenic greenhouse gas emissions (UNFCCC 1999). Most major sources and sectors are represented: emissions from agricultural residues, and methane and nitrous oxide from combustion and some industrial processes are not, although nitrous oxide emissions from transport are included.

All greenhouse gases in GTEM are expressed in carbon dioxide equivalent terms, based on their global warming potentials over a one hundred year time horizon as recommended by the International Panel on Climate Change (IPCC 1996a). Although the global warming potentials were updated in the IPCC Third Assessment Report (IPCC 2001), these updated values are not used in GTEM because the abatement targets for the first commitment period of the Kyoto Protocol are tied to the values from the IPCC Second Assessment Report.

The methodology described in Hester and Ahammad (2002) has been used to create an emissions database for all sources and regions identified in GTEM for 1997 and 1999. Table 2 shows the estimated global emissions from various sources in GTEM for 1997 and 1999.

Of the 18 commodities in Table 1, GTEM identifies five — brown coal, coking coal, steaming coal, natural gas, and petroleum and coal products — that are responsible for producing carbon dioxide when converted into other energy forms. In GTEM, changes in emissions from fossil fuel combustion are assumed to change proportionately to the quantity of fossil fuel consumed. Similarly, emissions from fertiliser use by agricultural industries are assumed to change

Table 2. GTEM Estimated Global Emissions from Various Sources, 1997 and 1999

	1997 a Mt CO ₂ -e	1999 Mt CO ₂ -e
Fossil fuel combustion		
Industry CO ₂	10131.5	10105.8
Private household CO ₂	3788.9	3885.7
Transport combustion N ₂ O	141.4	146.6
Noncombustion CO₂		
Oil extraction and refining	86.9	83.5
Natural gas production	43.7	47.9
Cement production	756.3	763.7
Aluminium production	34.8	38.0
Noncombustion CH₄		
Coal mining	735.4	678.6
Oil extraction, processing and transportation	108.1	110.8
Natural gas extraction, processing and transportation	759.7	793.1
Livestock	1777.2	1783.7
Paddy rice	258.8	269.2
Solid waste	769.3	780.7
Liquid waste	481.3	491.2
Noncombustion N₂O		
Nitric and adipic acid production	214.2	142.3
Fertilisers	1087.5	1117.7
Livestock	796.0	805.8
Total noncombustion	7909.3	7906.1
Total	29870.2	29969.1

a. 1997 estimates have been revised compared to those provided in Hester and Ahammad (2002)

proportionately to the quantity of fertiliser consumed. In line with the IPCC (1996b) recommended methodology, methane emissions from paddy rice are proportionate to the area harvested, while all other emissions (except those from waste) change in proportion to industry output. As recommended by contributors to the EMF 21 modeling exercise, emissions from liquid waste are assumed to change with population growth, while solid waste emissions in OECD regions except Japan are linked to population growth and per person real GDP in Japan and non-OECD regions.

2.2 Emissions Abatement in GTEM

In modeling the impact of greenhouse gas abatement policies in GTEM, emission abatement opportunities are available in combustion related emissions through energy efficiency improvements (induced as well as autonomous) and fuel switching as described earlier. Emission abatement opportunities in noncombustion sources are available through the adoption of new technologies and management

practices, which are implemented through emission response functions. Additionally, emissions abatement can occur in the electricity industry through the implementation of carbon capture and storage technologies. Other things being equal, reduced activity levels in emitting sectors will also lead to emission reductions.

2.3 The Emission Response Function

There are opportunities to reduce methane, nitrous oxide and noncombustion carbon dioxide emissions per unit of output from the majority of emitting industries in GTEM through the adoption of known technologies or management practices. In GTEM, the exceptions are fugitive emissions of carbon dioxide from oil and gas extraction, methane from liquid waste and nitrous oxide emissions from livestock production.

In GTEM, these abatement opportunities are represented by emission response functions. The response functions draw on data on the cost and emission reduction potential of known (and anticipated) technologies. The emission response data for methane and nitrous oxide were taken largely from Delhotal et al. (2005) (assuming 10 and 40 per cent discount and tax rates, respectively), while data for noncombustion carbon dioxide were largely taken from Cheminfo (1998). Additional information on the ability to reduce fertiliser usage was taken from Watson et al. (1996) and Cheminfo (1998). All data have been converted to the *percentage reduction* in emissions that is economically viable at different emission penalties and energy prices. This ensures that the abatement opportunities are independent of the projected emissions level in the absence of the technologies. Because of data limitations, various estimates assume that some abatement options are available in all regions. As large scale adoption of many of the technologies and management practices are likely to result in cost reductions over time, the real breakeven cost of all abatement options are assumed to fall by 1 per cent a year.

As discussed in Delhotal et al. (2004), the emission response for methane emissions from fossil fuel energy production, livestock and solid waste is also a function of energy prices because captured methane can be used to generate electricity or be pumped directly into a natural gas pipeline. Accordingly, the prices of electricity and natural gas are important determinants of the economic viability of such systems.

A lagged adjustment equation is used in the emission response functions to prevent industries from fully adjusting to price signals immediately. The functional form of this lagged response is discussed in Matysek et al (2005). The simulations in this analysis are based on the assumption that 95 per cent of possible reductions in emission intensity are realised within nine years.

2.4. Carbon Capture and Storage Technologies

In this analysis, carbon capture and storage (CCS) technologies are assumed to be available to coal and gas fired electricity generation in all regions.

Subject to storage availability, the electricity generators adopt a least cost combination of generating technologies with and without CCS (that is, adoption of CCS occurs if the costs of capturing and storing a unit of carbon dioxide is less than or equal to the carbon penalty that would otherwise be paid on these emissions). The additional cost of generating electricity with CCS technology comprises a capture cost and a transportation and storage cost. Capture costs are assumed to be \$30 and \$35 a tonne of carbon dioxide captured from coal and gas fired electricity generators, respectively (in 1997 US\$). Transportation and storage costs and storage potentials have been adapted from Hendriks et al. (2004), which provides detailed estimates of the costs and storage potential of five types of underground storage reservoirs in 18 regions.

As with the emission response functions, a lagged adjustment equation is used to prevent all coal or gas fired generation instantaneously adopting CCS technology once it becomes economic. The simulations in this report are based on the assumption that 95 per cent of possible CCS adoption is realised after 20 years.

Since capturing carbon dioxide requires energy, the amount of electricity produced from a unit of fuel by an electricity generation plant using CCS technology is less relative to a plant without CCS. The change in output per unit of fuel from generation plants with CCS is called an ‘energy penalty’.

In this analysis, energy penalties of 14.5 and 10.7 per cent are assumed for every unit of electricity generated using coal and gas fired CCS technology, respectively. That is, installation of CCS technology by coal fired generation technology decreases the quantity of electricity generated from a unit of coal by 14.5 per cent (or, alternatively, 17 per cent more coal is required to produce a unit of electricity). It is assumed that 80 per cent of carbon dioxide emissions are captured by plants that use CCS technologies, which reduces the average carbon equivalent penalty paid by emitters.

The costs, energy penalties and capture efficiency assumed in this analysis are based on current estimates and should be regarded as indicative only. Large scale deployment of CCS technologies is likely to lead to systems with lower costs, energy penalties and/or capture efficiencies. Such efficiency improvements are not considered here.

Because the installation of CCS technology is only economic if there is a penalty on the carbon dioxide emitted by generators, there is no uptake of CCS technology in the absence of such penalties.

3. REFERENCE CASE

As a dynamic model, GTEM requires a reference case (or base case) with which to compare the results of policy simulations. A reference case simulation provides a representation of the world economy over the simulation period in the absence of the policies under consideration — in this case, policies designed to reduce greenhouse gas emissions. Comparing the projections from a policy simulation with results from the reference case allows the effects of implementing a

policy change under a greenhouse gas abatement policy to be isolated. Results from the policy simulations are interpreted as deviations from the reference case levels.

The GTEM database starts at 1997 and is updated with the most recent data on emissions, gross domestic product and electricity technology shares available. Historical data for GDP are included from 1997 to 2003, and emissions for all regions are updated to 1999 using ABARE estimates, while all Annex B countries are updated using the most recent official national inventory data.

GDP projections to 2009 have been drawn from the International Monetary Fund forecasts (IMF 2004) as well as ABARE's own unpublished macroeconomic assumptions. Beyond 2009, the 'long run' GDP growth projections are made by fitting an appropriate ARIMA model to historical GDP growth rates (denoised using the wavelet method) for each individual GTEM region.

In the GTEM reference case, projections of the shares of various technologies in electricity generation between 1997 and 2030 are based on data from IEA (2002; 2004a; 2004b), IEEJ (2004), and various official government organisations. As fuel combustion in electricity generation is the largest source of greenhouse gas emissions in most countries, changes in the energy mix over the projection period are likely to be an important factor affecting emissions intensity.

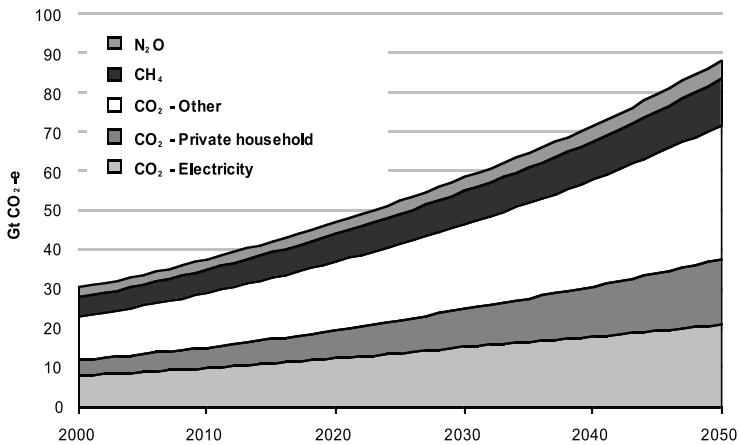
Reference case estimates of emissions from land use change and forestry activities have been taken from Sohngen and Sedjo (2005), while the growth in solid waste emissions to 2020 are assumed to change proportionately to the estimates provided by contributors to the EMF 21 modeling exercise and in USEPA (2001).

3.1 Projections

Global emissions of the three major greenhouse gases (carbon dioxide, methane and nitrous oxide) are projected to rise from 30.5 billion tonnes of carbon dioxide equivalent in 2000 to 88.3 billion tonnes by 2050 (Figure 1). The growth in global emissions is driven largely by high emissions growth in developing countries, which are projected to account for more than half of global emissions from around 2014. For a detailed examination of the driving forces behind developing country emissions growth see Polidano et al. (2000).

Key drivers of emissions growth are changes in population, GDP, emissions intensity of output (measured as greenhouse gas emissions per dollar of output), and the assumed level of emissions from land use change. All other things being equal, falls in emissions intensity reduce the rate of growth in emissions generated from increased economic activity. Changes in emissions intensity over the reference case reflect changes in the structure of the economy, in energy and process efficiency and in energy sources, particularly the fuel mix in electricity generation.

In the GTEM reference case, world population is expected to grow from approximately 6.1 billion people in 2000 to approximately 9.1 billion people in 2050, representing an average annual growth of 0.81 per cent a year. Total population in 2050 is projected to reach 917.3 million in OECD regions, 357.5 million in transition economies and 7.8 billion in the rest of the world.

Figure 1. Global Reference Case Emissions by Greenhouse Gas

Populations in China and India are projected to reach 1418 and 1576 million in 2050, respectively.

The GDP growth rates for the 16 GTEM regions used in this study are presented in table 3. Global real GDP is projected to grow by an average of 2.98 per cent a year between 2000 and 2050, which represents an over fourfold increase in world output.

Emissions intensities in all regions are projected to decline, with emission intensities in developing regions falling faster than in OECD regions (average annual growth of approximately -1.4 and -1.1 per cent a year from 2000 to 2050, respectively). On average, the emission intensity of transition economies is projected to fall fastest at a rate of approximately -2 per cent a year between 2000 and 2050.

Globally, carbon dioxide emissions are projected to grow faster than methane and nitrous oxide, rising from 76 per cent of global greenhouse gas emissions in 2000 to around 81 per cent at 2050 (excluding LUCF emissions) (Table 4). This is attributable to faster growth in carbon dioxide emissions from developing regions, where the share of carbon dioxide in total greenhouse gas emissions is projected to rise from around 69 per cent in 2000 to 81 per cent at 2050 (Table 4). This growth is driven by higher demand for fossil fuel based energy and cement relative to other emission sources as incomes in developing countries grow.

Fossil fuel combustion is the largest single source of greenhouse gas emissions in most developed countries and in a number of developing countries, and a major consumer of fossil fuels is the electricity industry. As a result, changes in the demand for and sources of electricity can affect global emission projections quite substantially. Global electricity production is projected to grow by an average

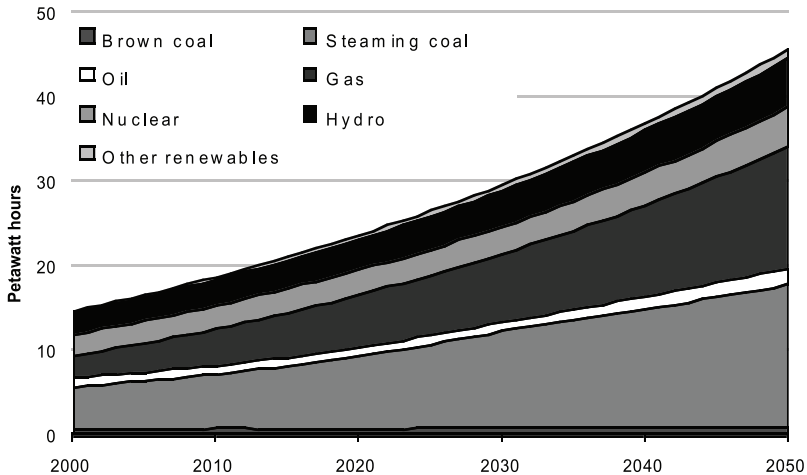
Table 3. Average Annual Growth in Real GDP and Emissions for GTEM Regions, Reference Case

	Real GDP			Emissions		
	2000–10 %	2010–25 %	2025–50 %	2000–10 %	2010–25 %	2025–50 %
United States	3.1	3.2	2.6	1.5	1.5	1.4
European Union (15)	1.8	2.1	2.1	1.0	1.0	1.1
Canada	3.0	3.0	2.4	2.0	1.6	1.4
Australia	3.4	3.3	2.9	1.5	1.8	1.5
New Zealand	3.1	3.3	2.8	1.3	1.6	1.6
Japan	1.4	1.5	1.4	0.6	0.5	0.5
EFTA ^a	1.6	1.8	1.7	1.2	1.2	1.4
Eastern Europe	3.7	3.3	2.7	0.6	0.9	0.6
Russian Federation	5.1	4.8	4.0	1.9	2.3	2.6
Other CIS ^b	5.5	3.7	3.3	2.4	1.8	1.8
China	7.8	5.6	4.1	3.5	3.4	2.4
Brazil	2.5	3.1	3.1	2.1	1.7	1.9
India	5.7	5.6	4.9	3.4	3.3	3.2
Mexico	2.6	4.0	3.8	2.5	2.6	2.9
OPEC	3.8	3.8	3.7	2.7	2.4	2.5
Rest of world	4.1	3.9	3.8	3.1	2.8	2.5
World	2.9	3.1	2.9	2.2	2.2	2.1

- a. European Free Trade Area: comprises Switzerland, Norway and Iceland.
b. Other Commonwealth of Independent States: comprises Azerbaijan, Armenia, Belarus, Georgia, Kazakhstan, Kyrgyz, Moldova, Tajikistan, Turkmenistan, Uzbekistan and Ukraine.

Table 4. Share of Major Greenhouse Gases in Reference Case Emissions

		2000 %	2050 %
Developed (incl. transition)	CO ₂	82.9	83.1
	CH ₄	11.9	12.5
	N ₂ O	5.1	4.4
Developing	CO ₂	68.6	80.7
	CH ₄	21.8	13.7
	N ₂ O	9.6	5.6
World	CO ₂	76.3	81.5
	CH ₄	16.3	13.2
	N ₂ O	7.4	5.3

Figure 2. Global Electricity Production by Technology, Reference Case

of 2.3 per cent a year between 2000 and 2050 (Figure 2). The gas fired and non-hydro renewable electricity industries are projected to experience the strongest growth in installed capacity, with total capacity increasing by 3.5 and 3.4 per cent a year between 2000 and 2050, respectively, to account for over a third of global electricity production (Table 5). Despite the strong growth in gas and renewable electricity generation, the share of coal fired electricity in global generation is projected to remain roughly constant over the period at 39 per cent (Table 5).

4. MODELING EMISSION ABATEMENT POLICIES

In the policy simulations presented in this paper, all regions are assumed to reduce their emissions gradually from 2010 in order to stabilise the average increase in global temperature due to human induced climate change at 3.0°C above pre-industrial (1750) levels by 2150. Accounting for the absence of various greenhouse gases from the GTEM modeling framework (using the adjustments recommended to modelers by the EMF 21 group), this is equivalent to stabilising the increase in radiative forcing at 4.452 Wm⁻² above the pre-industrial level by 2150.

As the version of GTEM used in this analysis is not well suited to very long term projections of the world economy, model projections have only been made to 2050. The equivalent radiative forcing target for 2050 is assumed to be 3.60 Wm⁻². As there are many different emission paths that can attain the 2150 stabilisation target, for comparability, the 2050 radiative forcing target has been used for all scenarios.

To analyse the effect of incorporating non-carbon dioxide greenhouse gases and carbon dioxide from land use change and forestry (LUCF) into global climate policy three scenarios are examined:

Table 5. Share of Electricity Generated by each Fuel under the Reference Case

	Coal		Oil		Gas		Nuclear		Hydro		Other renewables	
	2000	2050	2000	2050	2000	2050	2000	2050	2000	2050	2000	2050
	%	%	%	%	%	%	%	%	%	%	%	%
United States	52.0	49.9	2.6	1.6	16.1	25.9	19.2	13.6	8.1	5.6	1.9	3.5
European Union (15)	27.2	18.1	6.9	2.8	16.6	42.3	34.1	21.8	12.3	10.2	2.8	4.8
Canada	18.6	13.3	2.4	2.0	4.9	20.9	13.3	13.7	59.4	45.0	1.3	5.1
Australia	78.9	68.1	1.5	0.6	10.5	25.1	0.0	0.0	8.1	4.0	1.0	2.2
New Zealand	3.8	3.4	0.0	0.0	24.9	18.1	0.0	0.0	68.6	68.1	2.7	10.5
Japan	23.6	23.9	15.0	9.1	21.5	26.4	28.4	31.4	9.2	7.5	2.3	1.8
EFTA	0.1	0.1	0.1	0.1	0.6	3.4	13.6	14.0	84.8	81.8	0.9	0.7
Eastern Europe	58.5	59.1	4.6	6.2	6.9	14.9	20.7	14.0	8.8	5.1	0.4	0.8
Russian Federation	19.0	19.9	4.3	1.5	43.0	53.4	14.7	10.3	18.6	12.8	0.3	2.2
Other CIS	19.2	20.8	5.6	3.4	38.2	54.1	21.3	12.4	15.7	9.3	0.1	0.0
China	76.7	67.6	3.4	1.2	1.3	13.9	1.4	6.9	17.1	8.3	0.2	2.2
Brazil	2.4	3.3	3.6	4.1	2.4	27.0	2.8	4.2	85.8	57.4	3.0	4.0
India	69.2	54.5	4.9	1.4	9.8	23.0	2.8	4.3	12.9	14.7	0.5	2.1
Mexico	11.3	2.9	43.8	13.5	23.9	73.9	5.1	1.5	15.7	6.9	0.3	1.2
OPEC	8.4	16.5	33.1	24.2	45.0	44.8	0.0	0.0	13.4	14.2	0.1	0.3
Rest of world	31.7	29.3	14.1	5.2	19.9	40.2	9.3	8.1	24.5	15.3	0.6	1.9
World	38.6	39.0	7.8	4.3	17.8	31.6	16.9	10.1	17.6	12.5	1.4	2.5

- ***CO₂ only***: global emissions of carbon dioxide in GTEM are constrained to meet the 2050 radiative forcing target. LUCF emissions remain unchanged relative to reference case levels. Reference case projections of emissions from global LUCF activities are taken from Sohngen and Sedjo (2005).
- ***Multi-gas***: global emissions of all greenhouse gases in GTEM are constrained to meet the 2050 radiative forcing target. LUCF emissions remain unchanged relative to reference case levels.
- ***Multi-gas plus LUCF***: global emissions of all greenhouse gases in GTEM are constrained to meet the 2050 radiative forcing target. LUCF emissions are equal to the Scenario 5 projection in Sohngen and Sedjo (2005), which was used as it has the most conservative estimate of land area converted from potentially available forest land to managed and unmanaged forests by 2100. Globally, the Scenario 5 projection estimates that 325.7 and 257.7 Mt of carbon will be sequestered by LUCF activities in 2050 and 2100, respectively. This compares

to net emissions of 273.3 and 146.3 Mt carbon under the reference case in 2050 and 2100, respectively.

It should be emphasised, that, in order to meet the radiative forcing target, total emissions of greenhouse gases in the GTEM coverage differ substantially between the scenarios. For example, using the global warming potentials in IPCC (1996a), global carbon dioxide equivalent emissions are projected to be approximately 34 Gt under the *CO₂ only* scenario, but approximately 38 Gt under the *multi-gas* scenario. Hence, although both scenarios achieve the same radiative forcing at 2050, the relative emissions abatement is more stringent under the *CO₂ only* scenario than the *multi-gas* scenario.² All else equal, the greater relative abatement under the *CO₂ only* scenario will result in higher economic adjustment costs compared to the *multi-gas* scenario.

In GTEM, least cost modeling of emission abatement involves imposing a carbon equivalent penalty on greenhouse gas emissions. The penalty represents the broad class of least cost economic instruments that could be used by governments to reduce emissions. It could represent a domestic emissions trading scheme or a uniform carbon equivalent penalty applied in a particular region, and can be interpreted as the marginal cost to the economy associated with any least cost policy designed to achieve a given level of emission abatement. Revenue from the carbon equivalent emission penalty is assumed to be returned to the economy in a lump sum fashion, thereby having a neutral effect on economic agents. In practice, however, changing the way in which revenue is returned to the economy can alter the estimates of the economic impacts of emission abatement.

5. SIMULATION RESULTS

In interpreting the simulation results, attention will be confined to broad patterns affecting the world as a whole. A very detailed discussion would be required to explain the differences in impacts between regions.

The global carbon penalty at 2050 under the *CO₂ only* scenario is projected to be US\$1929 a tonne of carbon (in 2003 terms). Attaining the same radiative forcing target under the *multi-gas* scenarios is projected to significantly reduce the 2050 global carbon equivalent to US\$685 and US\$457 a tonne of carbon equivalent without and with policy induced LUCF, respectively. The projected carbon equivalent penalty falls as a result of extending the coverage of greenhouse gases and sources since their inclusion in the policy task provides new abatement opportunities that may be accessed at low cost (see Brown et al. 1999 and Reilly et al. 1999 for discussions).

2. This result is because the change in radiative forcing at 2050 resulting from reducing a unit of methane or nitrous oxide is different to the change in radiative forcing resulting from the abatement of a unit of carbon dioxide. Moreover, the IPCC (1996a) weights do not properly reflect the relativities and indeed, from this analysis, one would expect the relative importance of methane and nitrous oxide in meeting the 2050 radiative target modeled in this paper to be higher than those in IPCC (1996a). Due to the complexities of atmospheric chemistry, there is no simple solution to the weighting problem. A discussion of this issue can be found in Reilly et al. (2001).

The projected global carbon equivalent penalties in this analysis are significantly higher compared with other projections using GTEM (see Brown et al. 1999; Polidano et al. 2000; Jakeman et al. 2002, 2004). The main reason is because, to meet the 2050 radiative forcing target, global emissions in GTEM must fall by up to 61 per cent, relative to the reference case at 2050. This abatement task is significantly higher than those modeled in other analyses using GTEM, and to achieve it requires significant structural changes throughout the global economy.

Global real GDP under the *CO₂ only* scenario is projected to fall by around 7.1 per cent, or around US\$11.2 trillion, relative to the reference case at 2050 (in 2003 terms) (Figure 3). Under the *multi-gas* scenario, global real GDP is projected to fall by 3.3 per cent, or around US\$5.2 trillion, relative to the reference case at 2050 (Figure 3). Expanding the sources to include LUCF emissions is projected to reduce global real GDP by 2.3 per cent (US\$3.6 trillion), relative to the reference case at 2050 (Figure 3).

From Table 6 it can be seen that there are significant abatement opportunities from methane and nitrous oxide sources. In particular, although global non-carbon dioxide emissions fall by 23 per cent under the *CO₂ only* policy scenario, broadening the coverage of greenhouse gases in the *multi-gas* and *multi-gas plus LUCF* scenarios results in approximately a 50 per cent reduction in non-carbon dioxide emissions, relative to the reference case at 2050. The additional reduction in non-carbon dioxide gases reduces the burden placed on emitters of carbon dioxide to meet the radiative forcing target.

5.1 Detailed results for Multi-Gas plus LUCF scenario

In this section, results from the *multi-gas plus LUCF* scenario will be analysed in more detail to provide insights into the importance of various sources

Figure 3. Change in Global Real GDP under Various Scenarios, Relative to the Reference Case at 2050

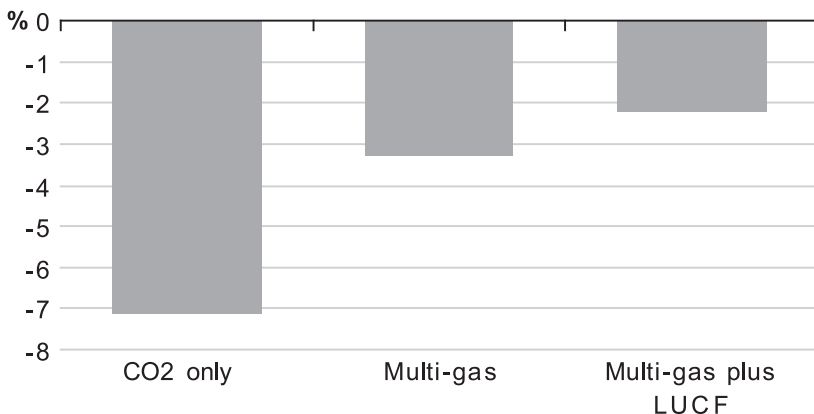


Table 6. Change in Greenhouse Gas Emissions from Various Sources Under Different Scenarios, Relative to the Reference Case at 2050

	CO ₂ only	Multi-gas	Multi-gas plus LUCF
	%	%	%
Combustion CO ₂	-69.4	-57.3	-51.8
Noncombustion CO ₂	-74.4	-69.8	-68.1
Total CO₂	-69.8	-58.2	-53.0
Fugitive fossil fuel CH ₄	-61.2	-79.1	-75.1
Other CH ₄	-4.7	-35.1	-34.0
N ₂ O	-13.3	-47.7	-46.1
Total non-CO₂	-23.3	-51.3	-49.2

of abatement in meeting the given radiative forcing target at 2050.

Global electricity production is projected to grow by an average 1.8 per cent a year between 2000 and 2050 under the *multi-gas plus LUCF* scenario. This corresponds to a 20 per cent decrease in global electricity production relative to the reference case at 2050. The share of electricity from coal fired power in 2050 falls slightly, from 39 per cent in the reference case (Table 7) to 37.5 per cent (Table 7). Underlying this relatively small reduction however, is a large switch from brown coal fired power to steaming coal fired power. The quantity of global electricity generated using brown coal technology is projected to fall by 74 per cent while electricity from steaming coal is projected to fall 54 per cent, relative to the reference case at 2050. This switch occurs due to the lower emission intensity of steaming coal fired electricity compared to brown coal fired electricity. Installation of renewable technologies is projected to grow faster than any other electricity technology, at an average growth rate of 4.1 per cent a year between 2000 and 2050.

Figure 4 shows the main sources of abatement in global emissions under the *multi-gas plus LUCF* scenario. As can be seen, reduction in industry output, particularly of emission intensive industries, is projected to account for approximately 30 per cent of the total greenhouse gas reduction relative to the reference case in 2050. Reductions in private household fuel use and industry fuel use are projected to account for 19 and 23 per cent of total abatement relative to the reference case, respectively.

Installation of coal and gas fired power with CCS technology is projected to be significant by 2050, with approximately 7.5 Gt carbon dioxide being captured and stored annually by 2050 under the *multi-gas plus LUCF* scenario (Figure 4). Uptake of CCS technologies however, is not projected to start until 2027, since they are not economic until the global carbon equivalent penalty rises above US\$125 a tonne of carbon (in 2003 terms).

Finally, technologies and practices that reduce the emissions intensity of noncombustion sources (modeled through the emission response functions) are projected to account for 12 per cent of total abatement from the reference case under the *multi-gas plus LUCF* scenario.

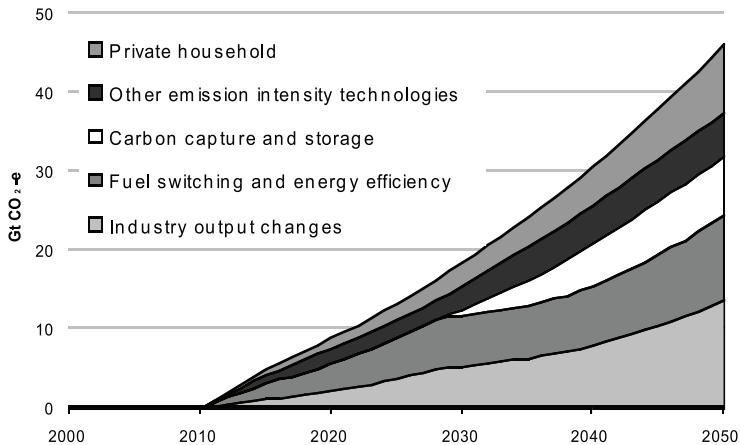
Table 7. Share of Electricity Generated by Each Fuel Under the *Multi-Gas Plus LUCF* Scenario

	Coal		Oil		Gas		Nuclear		Hydro		Other renewables	
	2000	2050	2000	2050	2000	2050	2000	2050	2000	2050	2000	2050
	%	%	%	%	%	%	%	%	%	%	%	%
United States	52.0	48.7	2.6	0.6	16.1	18.0	19.2	33.7	8.1	6.9	1.9	5.3
European Union (15)	27.2	14.8	6.9	1.5	16.6	27.7	34.1	39.9	12.3	12.0	2.8	6.6
Canada	18.6	9.4	2.4	0.5	4.9	14.5	13.3	21.0	59.4	49.4	1.3	6.9
Australia	78.9	64.6	1.5	0.8	10.5	27.2	0.0	0.0	8.1	5.8	1.0	4.7
New Zealand	3.8	3.4	0.0	0.0	24.9	16.3	0.0	0.0	68.6	67.6	2.7	12.0
Japan	23.6	23.9	15.0	6.1	21.5	22.6	28.4	44.0	9.2	8.4	2.3	3.4
EFTA	0.1	0.1	0.1	0.0	0.6	4.7	13.6	28.2	84.8	63.5	0.9	2.9
Eastern Europe	58.5	31.8	4.6	3.0	6.9	18.1	20.7	38.1	8.8	6.7	0.4	3.1
Russian Federation	19.0	17.4	4.3	2.3	43.0	43.2	14.7	23.5	18.6	15.2	0.3	3.5
Other CIS	19.2	20.9	5.6	0.9	38.2	35.7	21.3	30.4	15.7	22.9	0.1	1.2
China	76.7	67.6	3.4	1.3	1.3	8.3	1.4	26.2	17.1	31.9	0.2	4.0
Brazil	2.4	3.3	3.6	1.0	2.4	20.4	2.8	5.0	85.8	66.8	3.0	5.2
India	69.2	53.8	4.9	0.9	9.8	13.8	2.8	10.9	12.9	38.2	0.5	3.9
Mexico	11.3	0.3	43.8	3.6	23.9	72.2	5.1	3.8	15.7	17.8	0.3	2.4
OPEC	8.4	16.5	33.1	9.6	45.0	30.0	0.0	0.0	13.4	44.9	0.1	2.3
Rest of world	31.7	27.9	14.1	3.0	19.9	21.6	9.3	18.5	24.5	35.7	0.6	4.0
World	38.6	37.5	7.8	2.1	17.8	21.6	16.9	24.0	17.6	26.1	1.4	4.3

6. CONCLUSIONS

Although carbon dioxide constitutes the majority of anthropogenic greenhouse gas emissions, non-carbon dioxide greenhouse gases are also an important part of the problem of human induced climate change. Hence, any policy that aims to address climate change should ensure that, where practicable, all major greenhouse emissions from all sources are targeted. A multi-gas abatement policy will be more economically efficient than a carbon dioxide only policy because it broadens the number of low cost abatement opportunities. It will also be more environmentally effective — by accounting for gases with high radiative forcing effects. In addition, including emissions from a range of sources, equity between different emitters will be ensured compared with policies that focus solely on carbon dioxide emissions.

Figure 4. Sources of Abatement in Global Emissions – Multi-Gas Plus LUCF, Relative to the Reference Case



In this analysis, various scenarios using GTEM were modeled with the aim of stabilising the average increase in global temperature due to human induced climate change at 3.0°C above pre-industrial levels by 2150. It was shown that a multi-gas abatement policy can substantially reduce the economic cost (as measured by changes in global real GNP) of meeting the target compared with a policy framework that addresses carbon dioxide emissions alone. Broadening the sources of emissions targeted by climate policy to include emissions from land use change and forestry activities was shown to further reduce the economic cost of achieving a given stabilisation target.

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Multi-gas Mitigation Analysis on Stabilization Scenarios Using Aim Global Model

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Non-CO₂ gas (CH₄, N₂O and F gas) emissions account for 25 percent of all greenhouse gas in the year of 2000. Main sources of CH₄ and N₂O emissions are agriculture-related activities such as enteric fermentation, paddy rice cultivation, soil management. A recursive dynamic CGE (Computer General Equilibrium) model has been developed to analyze greenhouse gas reduction options including non-CO₂ gas abatement technologies. Multi-regional, multi-sectoral and multi-gas CGE model and simple climate change model simulated long-term climate stabilization emission path. Preliminary results showed that multi gas mitigation options including CH₄ and N₂O abatement technologies will reduce GDP loss more than CO₂ only mitigation options for long-term climate stabilization, even though CO₂ mitigation options will reduce not only CO₂ emissions but non-CO₂ gas emissions simultaneously. It is necessary to collect regional non-CO₂ gas data (emission, technology options, and so on) and conduct more sensitivity analysis with computer simulation model to reduce uncertainty of non-CO₂ gas.

1. INTRODUCTION

The effects of global warming will largely depend on the socio economic profiles of regions. In the year 2000, IPCC published the “Special Report on Emission Scenarios (SRES)” (Nakicenovic et al 2000) and depicted future socio-economic trends till the year 2100. Climate model simulation results based on SRES scenarios show that there is a high possibility of temperature rise in the

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range 1.4 to 5.8 degree by 2100. IPCC Third Assessment Report (TAR) (IPCC, 2001) indicated that to stabilize atmospheric CO₂ concentration at 550ppmv or lower beyond 2100, developed countries are required to reduce 20% of CO₂ emissions by 2030 compared to that of BaU scenario.

The ultimate target of global warming policies is to stabilize climate change to reduce impacts due to temperature raise. Though IPCC/TAR model analysis mainly focused on CO₂ concentration as a stabilization target, analysis on non-CO₂ gases such as CH₄, N₂O, F gas and other gases such as SO₂, black carbon, organic carbon are also important when considering climate change stabilization.

Non-CO₂ gases contribute to about a quarter of total global warming effect. However data related to Non CO₂ emissions, reduction technologies, countermeasures costs have not been well researched so far. USEPA (1999, 2001a, 2001b, 2003) and Ecofys have prepared non-CO₂ gases database for EMF (Energy Modeling Forum) analysis.

We have developed global CGE model to analyze economic impact of non-CO₂ gas reduction options to stabilize climate change.

2. MODEL STRUCTURE

2.1 Basic Framework

Multi-region/multi-sector/multi-gas model AIM/CGE (Asia) has been developed to analyze long-term stabilization scenarios. This model is a recursive dynamic CGE model based on GTAP-EG structure. It is programmed with GAMS/MPSGE. GTAP ver.5 database (base year=1997) is used for economic database and IEA energy statistics is used for energy database. This is a long-term model with a time horizon 1997 to 2100 and includes 18 world regions and 13 economic sectors (Table 1 and 2).

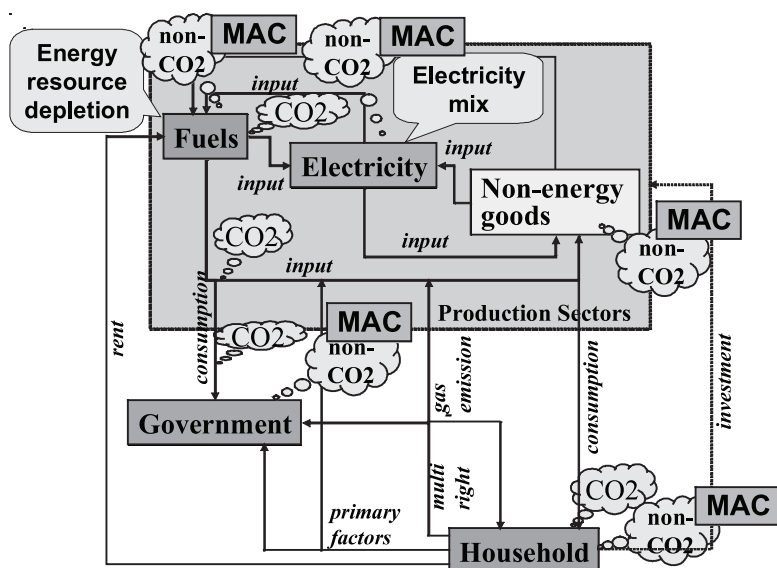
The structure of the AIM/CGE (Asia) model is illustrated in Figure 1. The AIM/CGE (Asia) is an update of the AIM/CGE (Energy) model (Kainuma et al 2003). The updated model includes framework for both CO₂ and non-CO₂ gases. The model has three sectors—the production, household, and government sectors—in each region. CO₂ and non-CO₂ gases are emitted by each of these sectors. The production of electricity and non-energy goods involves the production and use of fossil fuels leading to the emission of these gases. In addition, the use of automobiles and other direct use of fossil fuels by the household and government sectors lead to emissions. It is assumed that the household sector has multi gas emission rights and distributes them to the other sectors and within the household sector itself. Fossil fuels cannot be used without having such rights. The price of these rights depends on several factors such as emissions targets and the method of emissions trading. The household sector also supplies primary factors to the production and government sectors. An agent in the household sector determines consumption and savings. The marginal propensity to save is a calibrated function of a weighted aggregate of regional and global rates of

Table 1. Target Region

1	ANZ	Australia/NZ	10	OWE	Other Western Europe
2	JPN	Japan	11	EEU	Eastern Europe
3	KOR	Korea, Rep.	12	FSU	FSU
4	CHN	China	13	MEX	Mexico
5	IND	India	14	OPE	OPEC
6	SEA	South & SE Asia	15	BRA	Brazil
7	USA	USA	16	LAM	Latin America
8	CAN	Canada	17	AFR	Africa
9	WEU	Western Europe	18	ROW	Rest of the World

Table 2. Target Sector

1	GAS	Natural gas works	8	LVK	Livestock
2	ELE	Electricity and heat	9	FRS	Forestry
3	OIL	Refined oil products	10	FSH	Fishing
4	COL	Coal transformation	11	OIN	Other Industry
5	CRU	Crude Oil	12	TT	Transport
6	EII	Energy Intensive Industry	13	SER	Service
7	AGR	Agriculture			

Figure 1. Structure of AIM/CGE(Asia) Model

return on fixed capital. Regional investment is calculated using the GDP growth rate and regional and global rates of return. Investment is balanced with savings on a global scale. The model allows for trade in intermediate goods. It assumes identical preferences in all countries for foreign versus domestic goods; i.e., the elasticity of substitution is the same for all regions. Domestic and imported goods are not perfect substitutes.

2.2 Non-CO₂ Gas Reduction Module

The approach used to model the non-CO₂ gas emission reduction is in general different from that used to model the control of CO₂ gases emissions from fossil fuel combustion. Non-CO₂ gas emissions are usually not proportional to the sectoral activities and the reduction rates are different across sectors. The approach chosen for modeling non-CO₂ gases is to set the non-CO₂ gases emissions as inputs into the production function (Hyman et al 2002). Constant Elasticity of Substitution (CES) production functions expressed in equation (1) are used in the CGE model.

$$\left(\frac{Y}{Y_0} \right) = \left\{ a \left(\frac{X}{X_0} \right)^{-\rho} + (1-a) \left(\frac{Z}{Z_0} \right)^{-\rho} \right\}^{-\frac{1}{\rho}}, \quad \sigma = \frac{1}{1+\rho} \quad (1)$$

X : non-CO₂ gas emissions, Z : intermediate input, Y : output

Z_0, Y_0 : Base year value

a : cost share of non-CO₂ gas reduction

ρ : substitution parameter

There are several assumptions and limitations when CES production functions are applied. One assumption is that each input must always have a non-zero cost share. In economic terms, the actual input of GHG disposal is the cost of controlling emissions. If there is no such control under current conditions then the cost share becomes zero, which is inconsistent with the “necessary input” feature of CES functions. This problem is overcome by positing a very low initial price for each GHG. A second problem of the CES structure is that it constrains the elasticity of substitution to be identical between all pairs of inputs. To overcome this restriction a nested production structure is usually imposed, and with sufficient layers in the nest any degree of flexibility can be achieved in the representation of elasticities between individual input pairs (see Babiker *et al.* 2001). A third practical task is the estimation of the elasticity of substitution, for GHGs. This is achieved by making use of the observation that, once we have represented emissions as an input in the production function, the supply of abatement opportunities (often described as a marginal abatement curve or MAC), is the inverse of the input demand function for emissions.

2.3 Marginal Abatement Cost Curve from Bottom-up Data Analysis

MAC functions are often developed as a summary description of detailed process models that evaluate abatement options (*e.g.*, Brown *et al.* 1998; USEPA 1999, 2001a, 2001b, 2003). The input demand function can be derived directly from the CES production function, and the demand elasticity is directly related to the substitution elasticity. Thus an inverse input demand function can be fit to a MAC and elasticity of substitution that fits the underlying bottom-up data can be estimated (Hyman *et al.* 2002).

The bottom up data has been developed using the AIM/ Enduse Global model. The outputs from this model have been used to develop Marginal Abatement Cost curves, which is useful for estimating the demand functions and the elasticity of substitution for the top down analysis. As an example, the MAC curves developed for India for the steel sector and the CH₄ sector (for year 2020) are discussed next.

Figures 2 and 3 present abatement potential and marginal costs for green house gas abatement for some important sectors.

India produced 27.1 million metric tonnes of finished steel from main and secondary producers in 2000. The Indian steel industry has grown above 7% (compounded) per annum during the 1990s and is poised to grow even faster during the present decade due to thrust on infrastructure development and housing by the Government. The total steel production is projected to reach 52.5 Mt (in 2010), 81 Mt (2020) and 103 Mt (2030).

Figure 2. MAC Curve (Steel Sector) in 2020

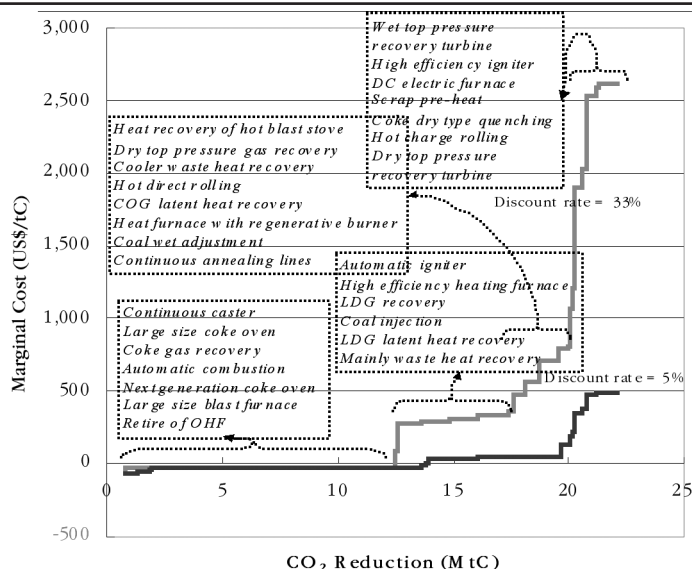
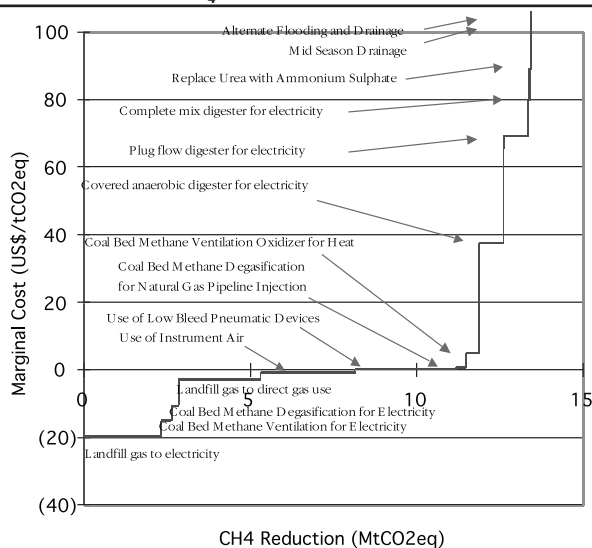


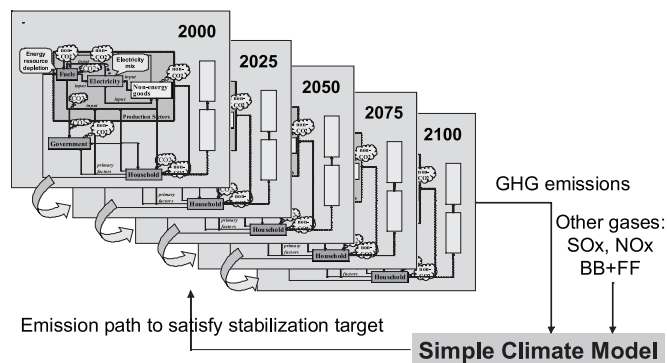
Figure 3. MAC Curve for CH₄ in 2020 Across Sectors

Presently, the Indian steel industry is about 1.5 times more energy intensive than the average international steel producers, both for the integrated steel plants and the medium and small steel-rolling mills. Therefore it has considerable potential for energy conservation. Figure 2 shows the CO₂ reduction potential in the steel sector and the associated costs of the technologies for the year 2020. Also, the cumulative carbon emissions from the Indian steel sector for 2000-2030 are projected to be about 1.5 billion tCeq. Energy conservation and carbon mitigation technologies may mitigate about one-third of these.

Figure 3 depicts the abatement options and the costs involved in mitigating CH₄ in 2020. Investigation on Coal Bed Methane for its commercial exploitation is a comparatively recent phenomenon in India. The government announced in October 2003 that 14 bids for eight blocks had been received under the second round of bidding for coal bed methane exploitation. Also, Indian cities are introducing private sector participation in Solid Waste Management. The aim is to attract funding and new technologies for better service delivery. The waste to energy technologies in India include incineration, pelletization and bio-methanation. The other sectors that have also been considered for estimating reduction potential are the paddy and the natural gas production and distribution sectors. The biomass and enteric fermentation sectors were outside the scope of this analysis.

2.3 Climate Model

The main issue addressed here is that of developing a scenario for long-term climate stabilization. To do this, we input the emissions paths calculated

Figure 4. Linkage Between Emission and Climate Models

using an AIM/CGE (Asia) model into a simplified climate model (based on a Joos model) (Matsuoka et al 2000), calculate temperatures, atmospheric concentrations, and degrees of radiative forcing, and perform calculations recursively until the emissions path reaches the target path (See Figure 4). As the main model is a recursive dynamic model, it calculates stabilization scenarios based on exogenously determined emissions paths. It should be noted that it does not reach an optimal emissions path during the time horizon of interest with specific objective function.

3. MODEL SIMULATION

3.1 Simulations

Three scenarios—BaU scenario and two stabilization scenarios have been developed and their results are presented. The stabilization scenarios are based on the radiative forcing of greenhouse gas emissions. The stabilization target is assumed to limit the increase of radiative forcing to less than 4.5 W/m² relative to that of before the Industrial Revolution. One stabilization scenario is a CO₂-only scenario in which target is reached solely through CO₂ reductions and the other stabilization scenario is a multi-gas scenario in which reductions are made in emissions of CO₂, CH₄ and N₂O. The results are discussed next.

3.2 Simulation Results

3.2.1 Greenhouse Gases Emissions

CO₂ emission projections are shown in Figure 5. Under the BaU scenario, no limit is placed on emissions and the levels of emissions are accordingly the highest. Under the CO₂-only scenario in which reductions are made only in

Figure 5. CO₂ Emissions Projections

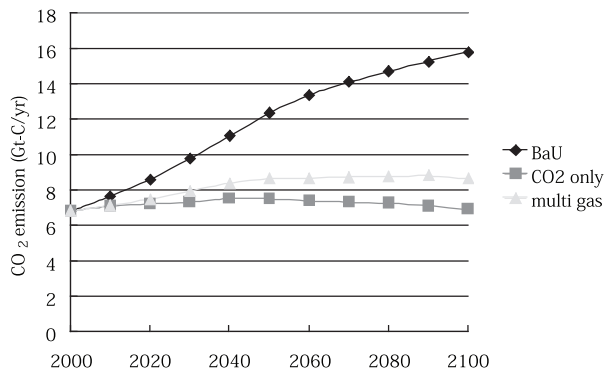


Figure 6. CH₄ Emissions Projections

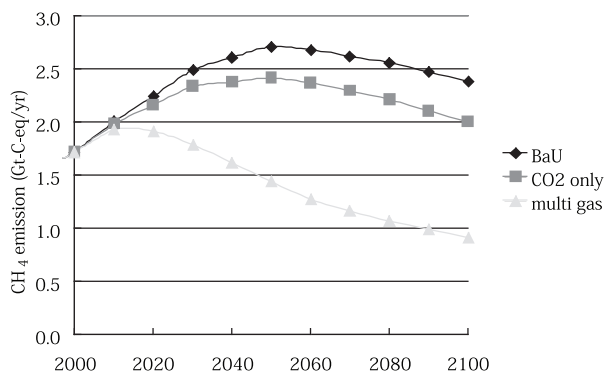
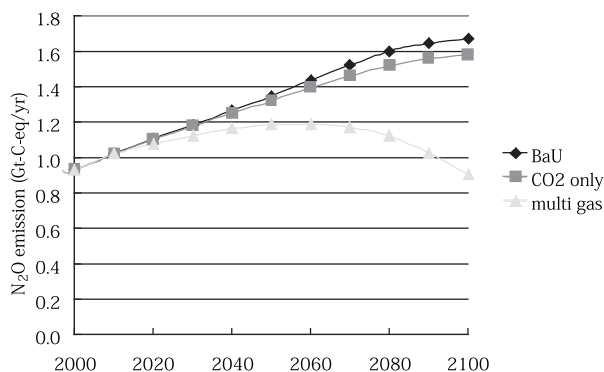


Figure 7. N₂O Emissions Projections



CO₂ emissions, the emissions levels are lowest. The emissions in the multi-gas scenario fall between the two. This is because restrictions on CO₂ emissions must be relaxed as measures to reduce CH₄ and N₂O are also taken to reach the same target level of radiative forcing. Figure 6 shows levels of CH₄ emissions and Figure 7 those of N₂O emissions. Under the CO₂-only scenario, emissions of CH₄ and N₂O also decrease marginally due of changes in supply and demand and decreases in manufacturing volumes resulting from CO₂ emissions reductions, even though no technologies are introduced to reduce emissions of other gases. In the multi-gas scenario, it could be possible to achieve major reductions in CH₄ and N₂O emissions as expected.

3.2.2 Economic Impact

Figures 8 and 9 show projections of global GDP and carbon prices respectively (marginal abatement costs) over the next century,. If we follow

Figure 8. GDP Projections

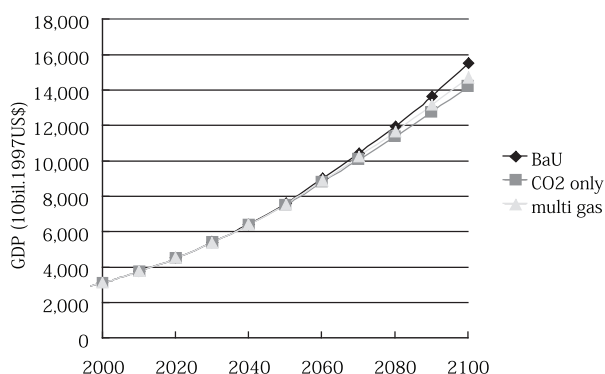
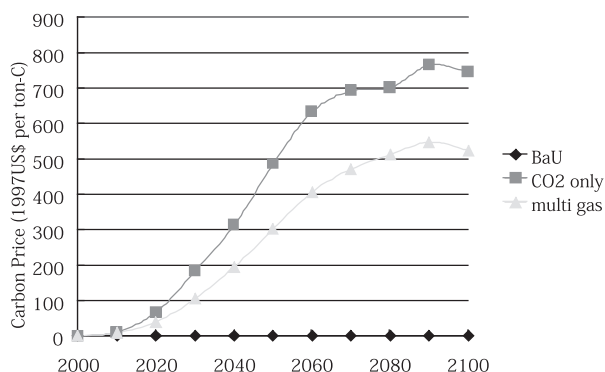


Figure 9. Carbon Price Projections



emission paths like those shown in Figures 5-7, it can be seen that differences in GDP begin to appear from 2050 onwards. This simulation shows that in 2100 the economic losses as compared to the BaU scenario would be 8.7% in the CO₂-only scenario and 5.1% in the multi-gas scenario. The model also shows quantitatively that the carbon price in the CO₂-only scenario is higher than that in the multi-gas scenario which results in differences in economic impacts.

4. CONCLUSION

This study developed a model to analyze not only the effects of measures to reduce CO₂, but also to reduce CH₄ and N₂O. Greenhouse gases emissions are projected and economic impacts are compared between the CO₂-only scenario and the multi-gas scenario. It is shown that measures to reduce Non CO₂ greenhouse gas (which include CH₄ and N₂O) would have less impact on GDP. The simulation results also show that through the multi-gas scenario, it would be possible to relax restrictions on concentrations of CO₂ in the atmosphere by about 20 to 70 ppmv by 2100. However, the uncertainties in non-CO₂ gases emissions and its abatement technologies may cause variations in results. These results may be further improved with more research on abatement cost technologies. This indicates that in order to construct scenarios concerning our ultimate objective of climate stabilization it will become increasingly important to continue to collect better information on non-CO₂ gases emissions and reduction technologies. It is therefore important to have a consensus on how such data should be used in models, and to reduce the level of uncertainties in such scenarios.

ACKNOWLEDGEMENT

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Technology Policy and World Greenhouse Gas Emissions in the AMIGA Modeling System

Donald A. Hanson* and John A. “Skip” Laitner**

In this paper we examine the interaction between technology policy and its impact on the full basket of worldwide greenhouse emissions over the 21st century. The heart of the analysis is the Argonne National Laboratory’s AMIGA Modeling System, a technology rich, general equilibrium model that (depending on data availability) characterizes as many as 200 sectors of the regional economies. We suggest in this paper that technologies and technology policies exist which could reduce carbon emissions enough to achieve stabilization targets at relatively modest costs given the size of the world economy. This can be accomplished largely through harnessing market forces and creating incentives with the use of efficient prices on greenhouse gas emissions, combined with complementary programs and policies to reduce market failures and to promote new technology improvements and investments.

1. INTRODUCTION

In this paper we examine the interaction between technology policy and its impact on the full basket of worldwide greenhouse emissions over the 21st century. Our assessment is part of the current Stanford University’s Energy Modeling Forum study on a multigas climate policy assessment (EMF-21). For this analysis we are using two models: the Argonne National Laboratory’s AMIGA modeling system (Hanson and Laitner, 2004; see also <http://amiga.dis.anl.gov>) and the National Center for Atmospheric Research’s MAGICC model (Wigley, 2003; and also see <http://www.cgd.ucar.edu/cas/wigley/magicc/>). The

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emission projections from the AMIGA model feed into the MAGICC climate model to estimate greenhouse gas concentrations, radiative forcing (in watts per square meter), and global mean temperature change.

For the EMF-21 exercise we explored two types of climate goals: (1) long-run climate stabilization at roughly 2 degrees centigrade higher than 1990 levels by the year 2100, and (2) a rate of temperature change constrained to an increase of no more than 0.2 degrees centigrade per decade beginning in 2030 through the year 2100. As part of this exercise, the EMF-21 study also examines the many carbon and non-carbon options which might slow the rate of temperature increases. The options included: (i) both efficiency gains and abatement reductions in the emissions from the full basket of greenhouse gases, (ii) slowing the rate of deforestation, and (iii) the examination of carbon sinks in soils and geological formations. In this paper we focus on the first of these technology paths. More specifically, we explore the influence of technology and technology policy on both the energy-related carbon dioxide emissions and the non-carbon dioxide emissions including methane, nitrous oxides, and the so-called fluorinated-gases.¹

2. THE GREENHOUSE GAS EMISSIONS AND TECHNOLOGY STORY IN BRIEF

We open the discussion by providing an overall context to help understand the analysis that follows. As mapped out in the description of the model runs that follow, we find that over the next 100 years oil and natural gas prices rise in the business-as-usual case. These price increases are partly due to more costly production and partly due to increased demand for energy services as incomes rise worldwide. This spurs the increased use of combined heat and power (CHP) and other waste-to-energy technologies, renewable energy resources, energy efficiency investments, advanced hybrid vehicles, and emission abatement systems. Increased experience with these different technologies (often referred to as “learning effects”) brings down their cost which, in turn, expands their market shares. This is a world similar to that characterized in the “Technology Triumphs” scenario of a previous EPA-Argonne study that occurs partly in response to the increasing relative scarcity of oil and natural gas resources (Hanson et al., 2004). Despite the improved rate of technological progress, however, total greenhouse gas emissions grow over the 100-year time horizon of the study.

Climate scientists continue to debate what would constitute prudent emission reduction trajectories. There are concerns about the effects of rapid

1. The fluorinated gases have very long atmospheric lifetimes, so controlling their emissions would have benefits for many centuries to come. However, this study examines only the climate effects over the next century. Methane, on the other hand, has a relatively short atmospheric lifetime of about 15 years. Atmospheric concentration reductions for methane by 2050 are important for slowing the rate of climate change, but would have little remaining influence by the year 2100. Long-term climate stabilization will likely require on-going control efforts for carbon, methane and other greenhouse gas emissions.

temperature change on bio-diversity and human societies. There is also concern about abrupt shifts in atmospheric-ocean interactions (Baranzini et al., 2003, Weart, 2003). As further climate data becomes available and as our interpretation and understanding of the information improves, there could be a need for aggressive reductions in all greenhouse gas (GHG) emissions to slow the rate of climate change. Medium-term reductions in methane and other non-CO₂ GHG would be important for slowing the rate of temperature change. For long-term stabilization with radiative forcing being gradually reduced, non-CO₂ greenhouse gas emission reductions can play an important role in lowering the cost of achieving the long-term target. Hence, it may be cost-effective to attain a long-term stabilization target using a larger set of greenhouse gases, rather than only reducing carbon emissions. A whole different set of technologies are applicable to non-CO₂ emission control. By simulating a multi-greenhouse gas long-term stabilization scenario, we examine a broader approach to environmental and technology policy.²

Below, we summarize the four GHG emission reduction scenarios for which least-cost control strategies are examined in this study. We consider three pure long-term stabilization cases and a fourth case with an additional constraint on the rate of temperature increase:

1. Achieve the given long-term stabilization target with carbon dioxide (CO₂) emission reductions, but without controls on emissions growth of other emissions, and using only the price mechanism to achieve those reductions;
2. Achieve a given long-term stabilization target with CO₂ emission reductions only, but implementing additional policies and programs to complement the price signal and ease the economic costs of the transition;
3. Achieve the same long-term stabilization target with reductions on both CO₂ and non-CO₂ emissions using both the price signal and other programs and policies; and
4. Limit temperature rise to 0.2 degrees centigrade per decade, starting in year 2030, using reductions of both CO₂ and non-CO₂ emissions, plus achieve the long-term stabilization target.

The least-cost policy approaches for these scenarios include efficient pricing of carbon dioxide and other GHG emissions (if other GHGs are controlled in the scenario). In addition, and following the success of existing programs (Climate Protection Partnerships Division, 2003, Laitner and Sullivan, 2001), we assume that cost-effective information and other voluntary programs and policies are used because of the economic and social importance associated with implementing a climate policy. These non-price programs and policies provide

2. The inclusion of non-CO₂ greenhouse gases and the constrained temperature scenario distinguish this EMF-21 study from our previous EMF-19 analysis (Hanson and Laitner, 2004).

guidance to early adopters of low-carbon technologies, promote earlier and more rapid technological learning, and address existing market failures.³

A number of caveats are in order. First, consistent with past EMF exercises, we are modeling for insights not for numbers. More specifically, we want to understand the technology and market relationships under different policy scenarios rather than create specific forecasts of greenhouse gas emissions and economic activity. Second, a full accounting for both costs and benefits clearly matter; yet, these have not always been adequately captured in most modeling exercises. The tendency is to understate both, with benefits receiving less attention both in past and (unfortunately) in these current exercises. Third, uncertainties abound. This is true whether we explore the pace and magnitude of climate change or the development of new technologies and innovative markets. Finally, as climate issues continue to receive more attention, the world community will undoubtedly provide continual adjustments in what it perceives as improved technology policies or strategies. In short, a world which acts, then learns (as it appears to be already doing with respect to climate-related markets and technologies), and then acts again is a world that is likely to embark on a different path than might be reflected in a set of modeling exercises from today's perspective and that do not incorporate information feedback. Hence, as we first noted, we are modeling for insights rather than precise estimates; the analyses and forecasts will surely be refined with time.

3. ABOUT THE MODEL

The heart of the analysis is based on the scenarios mapped into AMIGA (All Modular Industry Growth Assessment) modeling system. The system, programmed in the structured "C" language, is developed and supported by the Argonne National Laboratory in cooperation with the US Environmental Protection Agency's Office of Atmospheric Programs. AMIGA is a general equilibrium model that examines the impact of changes in more than 200 individual sectors (measured in dollar value and where appropriate in physical units as well). It integrates a detailed energy end-use and energy supply market specification within a structural economic model. The model allows firms to maximize net wealth and consumers to maximize intertemporal utility. In the absence of perfect foresight, agents act on approximate intertemporal rules. AMIGA calculates prices and macroeconomic variables such as consumption, investment, government spending, gross domestic product (GDP), and employment. In this exercise, the model provides equilibrium paths from the present through the year 2100.

AMIGA integrates eleven modules that describe the various economic

3. An example of an existing market failure is the absence of marginal cost pricing of electricity. We assume that market failures, such as this one, are gradually corrected over time. Correcting these market failures is critical to achieving cost-effective climate policy. Under a climate target scenario, combustion of fossil fuels is costly, encouraging the substitution of demand-side measures and low-carbon energy sources. However, if prices of electricity do not reflect underlying social costs, there will be an under-investment in valuable demand-side measures and renewable energy.

interactions among twenty-one world regions. For purposes of this analysis, however, we explore a more aggregated, three-region view of the world: the United States, other OECD countries, and the other nations of the world. Each region's assets include existing capital stock, labor resources, and exhaustible resources. The model tracks a detailed accounting of major goods and services demanded by households and the various production sectors of the economy that lead to changes in energy use and production, greenhouse gas emissions, and temperature changes. In short, AMIGA combines a bottom-up representation of the demand for energy and the many other goods and services sectors available with regional markets together with a detailed interaction among those sectors and among the regions of the world. Various choices within these sectors are modeled through nested constant elasticity of substitution (CES) production functions which determine how economic output is supported through inputs of capital, labor, electric and non-electric energy.

The model allows for autonomous improvements in technologies as well as both price and other policy-induced improvements which can lead to reductions in greenhouse gas emissions.⁴ AMIGA also incorporates macroeconomic feedbacks. Higher energy and other resource costs lead to substitution of capital and labor for energy. As previously suggested, a number of gases have been identified which contribute to climate changes and which have been mapped into the AMIGA model. In addition to the production of carbon dioxide (CO₂), emissions from methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF₆) are also included. The atmospheric impacts from these gases are estimated using the MAGICC model; or more formally, the Model for the Assessment of Greenhouse – gas Induced Climate Change. MAGICC is the climate model that has been used in the IPCC Second and Third Assessment Reports to produce projections of global-mean temperature. AMIGA estimates the annual worldwide emission reductions for each of the desired scenarios which are then passed to MAGICC as inputs. MAGICC then calculates the imputed GHG concentrations, radiative forcing and temperature that results from the emission paths. The projected climate impacts are compared with the climate goal for the scenario, and if they are not close, the AMIGA model is re-run with adjusted policy stringency. This iterative process continues until AMIGA/MAGICC converge on the same desired scenario target.

4. THE BASELINE ASSUMPTIONS

We next turn to the review of data that more specifically describe the macroeconomic and emissions trends in a non-policy baseline generated for this assessment. We have two overriding assumptions that underpin the reference case as well as the alternative policy scenarios. The first set of assumptions,

4. For a more complete description of how AMIGA incorporates other policy-induced improvements into emission scenarios, see Hanson et al. (2003).

drawing from an extensive literature reviewing economy-wide and sector performance, highlights an economy that is suboptimal in performance. By this we mean that while there is a level of robustness which underpins current growth patterns, it appears that price and non-price policies can encourage greater use of capital and other resources which are generally characterized as high-return energy efficiency applications that also reduce greenhouse gas emissions (see Table 4 for a summary of impacts and their resulting cost effects). The implication is, therefore, that under a different mix of prices and policies, an alternative pattern of technologies and market arrangements may emerge that can simultaneously maintain economic performance and reduce greenhouse gas emissions. The second major assumption is a continuing improvement in energy-related technology and markets that would be accelerated as a result of GHG price signals and complementary non-price policies.

As a result of these starting assumptions, we build a reference case economy (measured by world wide Gross Domestic Product) that follows a combination of population and productivity growth trends. Table 1 summarizes the regional GDP data for selected years. At the same time, the technology performance of the regional economies improves at a rate comparable to the change in regional greenhouse gas intensities summarized in Table 2 for those same years.

Table 1. Reference Case GDP (Trillion 2000 US Dollars)

Region	2000	2010	2020	2050	2100	AAGR
United States	9.7	12.7	16.3	31.1	60.6	1.8%
Other OECD	15.7	19.2	23.4	42.5	73.2	1.5%
Rest of World	7.5	10.4	14.3	37.5	162.1	3.1%
World Total	33.0	42.2	54.0	111.1	295.9	2.2%

Table 2. Reference Case GHG Intensity (grams per dollar of GDP)

Region	2000	2010	2020	2050	2100	AAGR
United States	190	158	137	93	66	-1.1%
Other OECD	129	114	100	69	53	-0.9%
Rest of World	659	528	439	243	80	-2.1%
World Total	268	229	201	135	71	-1.3%

Table 3. Reference Case Emissions (Million Metric Tons Of Carbon Equivalent)

Greenhouse Gas	2000	2010	2020	2050	2100	AAGR
Carbon	6,290	6,881	7,701	11,015	17,643	1.0%
Methane	1,610	1,782	2,040	2,630	2,074	0.3%
Nitrous oxide	838	880	914	981	854	0.0%
High GWP	82	115	196	335	352	1.5%
World Total	8,820	9,658	10,850	14,960	20,924	0.9%

Our baseline assumptions in Table 1 show different rates of economic growth for the US and other OECD countries compared to the other regions of the world. For all regions economic growth is expected to be somewhat faster in the next 20 years compared to the expected growth over the full century. Driven by larger population growth and productivity gains (in as much as they currently have less efficient technology on average but begin to catch up to OECD levels), the developing countries are expected to grow more rapidly than OECD countries. Overall world gross domestic product, measured in trillions of 2000 US dollars, increases at a 2.2 percent annual average growth rate (AAGR) over the period 2000 through 2100.

Table 2 summarizes the expected trends in technology performance as measured by declining greenhouse gas intensities (grams of carbon equivalent for all gases per dollar of GDP). Over the 100-year time horizon, technology worldwide is expected to improve at a moderate pace of 1.3 percent per year; or stated differently, technology is expected to improve so that annual GHG emissions intensities will decrease on average by 1.3 percent. The non-OECD regions are expected to improve more quickly since their level of GHG intensity is currently at a much higher level than either the US or the rest of the OECD nations.

Table 3 illustrates the interaction of economic growth together with a reasonable improvement in technology by charting the actual greenhouse gas emissions (in million metric tons of carbon equivalent). With the world economy expected to grow on average at about 2.2 percent annually over the next 100 years (see Table 1), and with technology improvements expected to reduce the economy's expected greenhouse gas intensities by about 1.3 percent each year, total greenhouse gas emissions are anticipated to grow at just under 1 percent annually. By the year 2100, total emissions are almost two and a half times larger than in the year 2000. Again these rates will vary by region.

5. EMISSION REDUCTION SCENARIOS

Current research suggests that in the year 2000 the worldwide average global temperatures were about 1 degree centigrade above the pre-1900 temperatures. Our reference case projections suggest that without further technology development and without implementation of additional policy options, the global average temperatures might be expected to climb to 4 degrees above pre-1900 levels, or 3 degrees above year 2000 temperatures. The goal of the EMF-21 exercise is to determine the impact of a variety of greenhouse gas emissions reduction options rather than to identify an optimal level of reductions. Thus, in our emission reduction scenarios, we explore the impact of technology and policy paths that might limit temperature changes to no more than about 2 degrees centigrade by the year 2100, or no more than 3 degrees centigrade higher than pre-1900 levels. In our four scenarios, this is achieved with and without policies and programs to complement a price signal, with and without non-CO₂ emission reductions, and with and without a constraint on the rate of temperature rise.

The first scenario that we describe is one which limits carbon dioxide emissions only through a price signal. That is to say, we assume the only mechanism to stimulate the development of and investment in low carbon technologies is through some form of cap on energy-related carbon dioxide emissions with energy users and/or producers required to hold a permit for each ton that is emitted. The permits would be issued either by an auction, or allocated through some market-based arrangement. As a result, the only stimulus to encourage the adoption of more energy efficient or low-carbon technologies is a set of higher energy prices stimulated by the emissions cap. The second scenario assumes both a price mechanism and the implementation of other energy policies such as greater emphasis on research and development initiatives, accelerated technology standards, and investment incentives — all of which might complement and interact with the price signal. These complementary policies reduce the level of carbon prices necessary to meet the desired temperature target.

A third technology path is to incorporate price and non-price policy options within a multigas, rather than a carbon dioxide only, framework. The evidence suggests that non-CO₂ emission reductions may be cheaper than many carbon dioxide reduction options. The assumption, therefore, is that a multigas scenario would be less costly than one that emphasizes only CO₂ emission reductions. Finally, we add a constraint on the rate of temperature change so that the change increases by no more than 0.2 degrees centigrade per decade starting in year 2030. This last technology path also includes the full spectrum of policies as well as the availability of non-CO₂ options to meet the long-term temperature target. The availability of multiple greenhouse gas emission reductions is important in being able to meet the rate of temperature change constraint.

Table 4 is designed to help explain the low cost of climate stabilization policies utilizing available technology options. In particular, both prices and program effort are important in driving changes in the low-carbon technologies that are employed in the future. As these technologies mature, they have roughly the same cost as today's energy-related technologies (especially when taking into account the long period of capital stock turnover and the offset from lower fossil fuel costs due to reduced demand for energy).

To further explain the impacts suggested in Table 4, we now briefly describe the variety of low-carbon technologies and abatement technologies to reduce other non-CO₂ emissions.⁵ Energy-efficiency technologies used in residential and commercial buildings and in industrial applications is a huge topic and has been treated in numerous other reports and papers. These technologies include efficient lighting and building shells, improved heating and cooling systems, combined heat and power and waste to energy systems, efficient appliances and electrical and electronic equipment (meeting or surpassing EPA

5. For greater description of carbon reduction technologies, see Interlaboratory Working Group (2000) and Hanson et al. (2004). For examples of other GHG abatement technologies, see Delhotal et al. (2004).

Table 4. Price Induced Substitutions and Cost Impacts: Broad Categories

Category of Impact	Price Effects	Cost Impacts
Learning and Technical Progress (Wene, 2000, McDonald and Schrattenholzer, 2001, Laitner and Sanstad, 2004)	Switch to technology paths that will allow economies of scale and experience with adoption of low-carbon technologies	Significant cost reductions can be achieved in the long run
Reduce barriers to distributed generation (Laitner et al. 1999, Lemar, 2001)	Encourage combined heat and power and waste to energy technologies	Both energy and economically efficient
Institutional Improvements (Argote, 1999, and Nadel et al., 2003, DeCanio, 1994, DeCanio et al., 2000)	Investment in electrical system network configuration and operations to be able to accommodate greater shares of intermittent and remote power sources	Cost lowering innovation
Efficient Pricing (Linton, 2004, Pizer, 2003, Newell et al., 1999)	Allow customers to see real time cost of supplying power (cycles significantly higher and lower than average costs),	Reduce a market failure that impedes the adoption of low-carbon technologies
End Use Opportunities (Metz et al., 2001, Interlaboratory Working Group, 2000, Nadel and Geller, 2001, and Energy Innovations, 1997)	Adopt cost-effective, efficient, energy-using technologies	Address information, principal-agent and other market failures to lower economy-wide costs
Gains from Systems Integration (Lipman et al. 2002, Interlaboratory Working Group, 2000)	Promote grid-connected hybrid vehicles to absorb and store surplus low-priced electricity when available	Reduce oil costs and increase national security through less imported oil.
Electronic controls and hybridization (Interlaboratory Working Group, 2000)	Take advantage of innovations in high tech fields to use energy smarter	Technology advance

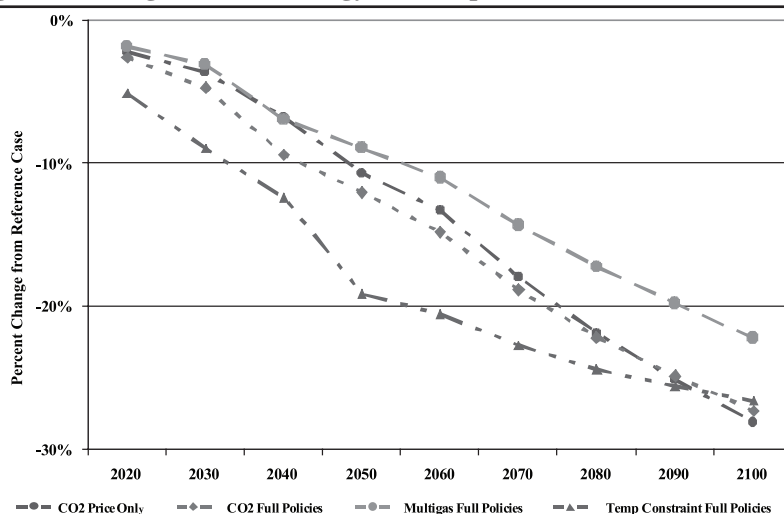
Energy Star standards), applications of sensors and automatic controls, and use of heat pumps, passive and active solar thermal energy, and photovoltaic panels in some markets. For personal transportation, the application of power electronics and other smart technologies to modular, optimized hybrid electric vehicles is just at the beginning of an evolutionary path with tremendous potential for efficiency and performance gains. These vehicles can be connected to the power grid through electromagnetic coupling or by direct connection. Hybrid electric vehicles are a natural storage device to absorb surplus, off-peak power from a diversified network that can provide large quantities of intermittent renewable electricity. The surplus, low-carbon electricity absorbed in storage technology will displace the need for oil, gas or coal-based power. For electric generation, many renewable energy resources (wind, solar power towers, geothermal) and waste to energy technologies (combined heat and power, pressure recovery

turbines, and gasification) are economic in the presence of even a modest carbon charge. Early adoption of many of these technologies, combined with large-scale manufacturing, will reduce costs and improve performance and customer satisfaction over time. Although these technologies are different than today's fossil fuel intensive technologies, they provide basically the same energy-related services. In some cases they have the potential to provide these services cheaper and more productively (see, for example, Martin et al., 2000).

No doubt there will be dramatic technological breakthroughs in many fields over the next century (largely explaining a much larger GDP to be expected in the future), but in this study we do not rely on unpredictable technological breakthroughs for GHG abatement.⁶ Hence, the technologies described here are either existing ones, or are ones that are based on foreseeable incremental and evolutionary developments from the existing technologies. If a model does not represent these kinds of either near-term or evolutionary technologies, then (presumably) the resulting scenarios would overestimate the costs of complying with low-carbon future scenarios. The AMIGA model has been designed to include low-carbon technologies and to represent endogenous technical progress as the economies of the world proceed down low-carbon paths under climate change constraints. In the AMIGA model, energy efficiency and low carbon energy sources are employed more or less rapidly and to greater or lesser extents depending on the price of carbon and the impact of other non-price policies. In the multigas scenario, somewhat less carbon reduction is needed. In the constrained temperature rate of change scenario, all measures available have to be pursued in the near term, substantially raising R&D and investments in energy efficient and renewable energy technologies.

Figure 1 shows the percentage reductions in World Total Primary Energy (TPE) in the four climate policy scenarios, compared with the Reference case described in Tables 1-3. As we might quickly note, the multigas stabilization path requires less reduction in energy consumption to achieve the same level of temperature stabilization. On the other hand, if the rate of temperature change needs to be constrained, energy demand would have to come down more rapidly over the next 50 years. In calculating TPE we value non-fossil generators (nuclear and renewable energy) at the average fossil generation heat rate (Btu/kWh) in the given year. These demand reductions (described generally in Table 4) are induced by the carbon charges along with significant voluntary program effort. The magnitudes of the price signal over time by scenario are shown in Table 5. The highest carbon charges are needed with a near-term effort to reduce temperature rise, and the lowest carbon charges are required under a broad-based, multigas, full policy, long-term stabilization target.

6. As one measure of technical progress, the largest rate of decline in worldwide energy intensity in any of the scenarios explored in this study is 1.5 percent annually, only slightly higher than the reference case rate of 1.2 percent suggested in the reference case assumptions. By contrast, a number of studies suggest that a 2.0 percent is technically possible and may be economically feasible with the advent of new materials, advances in microelectronics, and changes in consumer preferences (Laitner, 2004).

Figure 1. Change in World Energy Consumption**Table 5. Carbon Charge by Scenario (2000 US dollars Per Ton Carbon Equivalent)**

Scenario	2020	2040	2060	2080	2100
CO ₂ Reductions with Price-only Policy	92	148	183	203	216
CO ₂ Reductions with Full Policies	63	102	124	138	147
Multigas Reductions with Full Policies	43	68	84	93	99
Temperature Constraint with Full Policies	171	245	253	231	193

Figure 2 shows the energy expenditure path for the four climate policy scenarios relative to the reference case. Energy expenditures are the sum over all end-use purchases of energy price times the quantity demanded. The price will include the net pass through of a carbon charge, partially offset by the lower fuel prices that emerge in the energy markets due to lower demand for oil, natural gas and coal. At first energy expenditures increase due to higher energy prices which reflect the carbon charge. This is most pronounced with the high carbon charges under a temperature change rate constraint case. Later as the price elasticity works through the capital turnover process, energy demand is sufficiently reduced so as to reduce expenditures on energy. These effects are less pronounced under the multigas stabilization scenario, due to lower carbon charges needed in this case. Indeed, the significant reduction in energy demand in the second half of the century drives a total set of energy expenditures that are lower than in the reference case.

Under all climate policy scenarios, total investment in the various mix of technologies are higher in order to meet the necessary GHG reductions, as shown in Figure 3. This is most pronounced in the rate of temperature change

Figure 2. Change in World Energy Expenditures

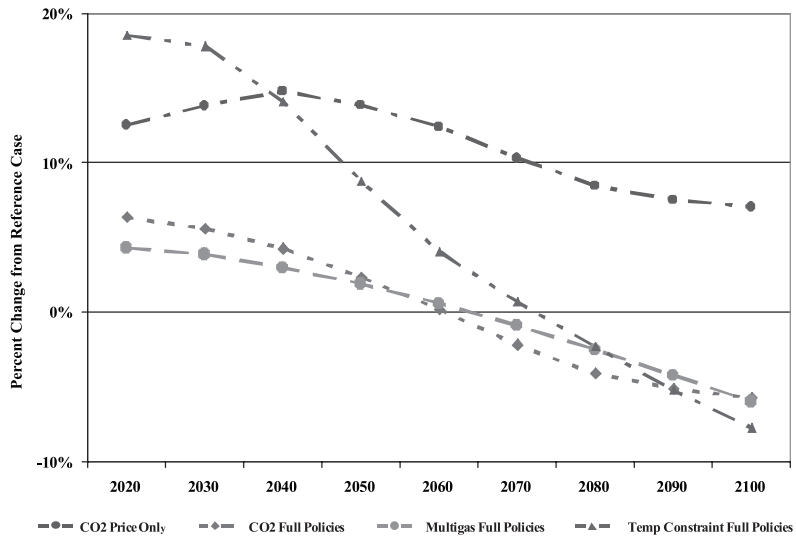
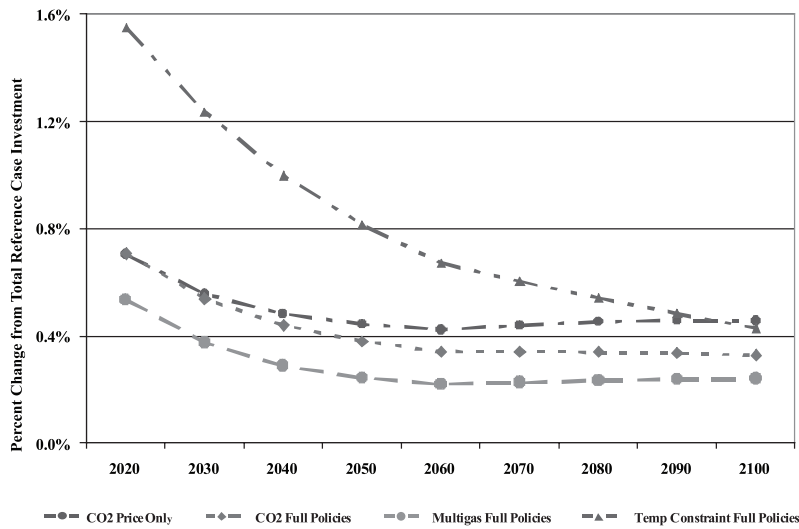


Figure 3. World Energy and Non-CO₂ Related Investments



constrained case in which substantial additional investments would be needed over the next 50 years. Figure 3 plots investments in each of the four scenarios by ten year intervals. Again, the temperature constrained scenario forces a more rapid turnover in capital stock in the early part of the century so that there is a big jump in capital outlays. Since replacement investments can swing substantially

from year to year as existing capital retires, investment charts for any given sector typically are not smooth over time. Nevertheless, the general patterns are clear. Again, the multigas stabilization scenario requires less investment to meet the long term climate change target compared with only CO₂ reductions.

To provide a clearer insight into the required investment patterns, the outlays for both energy-related and non-CO₂ abatement technologies are shown in Tables 6a through 6d for the US, other OECD nations, rest of world countries, and the world total. The categories of different investments shown as annual averages for the first and second half of the century are as follows:

- Incremental residential and commercial building-related efficiency investments,
- Incremental industry energy efficiency investments,
- Incremental cost of more energy-efficient cars, vans, and light trucks,
- Measures applicable to other transportation modes including aircraft and heavy duty trucks,
- Electricity supply investment which decreases with lower electricity demand but increases with the substitution of renewable energy for fossil fuels,
- Reduced investment requirements in other energy supply, such as oil and gas drilling, oil refining, coal mining, and fuel transportation and distribution,
- Investments in systems integration, such as standard interconnection for distributed generation, net metering, real-time electricity pricing, price sensitive sensors and demand controls, energy storage technologies, transmission grid enhancements, diversification of renewable sources to increase reliable power from renewable technologies, and facilities to distribute surplus intermittent renewable electricity to grid-connected vehicles and other storage capacity.

Tables 6a-6d apply to the multigas stabilization case. It is seen that the investments needed for non-CO₂ GHG abatement are substantially less than energy-related investments which would otherwise be required to achieve the climate stabilization target. Energy-related investments are higher for CO₂ only stabilization scenarios than shown in Table 6. However, investments under the constrained rate of temperature change scenario are substantially higher than shown in Table 6.

Table 6a. Average Annual Incremental Investment for USA: Multigas Long-term Stabilization Case (billion 2000 US dollars)

	2020-2060	2060-2100
Buildings-related	5.2	11.8
Industry	3.4	6.3
Light-duty Vehicles	4.8	11.3
Other Transportation	2.3	4.8
Electricity Supply	0.8	-8.9
Other Energy Supply	-2.9	-15.0
Systems Integration	2.0	13.5
Total Energy-Related	15.6	23.8
Non-CO ₂ gas reductions	0.3	1.0
Total Investment	15.9	24.8

**Table 6b. Average Annual Incremental Investment for Other OECD:
Multigas Long-term Stabilization Case (billion 2000 US dollars)**

	2020-2060	2060-2100
Buildings-related	5.5	11.9
Industry	3.6	6.1
Light-duty Vehicles	6.5	13.2
Other Transportation	2.5	5.1
Electricity Supply	0.4	-10.5
Other Energy Supply	-2.7	-13.1
Systems Integration	2.5	13.5
Total Energy-Related	18.4	26.2
Non-CO ₂ gas reductions	0.3	1.1
Total Investment	18.7	27.3

**Table 6c. Average Annual Incremental Investment for Rest of World:
Multigas Long-term Stabilization Case (billion 2000 US dollars)**

	2020-2060	2060-2100
Buildings-related	7.9	19.4
Industry	5.9	10.7
Light-duty Vehicles	11.1	32.8
Other Transportation	2.9	6.7
Electricity Supply	-7.4	-31.2
Other Energy Supply	-8.3	-50.3
Systems Integration	7.5	61.9
Total Energy-Related	19.6	50.1
Non-CO ₂ gas reductions	1.9	7.9
Total Investment	21.5	58.0

**Table 6d. Average Annual Incremental Investment for World Total:
Multigas Long-term Stabilization Case (billion 2000 US dollars)**

	2020-2060	2060-2100
Buildings-related	18.6	43.2
Industry	12.9	23.0
Light-duty Vehicles	22.4	57.3
Other Transportation	7.8	16.5
Electricity Supply	-6.2	-50.5
Other Energy Supply	-13.9	-78.4
Systems Integration	12.0	88.9
Total Energy-Related	53.6	100.1
Non-CO ₂ gas reductions	2.5	10.0
Total Investment	56.1	110.1

6. FURTHER DISCUSSIONS

From an investor's viewpoint the amount of capital necessary to switch from a development path dominated by fossil fuel technologies seems large as

Table 7. World GDP (Billion 2000 US Dollars Change from Reference Case)

Scenario	2020	2040	2060	2080	2100
CO ₂ Reductions with Price-only Policy	-14	-17	-23	-3	21
CO ₂ Reductions with Full Policies	-7	-9	-16	1	18
Multigas Reductions with Full Policies	-4	-2	-2	8	23
Temperature Constraint with Full Policies	-29	-43	-53	-35	-11

the emphasis shifts to one that relies primarily on energy-efficient, low-carbon technologies. But from the perspective of a world economy the total increase in new capital requirements does not seem quite so dramatic. As shown in Figure 3, incremental energy-related investments range from 0.2% to 1.6% of total investment in any given year, in order to achieve long-term climate stabilization. Compared to worldwide GDP, the scale of investment outlays is even smaller, ranging 0.1% to 0.6%.

The consequences for GDP, as shown in Table 7, are essentially in the noise. Above average rates of return on energy efficiency investments can have small positive effects in GDP. Displacements by climate stabilization investments of other investment will lead to a negative effect on GDP; but, again, this effect would be relatively small if the climate-related investments are relatively small. The case with the highest climate-related investments is the one where the rate of temperature change is constrained, as shown in Table 7. Note that the Table 7 changes in GDP are reported in billions of 2000 US dollars while the world economies are measured in trillions of 2000 US dollars.

Similarly, the change in the consumption path is relatively small. Reductions in consumption due to lower GDP and due to crowding out from increased investment expenditures are largely offset by increased real income in the non-OPEC world arising from lower oil import expenditures. Oil import expenditures are lower due to both reduced petroleum use in transportation and lower oil prices responding to reduced oil demand.

7. CONCLUSIONS

We have seen that methane and other non-CO₂ greenhouse gas reductions could significantly contribute to the low-cost achievement of climate goals, both for slowing the rate of temperature change and for long-term stabilization. However, carbon emission reductions will remain the primary objective. We have suggested in this paper that technologies and technology policies exist which could reduce greenhouse gas emissions sufficient to achieve the specified stabilization targets at relatively modest costs given the size of the world economy. This can be accomplished largely through harnessing market forces and creating incentives through the use of efficient prices on greenhouse gas emissions, combined with complementary programs and policies to reduce market failures and to promote new technology improvement.

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Multi-Gas Forcing Stabilization with Minicam

Steven J. Smith* and T.M.L. Wigley**

This paper examines the role of climate forcing agents other than carbon dioxide using the MiniCAM integrated assessment model for both no-climate-policy and policy emissions scenarios. Non-CO₂ greenhouse-gas forcing is dominated by methane and tropospheric ozone. Assumptions about the prevalence of methane recovery and local air pollution controls in the no-policy cases are a critical determinant of methane and ozone-precursor emissions. When these factors are considered, emissions are substantially reduced relative to earlier estimates. This reduces their potential as climate mitigation agents through specific climate policies. Nevertheless, the addition of non-CO₂ greenhouse gas and ozone precursor abatement options significantly reduces mitigation costs in the first half of the 21st century (by up to 40%) compared to the case where only CO₂ abatement options are pursued. While the influences of aerosols are small by the end of the century, there is a significant interaction in the early 21st century between policies to reduce CO₂ emissions and SO₂ emissions, even in the presence of SO₂-related pollution control policies. The attendant reduced aerosol cooling can more than offset the reduction in warming that accrues from reduced CO₂. When non-CO₂ gases are included in the policy, the net effect is that global-mean climate change to 2050 is practically unaffected by mitigation policy.

1. INTRODUCTION

While it has long been recognized that carbon dioxide emissions are not the only driver of climate change, other atmospheric forcing agents have only recently been incorporated into many integrated assessment models (Nakicenovic and Swart 2000). Incorporation of mitigation options for non-CO₂ gases has lagged behind incorporation of emissions. This is, in part, due to the difficulty of implementing the numerous possible mitigation options for these

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gases, emissions of which often occur in sectors other than energy production and combustion generally considered in models. Through the EMF21 project both non-CO₂ greenhouse gas emissions and emissions mitigation options have been incorporated in a number of integrated assessment models.

This paper reports on the results of the EMF21 baseline and mitigation scenarios as produced by the JGCRI MiniCAM (Mini-Climate Assessment Model) integrated assessment model. The results presented here use the latest version of the MiniCAM model, with a new realization of the SRES emissions scenarios. In order to place these results into context the next section presents an analysis of non-CO₂ greenhouse gas forcing in the SRES scenarios (Nakicenovic and Swart 2000). The methods used to incorporate non-CO₂ emissions and emissions mitigation into the MiniCAM is then described. General results from a new realization of the SRES emissions scenarios are presented, followed by a more detailed discussion of the reference and policy cases examined for the EMF 21 project.

2. SRES ANALYSIS

It is useful to examine first the state of the art in non-CO₂ greenhouse gas emissions as represented in the SRES scenarios (Nakicenovic and Swart 2000). These scenarios were the first set of scenarios from multiple models that contained emissions for all greenhouse and related gases.

In order to compare gases using a common metric we use radiative forcing, the only unambiguous metric available (Smith 2003). For context, Table 1 shows the radiative forcing from pre-industrial times to 1990 for greenhouse gases, aerosols, and tropospheric ozone. Forcing from the well-mixed non-CO₂ greenhouse gases (methane, nitrous oxide, and the halocarbons) plus tropospheric ozone is 1.1 W/m², or 80% of the forcing from carbon dioxide. Aerosols are thought to be currently offsetting a significant fraction of the forcing from greenhouse gases.

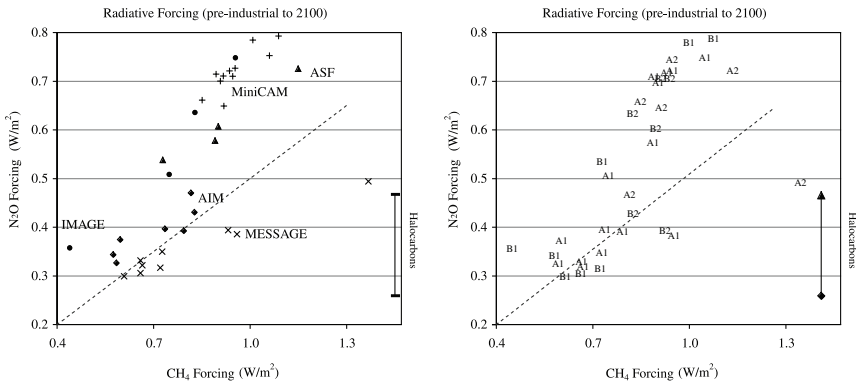
We first consider future forcing from methane and nitrous oxide. These two gases are considered together because their emissions are primarily from the agricultural sector and these emissions are not, in general, subject to mandated emissions controls (methane emissions from landfills are an exception).

Figure 1 shows the radiative forcing in 2100 for methane and nitrous oxide for each of the 35 scenarios that include emissions for these gases. The

Table 1. Estimated Radiative Forcing (in W/m²) from Greenhouse Gases and Other Compounds from Pre-industrial Times to 1990

Carbon Dioxide	1.3
Methane	0.4
Nitrous Oxide	0.1
Halocarbons	0.1
Aerosols	-1.3
Tropospheric Ozone	0.4

Figure 1. Forcing from Pre-industrial Times to 2100 for Nitrous Oxide and Methane in the 35 Scenarios



The dashed line indicates the point where forcing from nitrous oxide is half that of methane. Each of the five models used to construct these scenarios is identified by a different symbol (circle-IMAGE, diamond-AIM, "X"-MESSAGE, triangle-ASF, and cross-MiniCAM; Nakicenovic et al. 2000). The SRES scenario family for each point is indicated in Figure 1b.

range in forcing for the four halocarbon scenarios used in the SRES is also shown. These radiative forcing calculations employ the gas cycle models and forcing relationships used in the IPCC Third Assessment Report (Cubasch et al. 2001; Wigley and Raper, 2001, 2002; Wigley et al., 2002). Note that due to its relatively short lifetime, methane forcing is more sensitive to late period emissions than is nitrous oxide forcing.

Methane is the most important non- CO_2 greenhouse gas in all of the scenarios. The importance of nitrous oxide tends to increase with time, due the relatively long lifetime of this gas. By 2100, the ratio of nitrous oxide to methane forcing increases in most scenarios to between 40–80%, from a value of about 30% at present. Forcing from halocarbons (including SF_6) is comparable to the lower range of nitrous oxide forcing.

Note that there are only four separate scenarios for fluorinated gas emissions ("F-gases" HFCs, PFCs, and SF_6) in the SRES scenario set (one for each scenario family), and only one for the halocarbons controlled under the Montreal Protocol. Forcing for these gases increases to 0.3–0.5 W/m^2 by 2100. The increase is due to use of substitutes for ozone-depleting substances as well as increases in the use of extremely long-lived industrial gases such as the perfluorocarbons.

Figure 1 shows that emissions can be more a function of the model than the underlying driving forces. Recall that the SRES scenarios are grouped into four scenario families. We would expect that emissions would cluster together by scenario, since the underlying driving forcing are the same in each scenario family. Figure 1 shows that this is not the case, particularly for nitrous oxide. Each

integrated assessment model used to create the SRES scenarios is represented by a different symbol. We see that the points in the Figure cluster together as much by model as by scenario family (Figure 1b).

Note that we would expect, *a priori*, some clustering of the forcing values in Figure 1, with the B1 scenario family exhibiting the lowest forcing (due to low population levels and high levels of productivity and efficiency), A1 and B2 being somewhat higher, and the A2 scenario showing the highest levels (due to high population levels, and lower technology and productivity assumptions). The B1 and A2 scenario families are natural lower and upper bound scenarios for the SRES scenario set, although this does not mean that it is inconsistent for other scenarios to have higher or lower emissions.

Some degree of clustering for the A2, B1, and B2 scenarios is, indeed, observed. Results for the A1 scenarios, however, spread across nearly the entire range, particularly for nitrous oxide. If we examine the presumed lower (B1) and upper (A2) bound scenarios, three of the models (IMAGE, AIM, and MESSAGE) do have methane forcing for the B1 scenarios in the low end of the range, with forcing in the A2 scenarios in the mid to high end of the range. Forcing for nitrous oxide is similar, with slightly more scatter. Methane forcing in the B2 scenarios is narrowly centered near the middle of the range, with B2 nitrous oxide forcing distributed more widely. Note that the outputs from the MESSAGE model used agricultural emissions from the AIM model, so these two results are not independent.

Examining the results by model, the IMAGE model shows the largest range, with forcings that vary over much of the range of the complete scenario set. In addition, the results vary as expected, with the B1 scenario having the lowest forcing, the A2 scenario the highest. The ASF model results show a similar pattern, but with a more restricted overall range, particularly for nitrous oxide.

The remaining three models show a more restricted variation in forcing. Forcings from both the MiniCAM and AIM models are clustered with a fairly small variation with respect to scenario. Forcing from MiniCAM is consistently higher than that from the AIM model. Nitrous oxide emissions from the MESSAGE model, necessarily, have a distribution similar to those of the AIM model. Methane emissions from MESSAGE are distributed across the SRES range in the order expected.

We now move to consideration of forcing from tropospheric ozone and sulfate aerosols. These two substances arise indirectly from anthropogenic emissions; are short-lived and, therefore, not uniformly distributed; and their precursor compounds are subject to controls in many parts of the world. The concentration level of tropospheric ozone in the atmosphere is determined largely by the emissions of precursor compounds such as nitrous oxides (NO_x), carbon monoxide (CO), and volatile organic compounds (VOCs). Climate processes also play an important role for both ozone and aerosol production, although these are not considered here.

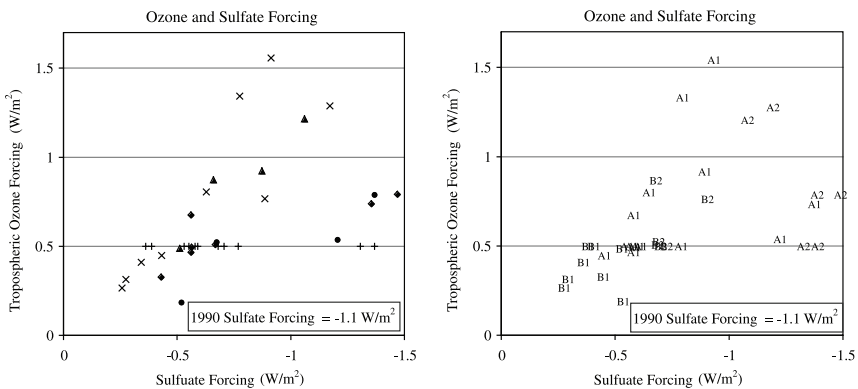
Sulfate aerosols are formed from sulfur dioxide (SO_2) emissions through both dry and aqueous processes in the atmosphere. The present-day radiative forcing

from sulfate aerosols is quite uncertain. Additional uncertainties in aerosol forcing stem from the fact that aerosols seldom consist of just one constituent. Nitrates, sea salt, black carbon, and organic carbon can form aerosols or mix with sulfates to form aerosol mixtures whose radiative properties are still poorly understood. Although these aerosols are considered in MiniCAM, it is not possible to address them or their associated uncertainties for the SRES scenarios. We focus therefore on aerosols formed as a consequence of sulfur dioxide emissions only, since these are currently thought to be the major anthropogenic aerosol forcing component.

Figure 2 shows the radiative forcing from tropospheric ozone and sulfate aerosols for the 35 scenarios considered in Figure 1. The results for these scenarios are generally more consistent than for methane and nitrous oxide in that results cluster by scenario family (Figure 2b) to a greater extent than by model. Radiative forcings in the B1 scenario family are consistently the lowest for both of these substances. Forcings in the A2 scenarios are generally at the high end of the range.

Only a few scenarios exhibit a sulfate aerosol forcing that is higher (in absolute magnitude) than the present-day sulfate forcing. Most of these are in the A2 family where low incomes in much of the developing world preclude significant actions to control sulfur dioxide emissions (Smith et al. 2005; SRES). Sulfur dioxide emissions, and therefore sulfate forcings, are also high in a few scenarios in the A1 family. This is difficult to reconcile with the high income levels and high level of technology assumed for this family. Most of the A1,

Figure 2. Forcing from Pre-industrial Times to 2100 for Tropospheric Ozone and Sulfate Aerosols Oxide in the 35 Scenarios



Note reversal of axis for aerosol forcing such that high absolute forcing is on the right. Each of the five models used to construct these scenarios is identified by a different symbol. Symbols represent the model (Nakicenovic et al. 2000). The SRES scenario family for each point is indicated in Figure 2b. Note that MiniCAM tropospheric ozone values are not considered in this analysis since emissions for precursor gases for the MiniCAM SRES scenarios were derived from other scenarios (MiniCAM ozone values were arbitrarily set to 0.50 W/m^2 in this Figure).

B1, and B2 scenarios have sulfate forcings that are significantly smaller than the present-day global value. With the exception of a few outlying scenarios, the SRES results for sulfate forcing show a fairly high degree of consistency.

Results for tropospheric ozone are not as consistent. Most industrialized regions of the world currently control emissions of ozone precursor compounds, particularly in urban areas, due to the adverse health effects of ozone. The World Health Organization has also established ozone standards, albeit standards that are routinely exceeded in many regions of the world.

We would expect that the current emphasis on limiting tropospheric ozone concentrations would continue into the future. Based on this expectation we would expect relatively low ozone concentrations in the “environmentally conscious” B1 scenarios, high ozone levels in the A2 scenarios, where low incomes and population pressures might preclude emissions controls in many regions, and intermediate levels in the A1 and B2 scenarios. The lowest ozone levels do occur for the B1 scenarios. While the A2 scenarios are among the highest ozone values, global ozone forcing levels twice the current level (Table 1) also occur in several of the A1 scenarios and two of the B2 scenarios.

One of the difficulties in evaluating the consistency of the ozone results is the non-linear relationship between ozone precursor emissions and local ozone concentrations. In addition, it is urban ozone levels that are often of most concern, while it is the regional ozone concentration that is relevant as a radiative forcing agent. This contrasts to sulfate aerosols, whose concentrations and impacts are, to first order, proportional to emissions of the primary precursor compounds.

Long-term tropospheric ozone concentrations higher than present-day levels would appear to be inconsistent with either a “dynamics as usual” scenario (*i.e.*, the B2 scenario family) or a “high income, high technology” scenario (*i.e.*, the A1 scenario family). Our conclusion is that the emissions of ozone precursor compounds in the majority of the SRES scenarios are not fully consistent with the scenario storylines. This appears to be due to a lack of inclusion of likely responses to local air pollution controls in the models used to generate these emissions (in contrast to the inclusion of such factors in deducing future sulfur dioxide emissions).

Note that the relationship between emissions of ozone precursor gases and tropospheric ozone concentrations used here (Wigley *et al.* 2002) was developed for use in the IPCC Third Assessment Report and was not available with the SRES scenarios were constructed. Given that the SRES presented the first comprehensive set of long-term scenarios for ozone precursor emissions, there has not been time for significant feedback between impacts and emissions modelers. The lack of consistency is, therefore, not surprising.

We find that future methane and nitrous oxide forcing in the SRES scenario set has a substantial model dependence. Results for most models show the expected dependence on scenario, although taken as a group, emissions depend as much on model as they do on the scenario assumptions. The SRES scenarios for sulfur dioxide are fairly consistent, clustering by scenario more than by model.

Our analysis of the results for tropospheric ozone indicates that most of the SRES scenarios do not appear to be consistent with the SRES storylines, primarily because the scenario producers did not have access to the ozone implications of their scenarios. A continuation of current trends toward controls on ozone precursor emissions would imply that, in a future world with sufficient resources to devote to pollution controls, ozone levels in the long term should not be too much higher than at present. Global ozone forcing in 2100 (relative to pre-industrial times) would therefore be of order 0.3-0.4 W/m². The SRES results show that less stringent controls on ozone precursor emissions, however, could result in a quite significant forcing from tropospheric ozone, up to more than 1 W/m².

We have not discussed industrial F-gas emissions since only one model was used to produce the four SRES emissions pathways.

Examination of Figures 1 and 2 shows that methane, tropospheric ozone, and sulfate aerosols have the potential for forcing effects of roughly equal magnitude. The potential for forcing effects of roughly equal magnitude. The forcing potential from nitrous oxide and halocarbons is smaller by about a factor of two. In a scenario with limited pollution controls, such as the A2 scenario, each of the three largest forcing agents could contribute over 1 W/m² (with the sign of the sulfate aerosol effect being negative) with an additional 1 W/m² from the combination of nitrous oxide and the halocarbons (all forcing values relative to pre-industrial). Thus a combined rough upper bound for forcing might be around 3 W/m² from non-CO₂ greenhouse gases plus sulfate aerosols (For a probabilistic assessment of this forcing and its importance relative to CO₂ forcing, see Wigley, 2004.).

These apparent inconsistencies point to the need for improved understanding of emissions of the non-CO₂ greenhouse gases and precursors. The SRES results are nearly 5 years old as of this writing and improvements in many of the models used therein have been made since that time. The EMF 21 project was aimed at advancing the treatment of non-CO₂ greenhouse gases (Weyant, de la Chesnaye, and Blanford 2006). Results for the newest version of the MiniCAM model are presented in this paper and compared with the previous SRES ranges.

3. METHOD

The calculations presented here were conducted with the MiniCAM 2001 integrated assessment model. Full documentation of the model can be found in Brenkert *et al.* (2003). MiniCAM is a partial equilibrium energy-economic-agricultural model that also incorporates the set of climate and atmospheric models known as MAGICC (Wigley and Raper 2001; Wigley and Raper 1992, 2001, 2002). The energy component of the MiniCAM solves for world and regional energy supply and demand with 14 world regions using a 15-year time step. The 14 regions are: United States, Canada, Western Europe (OECD90), Japan, Australia & New Zealand, Former Soviet Union, Eastern Europe, Latin America, Africa, Middle East, China/Asia Reforming Economies, India, South Korea, and Rest of South & East Asia.

Energy supply technologies include four end-use fuels (coal, oil, gas, biomass), electricity, and hydrogen. Electric generation technologies include fossil fuels (with or without geologic sequestration), biomass, and a number of non-carbon emitting technologies (wind, solar PV, fusion, nuclear, hydroelectric, etc.). The 2001 version of MiniCAM contains a number of model improvements, including: exact base-year calibration; incorporation of traditional biomass use; capacity limitations for intermittent renewable electric generation (*e.g.*, wind and solar PV); direct calculation of ozone levels with pollution-control-induced feedbacks on emissions of the precursor gases (similar to the way pollution controls are accounted for with SO₂ emissions; see Smith *et al.* 2005 and Smith 2005); and improvements to the gas-cycle and climate components as outlined in Wigley and Raper (2001, 2002).

With a focus on energy systems, and the relative simplicity of calculating CO₂ emissions, carbon dioxide emissions from the combustion of fossil fuels are directly modeled in the MiniCAM according to fuel consumed in each sector. Emissions other than carbon dioxide generally depend both on the technology used and the characteristics of any emissions controls. In order to maintain a fast, flexible modeling structure, emissions of non-CO₂ gases and aerosols are modeled in a reduced-form manner. For each emissions sector and region, non-CO₂ emissions are modeled as:

$$\begin{aligned} \text{Emissions} = & Em\_factor \cdot Driver \cdot (1 - Control \left(\frac{GDP}{Cap} \right)) \\ & \cdot (1 - MAC(C\_Price)) \cdot (1 - Eff(t)) \end{aligned} \quad (1)$$

where *Em_factor* is the emissions factor, which is generally determined from the input data set. *Driver* is the basic activity level for each emissions sector. The emissions sectors and drivers used for this study are shown in Table A1. Emissions are calculated for carbon dioxide, methane, nitrous oxide, sulfur dioxide, black carbon, organic carbon, nitrogen oxides, carbon monoxide, non-methane volatile organic hydrocarbons, and seven categories of industrial gases ("F-gases" -HFCs, PFCs, and SF₆).

For most sectors, future emissions are determined by a combination of three factors: a) the base-year emissions (which determine the aggregate emissions factor for each sector), b) the evolution of the driving activity level over time (Table 1), and c) changes in emissions controls (through the Control() function). Base-year emissions for methane, nitrous oxide, and industrial fluorinated gases were taken from the values provided to the EMF21 study (Scheehle and Kruger 2006, Delhotal *et al.* 2006, Ottinger *et al.* 2006), sulfur emissions are from Smith *et al.* (2001, as updated in Smith *et al.* 2004), carbonaceous aerosols from Bond *et al.* (2004), and reactive gases from a variety of sources (van Aardenne *et al.* 1999, Olivier *et al.* 1999, US EPA 2000, Environment Canada 2002, EEA 2002).

The MAC(carbon_price) function stands for a Marginal Abatement Curve (MAC), which allows emissions to decrease in response to the presence

of a price for greenhouse gases. MACs were implemented for methane, nitrous oxide, and industrial gases (DeAngelo et al. 2006, Ottinger et al. 2006). Several implementation decisions had to be made for these curves. First, some of the curves contained reductions at a negative carbon value, that is, reductions that the bottom-up analysis identified as being cost effective with no additional incentives (i.e., even in the absence of a carbon price applied to non-CO₂ GHGs). These reductions were assumed to be implemented in all scenarios over a 30-year period. We therefore assume that the MAC analysis is correct and that these reductions will be taken once sufficient time has passed.

The MAC curves for methane were supplied along with several energy price sensitivity cases. We incorporated a linear correction to the MAC proportional to natural gas prices. We therefore account for the overall shift in the MAC, but not any changes in the shape of the curve as natural gas prices change.

One last adjustment to the MACs is technical change. The MACs were calculated using technologies available today. Based on discussions with EPA staff, the maximum reduction amounts for some sectors were allowed to increase over time. More details and the effect of these assumptions will be explored in a later section.

Eff(t) is an exogenous factor that allows emissions in a given category and/or region to be changed as a function of time period due to factors not otherwise modeled.

Finally, Control(GDP/Cap) represents emissions controls that are assumed to be put into place as income increases. The emissions control function is taken to be an exponential logistic function of the following form:

$$\text{Control}\left(\frac{\text{GDP}}{\text{CAP}}\right) = \frac{f_{\max}}{\left(1 + e^{-c(\text{GDP/CAP} - \text{GDPCAP}_0)/\tau}\right)}, \quad (2)$$

where $f_{\max}$ is the ultimate reduction percentage and GDPCAP_0 is the mid-point of the control curve (in terms of GDP per capita), at which point emissions are reduced by $1/2 f_{\max}$. GDP/CAP is the GDP per capita and τ is the GDP per capita range over which the control percentage goes from 10% $f_{\max}$ to 90% $f_{\max}$. The constant “c” is equal to $2 \ln(9) = 4.394$. All GDP values are expressed in PPP-based GDP per capita. For further information see Smith *et al.* (2005).

The combination $\text{Em\_factor} \cdot \text{Control}$ can be considered the effective emissions factor as a function of time. We consider two types of change. First, for many combustion sectors, emissions factors in developing countries are higher than those in OECD regions. We assume that, as incomes increase, emissions factors improve to OECD values. We would also expect that emissions factors in OECD regions might also decrease with time. In effect, an asymptotic emissions factor is often specified and all regions move toward that emissions behavior as incomes increase. The rate of emissions factor decrease depends on the rate of economic growth through Equation 2. The effect of these assumptions on sulfur

dioxide emissions and NO_x emissions are described elsewhere (Smith *et al.* 2005, Smith 2005).

A large fraction of black carbon emissions are from transportation, both now and in the future, so the emissions assumptions from this sector have been further detailed. First, since there are efforts to control transportation emissions in most OECD countries we have assumed that the aggregate emissions factor for this sector eventually decreases below the current aggregate best performance. For the B1 and B2 scenarios, the emissions factor decreases about 0.14 g/kg, a value that is 20-30% of the present aggregate emissions factor in OECD regions in the Bond *et al.* (2003) inventory. The assumed asymptotic emissions coefficient is 0.28 g/kg in the A1 and A2 scenarios.

4. RESULTS

4.1 New MiniCAM non- CO_2 Scenarios — Comparison to SRES

To put the MiniCAM results into context we compare the new scenarios with the range in radiative forcings in the original SRES scenarios. See Smith *et al.* (2005) for a description of this implementation of the SRES emissions scenarios. Table 2 presents the range in radiative forcing in 2100 for the SRES scenarios as implemented in this version of MiniCAM. For most gases the MiniCAM range in emissions is similar to that of the entire SRES scenario set. We find significant differences for two gases, methane and tropospheric ozone, where maximum forcing levels are significantly lower than the maximums found in the original SRES scenario set.

The lower emissions for Methane are primarily due to the assumption that “below zero” options in the EPA MACs (§ 3) will be eventually implemented in the base case (even without carbon price). Coupled with technical change, this results in significantly lower methane emissions. Without these assumptions methane emissions would be far larger and more similar to the SRES range. For example, forcing in the B2 reference case by 2100 would be 55% higher without the implementation of economically-driven reductions (Figure 3).

Tropospheric ozone emissions are also significantly lower in the new MiniCAM scenarios. This is due to our assumption that emissions controls are implemented to control local air pollutants. All regions are assumed to eventually implement controls that are at least equal to the current best aggregate performance of each emissions sector within the MiniCAM OECD regions. In addition, significant advances over the next century are assumed for NO_x controls in transportation in particular. For further discussion of NO_x emissions see Smith (2005).

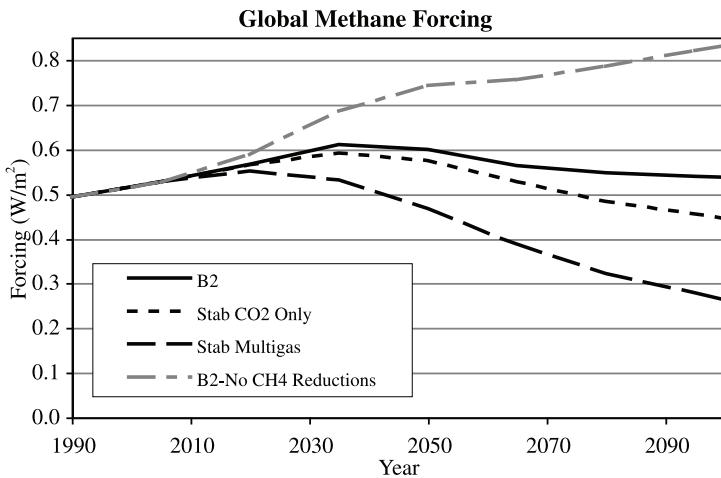
The result is that the global forcing from tropospheric ozone ranges from slightly above present levels in the B2 and A1G scenarios, to around 2/3 of today’s level in the B1 and A1T scenarios. Only in the A2 scenario do tropospheric ozone levels increase throughout the century, resulting in a forcing of 0.7 W/m^2 relative to pre-industrial by 2100. This is due to the lower levels of emission controls in

Table 2. The Range in Radiative Forcing (in W/m^2) from non- CO_2 Greenhouse Gases and Sulfate Aerosols from Preindustrial Times to 2100 in the SRES Scenario Set, Coupled with the Authors' Estimates of the Overall Consistency of the Global Model Results for each Substance

"Greenhouse" Gas	SRES Forcing range (W/m^2)	Modeling Consistency	New MiniCAM Forcing Range (W/m^2)
Methane (CH_4)	0.4 – 1.4 W/m^2	Low	0.5 – 0.7 W/m^2
Nitrous Oxide (N_2O)	0.3 – 0.6 W/m^2	Very Low	0.3 W/m^2
Sulfate Aerosols (SO_4)	-1.5 – -0.1 W/m^2	Good	-1.8 – -0.2 W/m^2
Tropospheric Ozone (O_3)	0.2 – 1.5 W/m^2	Moderate	0.2 – 0.7 W/m^2
Halocarbons	0.3 – 0.4 W/m^2	NA	0.3 – 0.4 W/m^2

Also shown is the forcing range for the new MiniCAM implementation of the SRES scenarios presented in this paper.

Figure 3. Methane Forcing for the MiniCAM B2 Scenario Relative to Pre-industrial



The top line shows forcing in the absence of any economically-driven methane reductions (and no technological change) in the B2 reference case. Methane forcing in the B2 reference case, the stabilization case with CO_2 reductions only, and the multi-gas stabilization case are also shown (see text).

the low income A2 scenario. This behavior is similar to that seen in the MiniCAM results for sulfur dioxide (Smith *et al.* 2005). Even our highest tropospheric ozone forcing, however, is significantly lower than the forcing from many of the SRES scenarios (Figure 2). We conclude that emissions of reactive gases are too high in a number of the SRES scenarios, with the resulting tropospheric ozone levels

inconsistent with the SRES storylines for some of the A1 scenarios in particular (as suggested by Wigley *et al.* 2002).

4.2 EMF-21 Reference Case

We now focus on the B2 emissions scenario, which is the reference case used for the EMF-21 exercise. In this scenario radiative forcing from non-CO₂ greenhouse gases increases from 1.1 W/m² in 1990 to 1.6 W/m² in 2095. All forcing values are relative to pre-industrial. Carbon dioxide forcing increases by a greater amount, however, so that non-CO₂ forcing amounts to only 30% of CO₂ forcing by the end of the century. The amount of aerosol cooling decreases substantially over the century, totaling only -0.5 W/m² by 2100, or less than 10% of the CO₂ forcing.

Compared to the full set of new MiniCAM scenarios (Table 2), the MiniCAM B2 scenario has lower methane emissions for most of the century than either the A1 or A2 scenarios. This is due to larger emissions from coal mining and natural gas production in the A1 scenarios, driven by their higher energy demands.

Tropospheric ozone forcing in the B2 scenario is larger than any of the A1 or B1 scenarios by the end of the century (largely due to the assumption of the availability of zero emission fuel-cell vehicles in the A1 scenarios and generally lower energy consumption in the B1 scenarios). While no individual forcing component is constant over time (Table 3), total non-CO₂ greenhouse gas forcing is nearly constant from 2050 to 2100 in the B2 reference case due to fortuitous cancellations between different gases. Total aerosol cooling decreases significantly from 2050 through 2100 (see also Smith *et al.* 2005).

Note that, while black and organic carbon are explicitly included in these scenarios, their combined forcing effect is small. The positive forcing from black carbon is offset by the negative forcing from organic carbon. These forcings will be explored further in future work.

4.3 Stabilization Cases

The EMF-21 policy case specifies that radiative forcing relative to pre-industrial levels should stabilize at 4.5 W/m². We specified a forcing target of 4.4 W/m² in 2100 (MiniCAM produces emissions only to 2095, so we extrapolated emissions to 2100). Since the rate of total forcing increase is slow near the end of the century in our runs, this should approximate the long-term target stabilization level (with perhaps a slight overshoot of the target forcing level). Pathways for forcing stabilization were adapted from the Wigley *et al.* (1996) CO₂ stabilization pathways. An intermediate emissions pathway that exactly met the specified 2100 target level was constructed from the Wigley *et al.* stabilization scenarios through interpolation.

Two stabilization policies were considered relative to the B2 reference case. In the first policy, labeled "CO₂ only", a price was applied to carbon dioxide

Table 3. Radiative Forcing (in W/m²) in the B2 Reference Case Used for the EMF-21 Exercise Along with the Two EMF21 Stabilization Cases (§ 4.3) for 2050 and 2100 Relative to Pre-industrial

2100 Forcing	CO₂	CH₄	N₂O	Indust	Trop O3	Total non-CO₂	SO₄	Total all Forcings
B2 Base	5.3	0.5	0.3	0.3	0.4	1.6	-0.4	6.4
Stab - CO ₂ Only	3.4	0.4	0.3	0.3	0.3	1.4	-0.3	4.4
Stab - Muligas	3.8	0.3	0.3	0.2	0.3	1.0	-0.3	4.4
Base-Multi-gas	1.5	0.3	0.1	0.1	0.2	0.6	-0.1	2.0
CO ₂ Only-Multi-gas	-0.5	0.2	0.0	0.1	0.0	1.4	0.0	0.0
2050 Forcing	CO₂	CH₄	N₂O	Indust	Trop O3		SO₄	Total
B2 Base	3.4	0.6	0.3	0.3	0.5	1.6	-1.0	4.0
Stab - CO ₂ Only	2.8	0.6	0.3	0.3	0.4	1.5	-0.4	3.7
Stab - Muligas	3.0	0.5	0.2	0.2	0.4	1.3	-0.5	3.7
Base-Multi-gas	0.4	0.1	0.0	0.0	0.1	0.3	-0.4	0.3
CO ₂ Only-Multi-gas	-0.2	0.1	0.0	0.0	0.0	1.5	0.1	0.1

The difference between the reference and multi-gas stabilization and the difference between the two stabilization cases is also shown.

emissions at each time period sufficient to lower emissions to the stabilization pathway specified above. In this case, changes in non-CO₂ greenhouse gas emissions occur only as a side effect of carbon dioxide mitigation. For example, reductions in methane emissions would occur if coal consumption decreased. In the second case, labeled “multi-gas”, a price was applied to both carbon dioxide and non-CO₂ greenhouse gases. The carbon price was converted to a carbon-equivalent price for each non-CO₂ greenhouse gas using the 100-year Global Warming Potential (GWP). For the results shown here the GWP was held constant over the entire model run. Reductions in non-CO₂ greenhouse gas emissions were determined by regionally specific MACs as described in Section 3. Reductions in aerosol and ozone precursor gases occur as an indirect consequence of the climate policy, but there are no direct reductions of these gases due to the climate policy.

The carbon price for meeting the specified target is (eventually) large, reaching \$1000/TonneC by the end of the century for the “CO₂ only” case. For simplicity these scenarios ignored the possibility of a hydrogen infrastructure nor did they consider possible geologic carbon sequestration. The addition of these technologies would lower this cost substantially.

In both of the policy regimes, the majority of the reduction in forcing by 2100 is, necessarily, from reductions in CO₂ concentrations (Table 3). The majority of the non-CO₂ forcing reduction is from methane and tropospheric ozone. 75% of the non-CO₂ greenhouse gas reduction in the multi-gas case is from these two sources. The remainder is from industrial gases and nitrous oxide. There is a small forcing offset from sulfur dioxide in 2100. Sulfur emissions are slightly lower than in the reference case scenario, reducing aerosol cooling and, therefore, increasing radiative forcing.

The magnitude of the reduction in methane and tropospheric ozone forcing, as compared to the reference case, depends strongly on reference case emissions. If troposphere ozone controls are more stringent in the base case then there will be a smaller reduction due to the climate policy.

Similarly, if fewer economic methane reduction opportunities are available in the reference case then larger methane reductions will occur in the policy case. If no “below zero” options occur then methane emissions will be much higher in the reference case, as illustrated in Figure 3. One third of the reductions due to policy (beyond the reference case) were due to the “knock on” effects of the carbon policy. This means that slightly more than two thirds of the reductions in methane emissions were due to the non-CO₂ policy in the multi-gas case.¹

Utilizing all gases in a mitigation strategy means that CO₂ concentrations can be allowed to go higher while meeting the same radiative forcing target. In the “CO₂ only” case the CO₂ concentration in 2100 is 520 ppmv, as compared to 570 ppmv in the multi-gas stabilization case. As would be expected from this result, the cost of meeting a forcing target decreases if the policy is extended to include all greenhouse gases. The cost savings due to the addition of non-CO₂ abatement options is much greater in early years. In the early years of the policy (2020-2050) the carbon price in the multi-gas case is 30-40% of the price in the CO₂ only case. At later times the carbon price has increased to a level where non-CO₂ options have been largely depleted. By 2100 the price in the multi-gas case is 70% of the price in the CO₂ only case. The total discounted cost of the multi-gas case is 40% of the cost of the CO₂ only case. In terms of forcing (Table 3) the additional non-CO₂ reductions allow carbon dioxide forcing to be 0.5 W/m² higher (in 2100) in the multi-gas stabilization case.

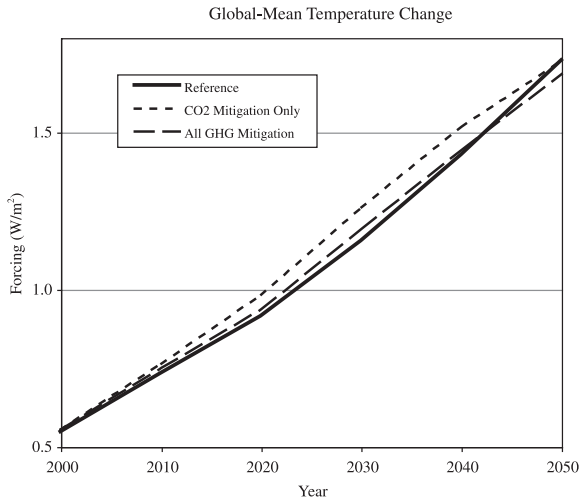
4.4 Aerosol Offsets and Forcing Path

While radiative forcing at the end of the century is an important target value, the path taken toward this goal is also of interest. Even though emissions reductions begin by 2020 in both of the policy regimes considered here, the effect on global climate is small until the second half of the century. This is a consequence of the offsetting effects of reduced aerosol cooling, as discussed above. In both of these policy cases, global-mean temperature does not depart from the reference case value by more than 10% until 2070.

In the CO₂ only case the initial global-mean temperature change is actually larger in the policy case than in the base case (Figure 4) due to the knock-on effects on SO₂ emissions (*cf.* Wigley, 1991). This difference peaks in about 2030 at nearly 10%. The difference between the policy and reference cases are much smaller for the multi-gas case. In this case, the larger reductions in shorter-

1. Since the CO₂ reduction in the multi-gas case are lower than in the CO₂ case, the “knock on” reductions of methane will be slightly smaller than the value in the CO₂ only case.

Figure 4. Global-mean Temperature Change for the Reference and Policy Scenarios Through 2050 Relative to Pre-industrial



lived gases, primarily methane, nearly offset the reduction in sulfate cooling. This is a previously not noticed benefit of non-CO₂ mitigation.

In the long-term, the aerosol offsets seen in these scenarios have little effect. The global-mean temperature in 2100 differs between the two stabilization cases by only 0.3%.

5. CONCLUSIONS

Non-CO₂ greenhouse gases, taken together, have contributed almost as much to anthropogenic radiative forcing as carbon dioxide. Non-CO₂ greenhouse gases are particularly important over the first half of the 21st century, a time during which their combined forcing continues to increase in all of our reference case scenarios. We find a significantly decreased importance of non-CO₂ greenhouse gases in the second half of the 21st century as the growth of some driving forces slows, use of methane recovery for energy use expands, and local air pollution controls limit the growth of global tropospheric ozone.

The picture for aerosols is similar. Here, the primary uncertainty arises through uncertainties in the forcing-emissions relationships rather than in the emissions. While aerosol cooling is thought to be a significant fraction of total greenhouse gas warming at present, total cooling by aerosols is small by the end of the century.

The inclusion of non-CO₂ greenhouse gases in a mitigation policy has a particularly important effect over the first half of the 21st century, where the annual cost of a mitigation policy is reduced substantially by non-CO₂ emissions reductions. Feedbacks due to sulfate aerosol reductions that occur as a consequence of carbon

dioxide emissions reductions are also very important through mid-century. These two effects act in opposite direction so that, in the mitigation scenarios examined here, global-mean climate change is essentially unchanged until 2050 due to the combination of inertia in the climate system and the offsetting effects of aerosols.

Non-CO₂ greenhouse gas forcing in the long-term is dominated by methane and tropospheric ozone. The level of recovery of methane for use as an energy source, which can occur in the absence of a carbon price, has a significant effect on future methane emissions. We find that the the availability of these options today, along with technological change and higher natural gas prices in the future, result in methane emissions that are significantly lower than in many previous no-climate-policy scenarios. This reduces the potential for climate policy-related methane emissions. Similarly, we also find that the imposition of emissions controls for local air pollutants, and nitric oxides in particular, result in global tropospheric ozone forcing that is only slightly higher than at present by the end of the century in our reference case. Again, this reduces the potential for radiative forcing reduction through direct climate policies—as noted by Smith et al. (2000) and Wigley et al. (2002).

6. FUTURE WORK

The MiniCAM integrated assessment model, as with most such models, has traditionally focused on energy systems. Several years ago (Edmonds *et al.* 1996) agriculture and land-use was added to the MiniCAM model. The subsequent addition of non-CO₂ greenhouse gas emissions has reinforced the importance of non-energy sectors in the total greenhouse gas picture (Table A1).

Further work is needed to clarify important emissions sectors. Two areas of particular importance are waste flows and nitrogen management. Urban wastes account for a large portion of methane emissions as well as nitrous oxide emissions. Such wastes also have potential as bioenergy feedstocks, as do agricultural residues — also a source of local air pollutant emissions. A more consistent treatment of waste and residue flows, and associated emissions, is needed.

Nitrogen balance is also an important area to examine. Emissions from managed soils account for most nitrous oxide emissions. The relative lack of variation in nitrous oxide forcing by scenario in our model, while accounted for in part by the long atmospheric lifetime of nitrous oxide, indicates that further examination of the connections between fertilizer use, emissions, and agricultural productivity is warranted.

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APPENDIX

Table A1. Emissions Sectors and Primary Drivers in the MiniCAM Model as Used for this Study

Emissions Sectors	Emissions Driver ³	CO ₂	CH ₄	N ₂ O	SO ₂	NO _x	VOC	CO	BC	OC	F gases
Fossil Fuel Combustion											
Elec Gen - Coal	Coal use	X	X ¹	X ¹	X	X	X	X	X	X	
Elec Gen - Oil	Petroleum Use	X	X ¹	X ¹	X	X	X	X	X	X	
Elec Gen - Gas	Natural Gas Use	X	X ¹	X ¹	X	X	X	X	X	X	
Indust - Coal	Coal use	X	X ¹	X ¹	X	X	X	X	X	X	
Indust - Oil	Liquid Fuel Use	X	X ¹	X ¹	X	X	X	X	X	X	
Indust - Gas	Natural Gas Use	X	X ¹	X ¹	X	X	X	X	X	X	
Indust - Biomass	Biomass Use		²	X	X	X	X	X	X	X	
Buildg - Coal	Coal use	X	²		X	X	X	X	X	X	
Buildg - Oil	Liquid Fuel Use	X	²		X	X	X	X	X	X	
Buildg - Gas	Natural Gas Use	X	²		X	X	X	X	X	X	
Buildg - Biomass	Biomass Use		X	X	X	X	X	X	X	X	
Transp - Coal	Coal use	X	²		X	X	X	X	X	X	
Transp - Oil	Liquid Fuel Use	X	X	X	X	X	X	X	X	X	
Transp - Gas	Natural Gas Use	X	²		X	X	X	X	X	X	
Fossil Fuel Production											
Coal Mining	Coal Cons & Production	²	X								
Natural Gas Production	Gas Cons & Production	²	X		X ¹						
Oil Production	Oil Production	²	X		X ¹						

Emissions Sectors	Emissions Driver ³	CO ₂	CH ₄	N ₂ O	SO ₂	NO _x	VOC	CO	BC	OC	F gases
Industrial (non-combustion) Processes											
Cement Production	GDP & Population	X									
Other Industrial	GDP		X		X	X	X	X			
Nitric and Adipic Acid Production	GDP			X							
Metal Smelting	GDP				X						
"F-gas" emissions ⁴	Varies (Pop, GDP)										X
Land-Use & Land-Use Change											
Rice Cultivation	Area of Rice Lands		X								
Agricultural Soils	Agricultural Production		X	X		X					
Livestock Manure	Animal Production (Beef, Pork, etc.)		X	X		X					
Enteric Fermentation	Beef Production		X								
Savannah Burning	Area of Grassland			X	X	X	X	X	X	X	
Deforestation	Above-ground Biomass deforested	X	X	X	X	X	X	X	X	X	
Ag Residue Burning	Agricultural Production		X	X	X	X	X	X	X	X	
Forest Fires	Forest Area								X	X	
Urban Emissions											
Landfills	Income & Population		X								
Wastewater & ww treatment	Population		X	X							
Transport AC ⁵	Transportation Demand										X
Commercial and Residential Building AC ⁵	Regional Cooling Demand										X
Food Dist. & Household Storage	Processed Food Demand										X

"F-gases" are disaggregated into seven gas categories (HFC245fa, HFC134a, HFC125, HFC143a, SF₆, C₂F₆, CF₄) and 12 source categories

1 Due to the small emissions from these categories these source sectors were combined for this gas.

2 Emissions accounted for in another category.

3 Note that emissions for non-combustion sectors are not always proportional to the driving variables.

4 Eight separate categories of "F gases" emissions (in addition to the urban emission categories shown in the Table) are considered: foams, aerosols, solvents, fire extinguishers, electricity generation, semiconductor manufacture, Al & Mg smelting, and HCFC-22 production.

5 Air conditioning.



The Role of Non-CO₂ Greenhouse Gases and Carbon Sinks in Meeting Climate Objectives

Alan S. Manne* and Richard G. Richels**

When conducting a multi-gas analysis, there are distinct advantages in moving from concentrations to radiative forcing. With the former, it is customary to use Global Warming Potentials (GWPs) for making tradeoffs among greenhouse gases. A number of studies have shown the arbitrariness of this approach and have argued that tradeoffs should be based on the contribution of each gas to achieving a particular target.¹ Focusing on radiative forcing bypasses the need to rely on GWPs and provides for tradeoffs among gases based on their relative value.

1. INTRODUCTION

In designing a strategy for greenhouse gas (GHG) abatement, perhaps the most important single component is energy-related CO₂. This is where most of the analytic effort has been centered. Non-CO₂ greenhouse gases and carbon sinks have received less attention, but are important enough to warrant consideration.² This topic was the focus of the Energy Modeling Forum study 21 in which we participated.³ This paper describes our efforts to incorporate multiple

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This paper was undertaken as part of our participation in EMF 21. We have benefited from discussions with Francisco de la Chesnaye, Jae Edmonds, Casey Delhotal, Willy Makundi, Jayant Sathaye, Roger Sedjo, Brent Sohngen, John Weyant, and Tom Wigley. Thanks go to Christopher Gerlach and Charles Ng for their work as research assistants in the preparation of this paper. Funding was provided by the Electric Power Research Institute (EPRI). The views presented here are solely those of the authors.

1. Manne, A. S. and R. G. Richels (2001). "An Alternative Approach to Establishing Trade-offs Among Greenhouse Gases", *Nature*, **410**, 675-677.

2. Reilly, J., R. Prinn, J. Harnisch, J. Fitzmaurice, H. Jacoby, D. Kicklighter, J. Melillo, P. Stone, A. Sokolov and C. Wang (1999). "Multigas Assessment of the Kyoto Protocol", *Nature*, **401**, 549-555.

3. Stanford EMF (Energy Modeling Forum) (2004). (this volume)

GHGs and sinks into the MERGE model, and discusses some of the implications for mitigation cost assessments.

The focus of efforts to reduce the threat of global climate change has shifted over time. Initially, the goal was to stabilize or reduce CO₂ emissions. With the UN Framework Convention on Climate Change, the focus shifted to stabilizing atmospheric greenhouse gas concentrations.⁴ Although this represents a step forward, it may not go far enough. There are many uncertainties in the causal chain connecting human activities to impacts. These relate to emissions, the carbon cycle, radiative forcing, climate change, and market and non-market impacts. In Energy Modeling Forum study 21 (ref. 3), the target was extended beyond atmospheric concentrations to radiative forcing.

When conducting a multi-gas analysis, there are distinct advantages in moving from concentrations to radiative forcing. With the former, it is customary to use Global Warming Potentials (GWPs) for making tradeoffs among greenhouse gases. A number of studies have shown the arbitrariness of this approach and have argued that tradeoffs should be based on the contribution of each gas to achieving a particular target.⁵ Focusing on radiative forcing bypasses the need to rely on GWPs and provides for tradeoffs among gases based on their relative value.

We begin with a description of how the MERGE model has been modified to include multiple greenhouse gases and sinks. We then examine the implications of constraints on radiative forcing under a "CO₂ only" control scenario and a "multi-gas and sinks" control scenario. Finally, we add a decadal constraint on temperature change. We find that mitigation costs are substantially higher when the focus is on the rate of change rather than on absolute change. The timing of costs is also significantly changed.

Two caveats are in order. First, we assume complete "when" and "where" flexibility. That is, emission reductions are made both when and where it is most economical to do so. To the extent that these two principles of economic efficiency are violated, mitigation costs may be substantially higher. Second, in this paper, we provide only one component of the cost/benefit calculus. Our focus is exclusively on mitigation costs. No attempt is made to calculate the value of the damage reductions achieved with the adoption of a particular policy initiative. Clearly, such information is essential for informed policy making. However, the necessary analysis is well beyond the scope of the present effort.

2. THE MODEL

MERGE is a model for evaluating regional and global effects of greenhouse gas emission reductions. For technical details, see our website: www.stanford.edu/group/MERGE. A computer listing is available at that website.

4. Intergovernmental Negotiating Committee for a Framework Convention on Climate Change (1992). Fifth Session, Second Part, New York, NY, 30 April-9 May.

5. Manne, A. S. and R. G. Richels (2001). "An Alternative Approach to Establishing Trade-offs Among Greenhouse Gases", *Nature*, **410**, 675-677.

MERGE contains reduced-form sub-models describing: the domestic and international economy, CO₂ emissions, the carbon cycle, global climate change, and market and non-market impacts. Although initially the model accounted for the emissions and decay of methane (CH₄) and nitrous oxide (N₂O), these gases were not included in abatement strategies. Moreover, due to a paucity of data, the earlier treatment of carbon sinks can be characterized as rudimentary, at best. In more recent versions, the model has been modified to include a more sophisticated treatment of the roles of non-CO₂ GHGs and terrestrial carbon sinks.

Each region's domestic economy is viewed as though it were a Ramsey-Solow model of long-term economic growth.⁶ The time paths of investment and consumption are strongly influenced by the choice of a "utility" discount rate. In the following calculations, we have based this rate upon a market-oriented "descriptive" viewpoint.⁷

Energy-related emissions in MERGE are projected through a bottom-up perspective. Fuel demands are estimated through "process analysis" and a top-down production function of the inputs of capital, labor, and electric and non-electric energy. Conservation is both price-induced and non-price-induced. Specific allowances are made for technical progress and for learn-by-doing.

Each period's emissions are translated into global concentrations and, in turn, to the impacts on mean global indicators such as radiative forcing and temperature change. The MERGE model may be operated in a "benefit-cost" mode – choosing a time path of emissions that maximizes the discounted utility of consumption, after making allowance for the disutility associated with climate change. It may also be operated in a "cost-effective" mode – supposing that international negotiations lead to a time path of emissions that satisfies a constraint on concentrations, on radiative forcing, or on temperature change.

Individual geopolitical regions are distinguished in the MERGE model. Abatement choices are distinguished by "where" (in which region?), "when" (in which time period?), and for some cases "what" (what greenhouse gas to abate?). As a result, all of our estimates must be viewed as lower bounds on the actual future costs. Since no quota rights are specified for each region, we do not report the regional costs of emissions control. We only provide the global control costs – expressed in terms of consumption losses. These losses are independent of the burden sharing arrangement.

3. POPULATION AND REGIONAL GDP PROJECTIONS

Greenhouse emissions are *not* proportional to population and GDP, but they can be quite sensitive to these projections. For this purpose, we have used what we believe to be a middle-of-road projection of the global population

6. Solow, R. M. (1970). *Growth Theory: An Exposition*, Oxford University Press, New York, NY.

7. Portney, P. R. and J. P. Weyant (Eds.) (1999) *Discounting and Intergenerational Equity*, Resources for the Future, Washington, D.C.

– assuming that it will rise from 6 billion people in 2000 to 10 billion in 2100, and that it will stabilize thereafter. Virtually all of this growth will take place in the developing countries.

Separate projections are provided for each of nine regions. There are four high-income regions. These constituted the OECD in 1990: 1) USA, 2) Western Europe, 3) Japan, and 4) Canada and Australia-New Zealand. There are also five low-income regions: 1) Eastern Europe and former Soviet Union, 2) China, 3) India, 4) Mexico and OPEC nations, and 5) ROW (rest of world). The model employs ten-year time steps extending from 2000 through 2150.

Population projections may be debatable, but there are even more controversies with respect to productivity and per capita GDP growth. Through 2020, we have taken over these projections from the “reference case” defined by the Energy Information Administration.⁸ Thereafter, we have extrapolated by using logistic functions. The initial point is the EIA projection for 2020. Each of our logistic functions converges to the identical asymptote. The “limit to growth” is \$200 thousand per capita, but this limit is not reached for several centuries. This value is astronomical in comparison with today’s GDP in India, China, and other low-income nations. It was chosen so that there would not be an immediate decline in the growth rate of the high-income regions.

For each of the nine regions, the third point along the logistic curve is an arbitrary individual estimate of the per capita GDP in the year 2100. These values were chosen so as to allow for a smooth transition post-2020 – and a *partial* convergence of the low-income countries to those with high incomes by 2100. For example, the U.S. grows from \$36 thousand in 2000 to \$115 thousand by 2100. India grows rapidly (from \$0.5 to \$25 thousand), but is still far behind the U.S. by the end of the century.

All dollar values here are expressed in dollars of 2000 purchasing power, and are shown at market exchange rates. If, instead, we had employed “purchasing power parity”, there would have been much higher initial GDP values for the low-income nations, but lower growth rates of GDP and of emissions. With PPP, we have found only minor changes for the high-income nations.

4. EMISSIONS AND ABATEMENT OF NON-CARBON GREENHOUSE GASES

Our near-term estimates for the baseline trajectories and the abatement costs of the non-carbon greenhouse gases are based on the guidelines for the EMF 21 study (ref. 3). A distinction is made between short-lived and long-lived F-gases. The dynamics of the problem are governed by the abundance of these gases in the atmosphere, the rate of future emissions, differences in their lifetimes, and their contribution to radiative forcing. We deal with these directly, rather than

8. Energy Information Administration (2003). “International Energy Outlook 2003”, U.S. Department of Energy, Washington, D.C.

Table 1. Selected Characteristic of Non-CO₂ Greenhouse Gases⁹

Non-CO ₂ GHG	Abundance ppt (1998)	Decay rates (fraction per year)	Lifetimes (years)
Methane	1,745.0	0.083000	12.0
Nitrous oxide	314.0	0.008300	114.0
Short-lived F-gases	20.2	0.069000	13.8
Long-lived F-gases	24.9	0.000313	3,200.0

through the comparison of their GWPs. See Table 1 for a description of some of the key characteristics of these gases.

MERGE is based on a simple decay model for each of the non-CO₂ gases. From these decay rates, one can see that methane abatement could play a strategic role if there is a need for an immediate reduction in radiative forcing. The short-lived F-gases could play a similar role but their volume is quite small. With nitrous oxide and the long-lived F-gases, there is no possibility of a quick turnabout. Even with extensive near-term abatement, their concentrations would decay slowly.

With the exception of N₂O, we took the 2000-2010 baseline emission trajectories from EMF 21 (ref. 3) and extrapolated them *linearly* from 2010 through 2100. Thereafter, it was assumed that there would be no change. With N₂O, we assumed that emissions remained constant at their 2000 level.

For each gas, we expressed estimates of abatement costs as a percentage of the baseline for that year. We then supposed that there would be technical progress in abatement over time. Specifically, we assumed that within each cost category, there would be 1.5 times the 2010 percentage of abatement in 2050 and twice the 2010 percentage in 2100, etc.

5. CARBON SINKS

Our estimates of carbon sinks are based on the global results from two of the forestry models participating in EMF 21 (ref. 3): GCOMAP and GTM. For details on these models, see, respectively, refs. 10 and 11.^{10,11} Each of these is a dynamic partial equilibrium model of the timber industry. That is, both of these models take the efficiency price of carbon as an input datum. Each allows for the carbon uptake in the timber growth cycle, and each gives an estimate of supplies, demands and timber prices in individual markets.

GCOMAP and GTM were each run under six standardized scenarios

9. IPCC (Intergovernmental Panel on Climate Change) (2001). *Climate Change 2001. The Science of Climate Change*, Cambridge University Press, UK.

10. Sathaye, J., P. Chan, L. Dale, W. Makundi and K. Andrasko (2003). "A Summary Note: Estimating Global Forestry GHG Mitigation Potential and Costs: A Dynamic Partial Equilibrium Approach", working draft, August.

11. Sohngen, B. and R. Mendelsohn (2003). "An Optimal Control Model of Forest Carbon Sequestration", *American Journal of Agricultural Economics*, **85**(2), 448-457.

with respect to the global efficiency price of carbon. For each of these scenarios, the models then reported the year-by-year net absorption of carbon through afforestation sinks. In turn, the two models were each coupled to MERGE by taking a convex combination of the six time-phased scenarios – and also allowing for the possibility of a delay in initiating them.

At this point, our calculations lead us to believe that afforestation sinks will not have a major impact upon the optimal price and quantity of carbon abatement. There are differences between the results from GCOMAP and GTM, but the optimal afforestation sinks are small in relation to the total quantity of carbon that would need to be abated in order to meet a radiative forcing target.

6. STABILIZING RADIATIVE FORCING

In this section, we examine how radiative forcing might evolve under “business as usual”, and compare this with a 4.5 or a 3.5 w/m² (watts per square meter) ceiling on radiative forcing. For the control scenarios, we explore two alternatives for complying with a cap on radiative forcing. In one, we rely exclusively on reductions in fossil fuel emissions (a “CO₂ only” scenario). In the other, we rely on the full range of trace gases, described earlier, and afforestation (a “multi-gas and sinks” scenario).

Figure 1 shows radiative forcing with the proposed caps and compares these trajectories with those for the reference case, i.e., the “no policy” scenario. With a cap, radiative forcing initially rises faster under the “multi-gas and sinks” scenario. This is because here we are able to take advantage of the short-lived nature of CH₄. This allows us to slow the rate of increase of radiative forcing more quickly as we approach the ceiling.¹²

Figure 2 focuses on temperature change, a metric that is perhaps more understandable to non-physical scientists. For these calculations, we assume a climate sensitivity of 2.6 degrees C and a thermal ocean lag of 25 years. In the absence of climate policy, the temperature increase over the 21st century would exceed 3 degrees C. With a cap on radiative forcing of 4.5 and 3.5 w/m², the temperature increase over this period is approximately 2.5 and 2.0 degrees C, respectively.

Although we have argued that concentrations are an inappropriate end-point for a multi-gas analysis, nevertheless it is useful to examine the implications of stabilizing radiative forcing on concentrations. Figure 3 shows CO₂ concentrations for our various scenarios. A multi-gas approach increases the allowable level of CO₂ concentrations in the atmosphere by approximately 50 ppmv in 2100.

Figure 4 shows the implications for energy-related CO₂ emissions. In the case of the tighter cap, it is particularly important to have multiple gas and afforestation options. Otherwise there would be a need for an immediate and

12. We note that 2150 is the time horizon for the EMF 21 study (ref. 3). In some cases the EMF cap does not become binding until post-2100.

Figure 1. Radiative Forcing from 1750

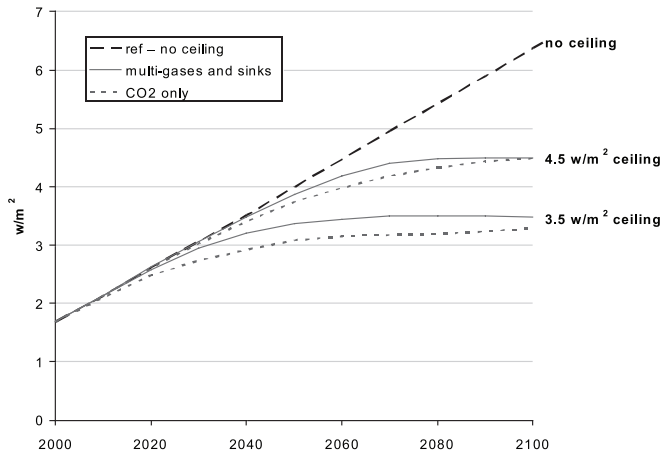
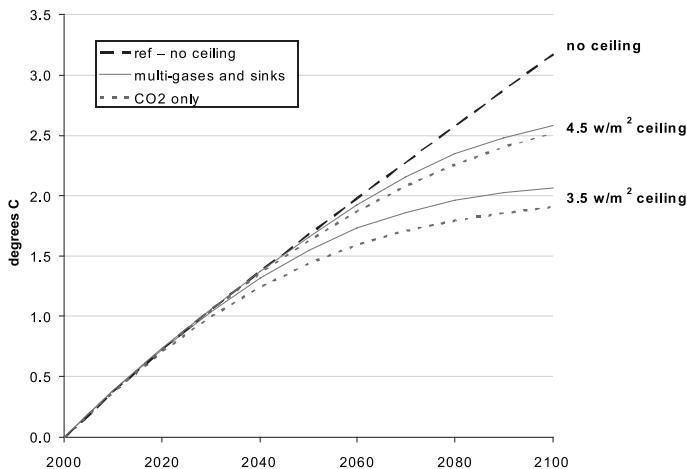


Figure 2. Comparison of Temperature Change



rapid departure from the baseline. This is reflected in the carbon tax that would be required under such a scenario (see Figure 5). In the remaining scenarios, the taxes start at much lower levels but nonetheless rise substantially over time.

7. A DECADAL CONSTRAINT ON TEMPERATURE CHANGE

There is concern not only about the absolute temperature level but also the rate of temperature change. For example, some ecosystems may be able to adapt if climate change is gradual. But abrupt change may be problematic. The issue of what constitutes “abrupt” remains unclear and is likely to vary from

Figure 3. Comparison of CO₂ Concentrations

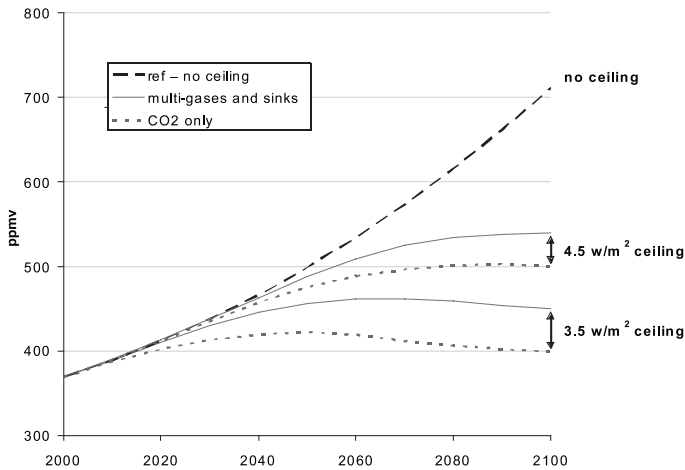
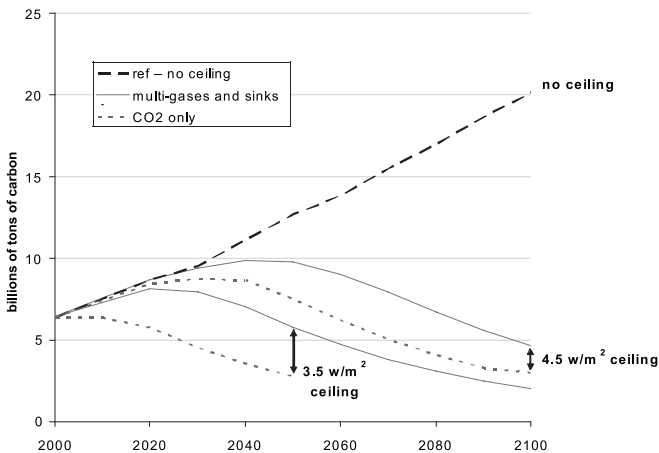


Figure 4. Comparison of CO₂ Emissions



one species to another. In this section, we examine the implications of imposing an additional constraint on climate change, i.e., decadal temperature change is limited to 0.2 degrees C. As in previous sections, our focus is exclusively on mitigation costs. We make no attempt to examine the implications for the value of damages avoided. Again, such analysis is critical but well beyond the scope of the present effort.

Figure 6 shows decadal temperature change for the reference case and the control policy cases. For the latter, we assume that multiple greenhouse gases and afforestation are among the options for meeting a constraint. Because of

Figure 5. Comparison of Carbon Taxes

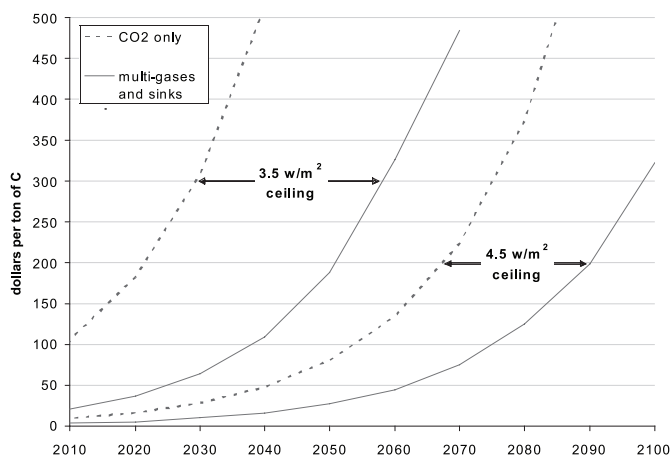
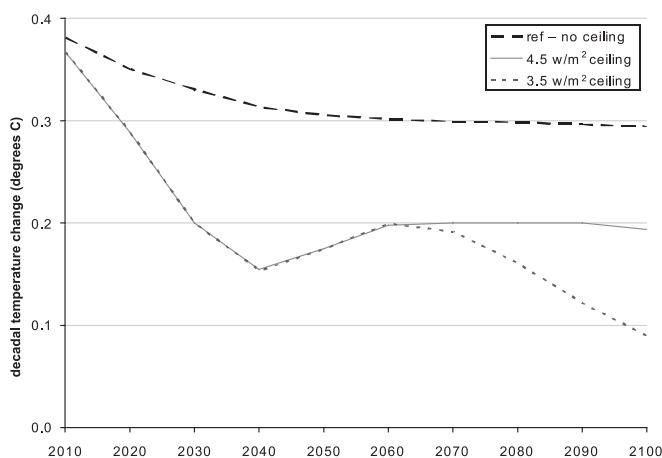
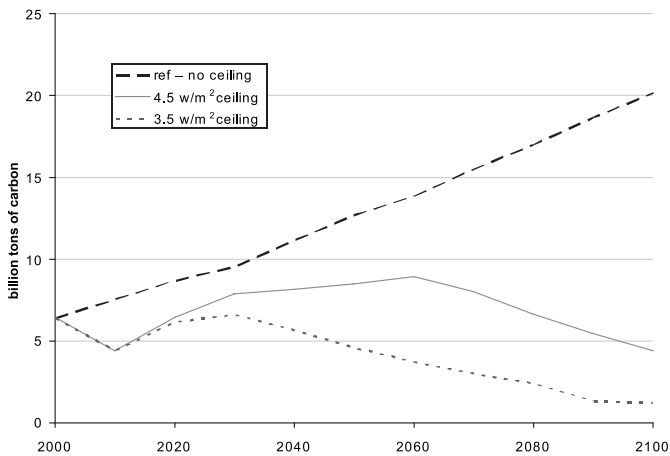


Figure 6. Constraint on Decadal Temperature Change



the lags in the climate system, we find it virtually impossible to impose a 0.2 degrees C decadal constraint prior to 2030. Figure 7 suggests that in the absence of climate policy, the rate of decadal change would exceed 0.3 degrees C for the entire 21st century. For the control cases, the least-cost pathway is governed by the decadal constraint until 2060. After that, the constraint on radiative forcing causes the pathways to diverge.

Figure 7 compares CO₂ emissions for our reference and for two control scenarios. Notice that both control cases require a rapid departure from the reference case. The “look ahead” feature of the model is the reason for the substantial

Figure 7. Implications of 0.2 degrees C Decadal Constraint on CO₂ Emissions

reductions prior to the imposition of the decadal constraint. That is, anticipating a sharp constraint on decadal temperature change in the future, the economic system begins reconfiguring itself immediately to adapt to such a constraint.

8. ANNUAL CONSUMPTION LOSSES

One measure of the welfare impact of a particular policy on consumers is the impact on aggregate consumption. This can be expressed in a number of ways. One is to compare the present value of consumption with and without the climate policy. We can then calculate the aggregate loss in consumption. See Figure 8. Not surprisingly, the rate of change constraint entails much higher losses than those for a constraint on absolute change. For the latter, as we would expect, total losses are higher with the tighter constraint on radiative forcing and when the burden for meeting the constraint is placed entirely on CO₂.

Although Figure 8 is informative, it is perhaps more instructive to examine the annual loss in consumption under alternative policies. See Figure 9. Given the momentum in the climate system, keeping decadal change beneath 0.2 degrees C will require a major change in several economic sectors, most notably energy. The majority of the losses are incurred during the first half of the century. A substantial investment would be required to stay within the constraint. With an absolute constraint on radiative forcing, both the magnitude and timing of the losses differ from those for the rate of change constraint. For example, post-2050 losses are substantially higher with an absolute constraint, which must be met solely through reductions in CO₂ emissions. The timing of losses is obscured when the focus is on aggregate century-scale results.

Figure 8. Consumption Losses over 21st Century – discounted to 2000

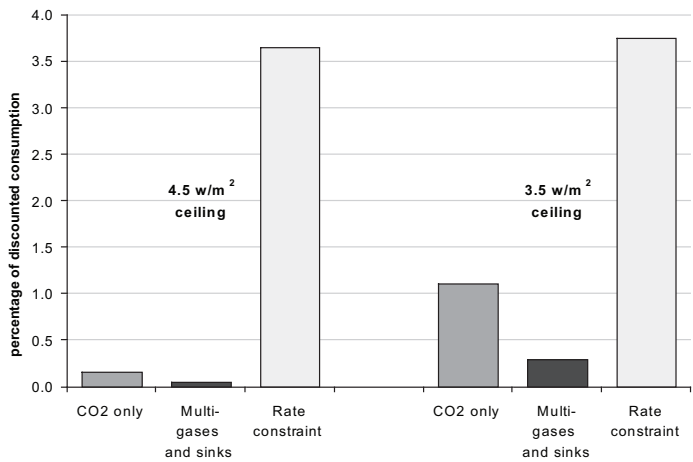
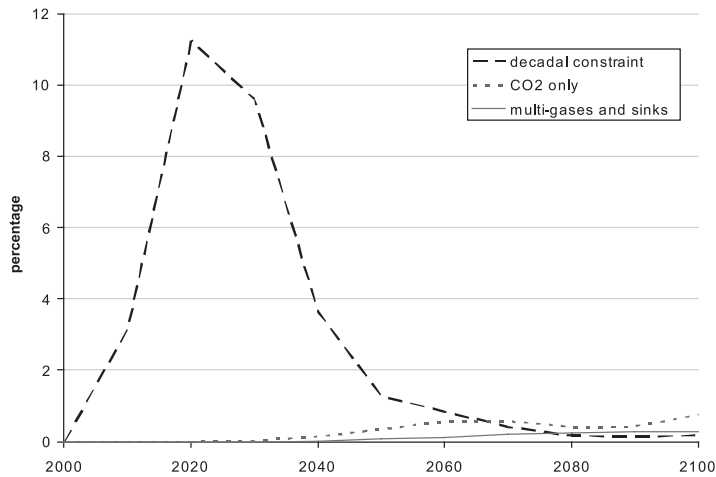


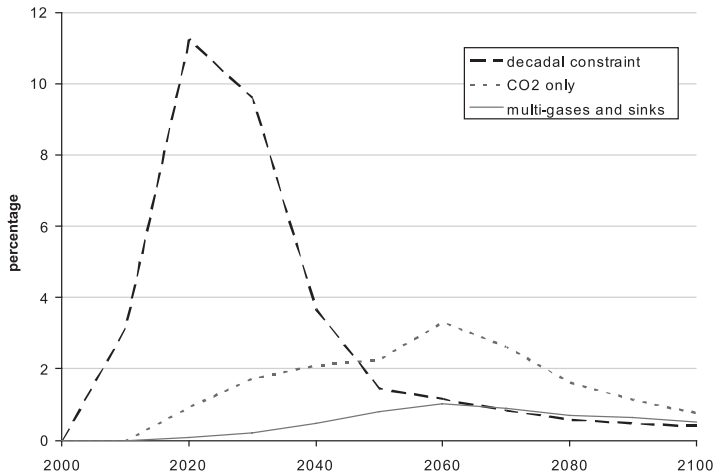
Figure 9. Loss in Annual Consumption

a) 4.5 w/m² Ceiling Constraint on Radiative Forcing



9. SOME CLOSING COMMENTS

For its long-term stabilization target, the EMF 21 study (ref. 3) chose radiative forcing rather than atmospheric concentrations for a ceiling. Using the latter is problematic since it requires an *arbitrary* way to make trade-offs among gases. By choosing a ceiling to which each gas contributes (i.e., radiative forcing), the trade-offs among gases can be based on the relative prices of each gas as

Figure 9. Loss in Annual Consumptionb) 3.5 w/m^2 Ceiling Constraint on Radiative Forcing

determined by its contribution to the ceiling. This approach, which includes both physical and economic considerations, avoids the methodological problems associated with the use of GWPs.

The results of the present study show that total abatement costs can be reduced (in some cases substantially) when multiple greenhouse gases and sinks are included in the abatement strategy. Although the focus is on limiting radiative forcing, we also calculate the concentration levels associated with each gas in order to meet a particular target. Hence, if policy-makers still choose to continue to focus on atmospheric concentrations, we can provide more defensible cost estimates for complying with a prescribed ceiling.

Recently, there has been some effort to extend the analysis further along the causal chain connecting human activities and impacts.¹³ The goal is to incorporate such uncertainties as climate sensitivity and ocean heat uptake into the analysis. Given the current uncertainties in our understanding of the climate system, it is impossible to project with any degree of confidence the effect of a given concentration ceiling on the things we care about. Extending the analysis to temperature change will help policy-makers gain a more realistic understanding of the consequences of their actions.

13. Richels, R. G., A. S. Manne and T. M. L. Wigley (2004). "Moving Beyond Concentrations: The Challenge of Limiting Temperature Change", AEI-Brookings Joint Center for Regulatory Studies, *Working Paper 04-11*, April.



Efficiency Gains from “What”-Flexibility in Climate Policy An Integrated CGE Assessment

Christoph Böhringer, Andreas Löschel**
and Thomas F. Rutherford****

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 economic adjustment costs. When comparing policies that simply involve long-term temperature targets against more stringent strategies with constraints on the rate of temperature increase, it turns out that the latter involve much higher costs. The cost difference may be interpreted as additional insurance payments if climate damages should not only depend on absolute temperature change but also on the rate of temperature change.

1. INTRODUCTION

Flexibility is a central element of market-based economies fostering the efficient use of scarce resources. In the context of climate policy, efficiency translates into questions of how much and what kind of 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

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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 have not even reached agreement on the methodology to be used for valuing climate change impacts such as the extinction of a species. The large uncertainties in predicting global climate change, as well as quantifying and monetizing the associated biophysical effects 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 relying 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 explicit 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 GHG concentrations with an associated range of expected increases in the global mean temperature (IPCC 2001). Given some targets for stabilization of GHG concentrations or likewise temperature, rational climate policy should minimize the associated net economic costs. Cost-effectiveness suggests that the marginal costs of emission control are 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, regardless of the geographical location. With the second, reductions should take place *when* it is least costly. 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 CO₂ 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.

1. Note that – in contrast to a comprehensive cost-benefit analysis – the cost-effectiveness approach does no longer assure that marginal costs are equal to the marginal benefits of emission reduction.

Against this background, the primary objective of this paper is to investigate the relative importance of a multi-gas emission control strategy (in our case: CO₂ and CH₄) vis-à-vis a CO₂-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 climatic relationships into a dynamic multi-sector, multi-region computable general equilibrium (CGE) model of global trade and energy use.

Based on numerical simulations 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 with constraints on the rate of temperature increase, it turns out that the latter involve much higher costs. The cost difference may be interpreted as additional insurance payments if climate damages should not only depend on absolute temperature change but also on 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. In section 2 we lay out the generic general equilibrium framework that serves as a starting point for subsequent extensions to accommodate integrated assessment of multi-gas abatement strategies. In section 3 we describe the baseline calibration of our model to long-term projections on economic growth and energy use. In section 4 we explain the inclusion of non-CO₂ greenhouse gases – in our case: CH₄. In section 5 we provide a summary of the reduced-form climate sub-module and its linkage to the energy-economy model. In section 6 we outline the specific policy scenarios and interpret the simulation results. In section 7 we conclude.

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 setting is indispensable for the economic impact analysis of global GHG emission constraints: In a world that is increasingly integrated through trade, policy interference in open economies not only causes adjustment of domestic production and consumption

patterns but also influences 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 main 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 explicitly dynamic framework as climate change is a long-term phenomena which requires policy interference over a longer time horizon: 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 model builder, implies a model with “consistent expectations” or “perfect foresight” where 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 consistent measurement of transitional effects that can be significant relative to long-term impacts.

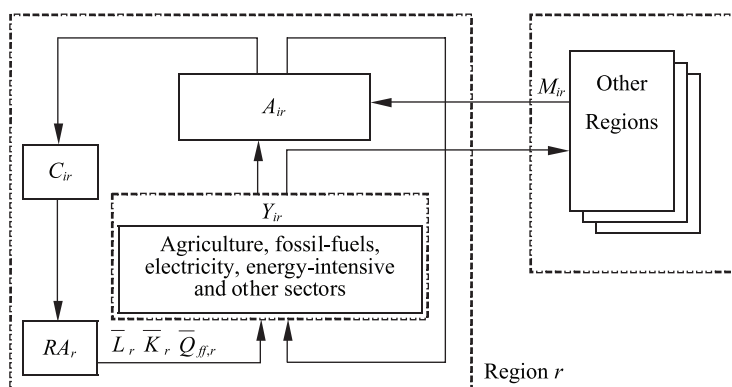
Below, we first provide a non-technical summary on the static intra-period sub-module and then describe the dynamics of the overall model. Finally, we point out the advantage of implementing the model in a mixed complementarity format rather than adopting an explicit optimization (mathematical programming)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

2.1 The Static Sub-Module

Figure 1 lays out the diagrammatic structure of the static intra-period sub-module that underlies our dynamic multi-sector multi-region CGE model of global trade and energy use. 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 commodity 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 substitution possibilities in domestic production sectors between capital, labor, energy, and non-energy intermediate inputs.

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

Figure 1. Structure of the Intra-Period Sub-Module



functions. CO₂ 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.

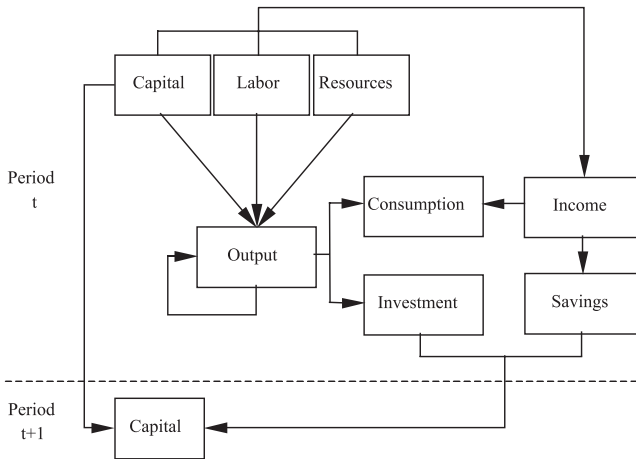
Endowments of labor and the specific resources are fixed exogenously. Capital supplies are price-responsive (see section 2.2.). Within any time period, we assume competitive factor and commodity markets such that prices adjust to clear these markets.

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 future 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 . Output is divided between consumption and investment, and investment

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

augments the (depreciated) capital stock in the next period. Capital, labor, and the energy resources earn income, which is either spent on consumption or retained for savings, i.e., investment.

Investment is driven by consistent expectations, where the return on investment 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; rapid changes in the regional capital stock are costly implying a slower speed of adjustment of capital stocks to changes in the rate of return.³

Dynamic general equilibrium models exhibit a turnpike property to be exploited upon approximation of an infinite horizon equilibrium within a finite horizon model: In order 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 periods of the model and (ii) terminal assets are determined in consistency with budget balance and steady-state growth for the post-terminal horizon.

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

2.3 Mixed Complementarity 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 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, ad-valorem taxes, income effects, spillovers and other externalities, interfere with the skew symmetry property which characterizes first-order conditions of mathematical 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 settings with initial inefficiencies. 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 or baseline - usually termed business-as-usual (BaU) - where no policy changes apply. When we want to simulate the potential effects of a specific 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 example, the more exogenous policy constraints – such as stabilization or temperature targets – will bind future economies, the higher the projected BaU growth in GHG emissions. Substantial differences in model-based analysis can often be traced back to different assumptions about the reference situation. Yet, the central role of BaU assumptions in general receives little attention in the literature. Regarding long-term climate policy analysis, the issue of BaU projections becomes very critical in view of the tremendous uncertainties regarding developments over several decades. Not only is there the question why one set of BaU assumptions should be preferable over another, but often projections derived from various partial equilibrium analyses stand out for larger internal inconsistencies.

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.

Against this background, a careful documentation of the BaU 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 describe the 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 the 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, benchmark data sets typically do not satisfy the steady-state conditions for arbitrary assumptions on dynamic parameters such as the growth, interest, and depreciation rates: If we assume for example plausible values for the latter parameters, the capital value shares implied by steady-state growth 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 which requires an explicit computation of the baseline equilibrium to assure mutually consistent steady-state development at the regional level. 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 matching exogenous projections on economic variables 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 region grows faster, one may assume 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, the cost of a unit of the aggregate commodity remains unchanged at base year prices, even though there may be larger differences in the relative growth rates across countries. A final problem after the adjustment of the Armington demand functions is related to assets rather than terms of trade and becomes evident in deviations between the computed base-year consumption and the officially reported 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.

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 CO₂ 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, which means 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. 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 regions and 57 commodities in the year 1997 (Dimaranan and McDougall 2002).

Considering the regional resolution of our specific 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, carbon emissions as well as methane emissions until 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,

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

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.

4. NON-CO₂ ABATEMENT OPTIONS

CO₂ is the major anthropogenic greenhouse gas contributing to global warming. However, other greenhouse gases including CH₄, N₂O, and a number of industrial process gases are also relevant to climate change. In our multi-gas simulations below we track emissions of CO₂ and CH₄ emissions as the most important non-CO₂ greenhouse gas. We endogenously determine the level of CO₂ and CH₄ emissions thereby taking into account the various sources of anthropogenic CH₄ emissions and the technological options to abate them.

Agriculture is a primary source of CH₄ emissions. Especially livestock contributes to the overall amount of CH₄ emissions from the agriculture sector through enteric fermentation and the (anaerobic) decomposition of manure. Another important source of CH₄ emissions in agriculture is rice cultivation. Furthermore, fugitive CH₄ emissions from natural gas and oil systems, especially from the production, processing, transmission and distribution of natural gas are substantial. Coal production (mining and post-mining activities) also produces CH₄ emissions through the process of coal formation which results in CH₄ that is stored in the coal. Municipal and industrial waste (solid waste land filling and wastewater treatment) leads to CH₄ emissions through anaerobic decomposition of waste and thereby. Other CH₄ emission sources include, e.g., stationary and mobile combustion and biofuel combustion.

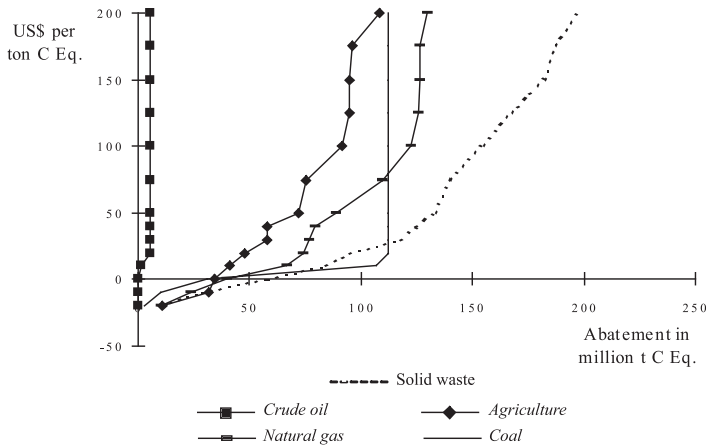
Table 3 provides an overview of the CH₄ sources, baseline emissions in 2010 provided by the United States Environmental Protection Agency (EPA) and the mapping of CH₄ sources to the sectors incorporated in our model.

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

Table 3. CH₄ Sources, Emission Baseline and Corresponding Model Sectors

CH ₄ emission sources	EPA Baseline 2010 (in MMTCE)	Model sector
Rice cultivation	187.4	Agricultural production
Enteric fermentation	557.9	
Manure management	65.3	
Biomass burning (agricultural residue burning)	75.1	Coal
Coal production (underground and surface mining and post-mining)	140.9	
Crude oil production	19.4	
Natural gas systems (production, processing, transmission and distribution)	316.3	Natural gas
Industrial sewage (wastewater)	174.3	Energy-int. sectors
Domestic sewage (wastewater)		
Landfills of solid waste	239.0	Household
Stationary and mobile combustion	19.2	
Biofuel combustion	64.1	
Other	5.5	

Figure 3. Global Marginal Abatement Cost Curves for CH₄ Emission Sources in 2010



proportions to activities as there are technical possibilities to reduce emissions per unit of activity. EPA provides country-specific bottom-up estimates of marginal abatement costs for CH₄ emissions across 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 CH₄ emission are hence supplemented with engineering information about technical options for potential emission abatement. Figure 3 illustrates marginal abatement cost curves for different CH₄ emission sources in the year 2010.

To incorporate the step-wise marginal abatement cost curves for CH₄ in each model sector and region, we first compute an equilibrium path of the counterfactual GHG abatement scenario without CH₄ abatement options. Next, we evaluate the solution with respect to carbon prices. We then assume that all potential cost-effective CH₄ abatement options in each sector and region are implemented. This gives us a point estimate of CH₄ abatement levels, marginal cost of abatement, and the average cost increase of CH₄ 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 CH₄ emissions. Using the new equilibrium path, we can update the CH₄ abatement and cost fractions. In our policy simulations, the iterative CH₄ 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

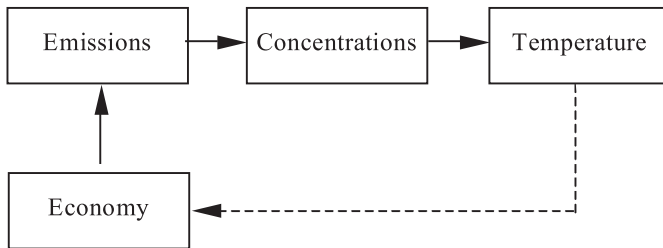
change in an integrated assessment model. Climate-change modeling is introduced through the geophysical module of the RICE-99 model (Regional Integrated model of Climate and the Economy) by Nordhaus and Boyer (2000). It contains a number of geophysical relationships that link together the different forces affecting climate change. The geophysical relations are simplified representations of more complex models and give a reduced-form description of emissions, concentrations, and global average temperature change. Economic activity leads to CO₂ emissions which affect climate through their radiative forcing. Accumulation and transportation of CO₂ emissions is modeled as a linear three-reservoir approach calibrated to more complex 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 CO₂ emissions in the atmosphere leads to an increase in radiative forcing.⁵ 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 climate sub-module only CO₂ is endogenously modeled. Other greenhouse gases and their radiative forcings are assumed to be exogenous. For our multi-gas analysis we endogenize CH₄ as the most important non-CO₂ greenhouse gas. The calibration of the extended climate sub-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 CH₄ stock. The base-year stock of methane amounts to 4.850 billion tons of CH₄, of which 60 % are subject to decay with a yearly retention factor of 8.3 % reflecting the atmospheric lifetime. The increase in the methane stock 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 CH₄ and N₂O. The aggregate radiative forcing is again the sum of the radiative forcing for CO₂, CH₄, 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 (CO₂ and CH₄ 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 productivity changes, capital depreciation) and non-market impacts (such as biodiversity losses, natural disasters): There is only a one-way link between economic variables and biophysical variables. As a consequence, the welfare analysis of climate policy scenarios is solely driven by economy-wide adjustment costs – in the absence of major second-best effects (due to initial market distortions)

5. The radiative forcing equation of RICE-99 includes the forcings of other greenhouse gases (CH₄, N₂O, CFCs and ozone) and aerosols as an exogenous component.

Figure 4. Coupling of Economic System and Climate System for Integrated CGE Assessment

restrictive GHG emissions control policies are necessarily welfare decreasing.

The coupling of the economic system and climate system for our integrated CGE assessment is depicted in Figure 4.

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).⁶

In order to assess the importance of “what”-flexibility we combine each of the two control schemes with alternative assumptions on the greenhouse gases that are explicitly abated. Variant *CO₂* covers the case where only carbon emissions are subject to direct emission control measures. Variant *Multigas* includes CH₄ as an additional targeted greenhouse gas within the abatement strategy. In total, we obtain four scenarios whose characteristics are summarized in Table 4. Across all scenarios, comprehensive “where”- and “when”-flexibility applies.

In the exposition of results from our large-scale multi-sector, multi-region CGE model, we focus on global cost implications across the different scenarios. At the regional level, compliance costs will to a large extent depend on

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

Table 4. Central Case Scenarios

	Control scheme	Emission s.t. control policy
CO_2-T_{Target}	Temperature target	CO ₂ only
$Multigas-T_{Target}$	Temperature rate	CO ₂ and CH ₄
CO_2-T_{Rate}	Temperature target	CO ₂ only
$Multigas-T_{Rate}$	Temperature rate	CO ₂ and CH ₄

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 of how abatement duties – or likewise emission entitlements – shall be allocated across countries. We do not want to enter the controversial and highly subjective debate on burden sharing rules 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.⁷

Table 5 reports the global compliance costs across the four GHG abatement scenarios. The 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. More specifically, the results 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 expensive – in fact, the compliance costs are an order of magnitude higher than in the respective scenarios that only involve a long-term temperature target. Second, “what”-flexibility provides substantial efficiency gains cutting the compliance costs vis-à-vis a CO₂-only strategy roughly to 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

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

Figure 5. Global Mean Temperature (Degrees Celsius)

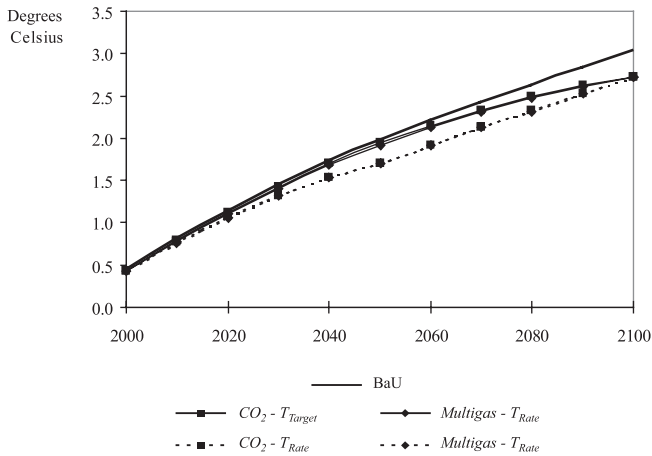
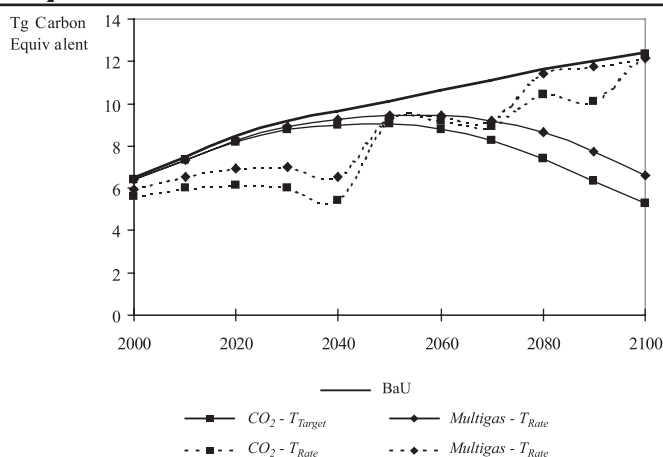
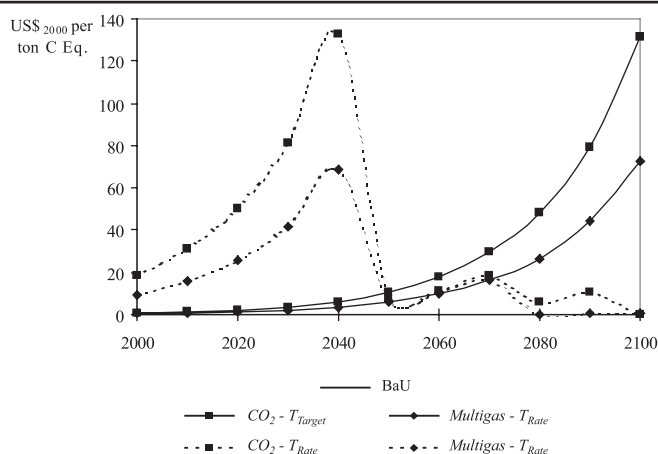


Figure 5 depicts the trajectory of the global mean temperature. Policies which restrict the increase in global mean temperature in 2100 to 90 % of the BaU value involve little temperature decreases vis-à-vis the business-as-usual until the mid of the century. Policies that in addition limit the decadal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

Figure 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 constraints allow for substantial increases in emission levels from current levels to the mid-century.

The cutback requirements from BaU are relatively modest till 2050 but thereafter emissions must be reduced drastically to achieve the temperature target: 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 emission trajectories for the scenarios with decadal rate constraints reflect the discrete upper bounds on permissible rate increases. There is no leeway for smoothing the carbon profile as is the case for the target-only scenarios. “What”-flexibility allows for higher CO₂ emissions for both climate control schemes (*Target* and *Rate*) since CH₄ 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

Figure 6. CO₂ Emissions from Fossil Fuels (Tg of C eq.)**Figure 7. Incremental Value of Carbon Permit / Carbon Tax (US\$₂₀₀₀/metric ton C Eq)**

be cut back and the later in time abatement takes place, the less costly the control scheme is. Not surprisingly the *Multigas-T_{Target}* scenario turns out as the least-cost strategy.

Figure 7 shows the magnitude of implicit carbon values that would be required to achieve the long-term temperature target and rate constraints.

The course of the tax trajectories mirrors 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 the economic rationale to postpone abatement as long as possible. Rate

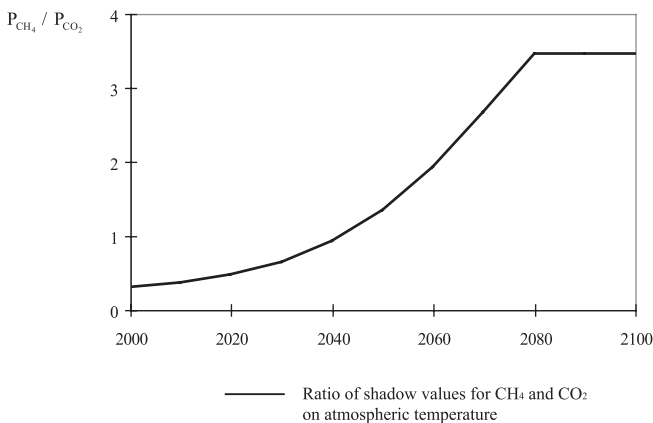
constraints trigger very high shadow prices in the initial periods whereas prices become very small or even zero towards the end of the model horizon (as rate constraints may no longer be binding).

Figure 8 illustrates the trade-offs between CO_2 and CH_4 based on efficiency prices, i.e., the ratio of shadow values for these gases with respect to the long-term temperature target (scenario: $\text{Multigas-}T_{\text{target}}$). 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 is augmented 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 ratios may vary substantially over time – in addition they are sensitive to the ultimate temperature goal (see Manne and Richels 2001).

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 analyses, 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

Figure 8. Ratio of Shadow Values for CH_4 and CO_2 on Atmospheric Temperature



increase. We have also highlighted the shortcomings of the GWP approach to represent the contribution of different greenhouse gases to radiative forcing.

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 form representation of the climate dynamics is very simplistic. Against this background we caution against too literal an interpretation of our numerical results.

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Economic Impact Assessment of Climate Change— A Multi-gas Investigation with WIAGEM-GTAPEL-ICM

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Climate change is a long-term issue due to the long lifespan of greenhouse gases (GHG) and the delayed response of the climate system. This paper investigates the long-term economic consequences of both climate change impacts and mitigation efforts by applying the multi-regional, multi-sectoral integrated assessment model WIAGEM based on GTAP-EL coupled with the reduced-form multi-gas climate model ICM. We investigate emissions reduction paths to reach a radiative forcing target of 4.5 W/m². Economic impacts are studied and compared with and without the inclusion of all GHG gases. We find that multi-gas emissions reduction causes less economic losses compared with a case where only CO₂ emissions reductions would be considered.

1. INTRODUCTION

A continued accumulation of anthropogenic greenhouse gases (GHGs) will have severe consequences on our climate, ecological and social systems. Irreversible climate changes are expected to induce significant costs, and no future efforts can nullify the resulting damage. Climate change is a long-term issue because of the lifespan of greenhouse gases. In order to assess the total impacts of climate changes, short and long-term costs and benefits need to be assessed and compared. Increasing atmospheric concentrations of greenhouse gases have a substantial impact on global temperature change and sea-level rise, which might create extensive economic, ecological and climatic impacts. The threat of climate change makes economic development strategies as well as energy and environmental policies increasingly important. Climate change is a global problem requiring a global solution.

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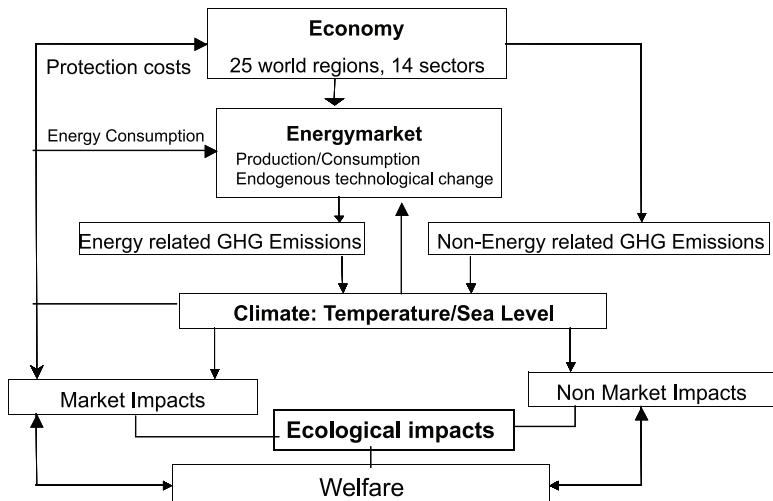
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Because of the long-term time horizon of climate change, climate policy involves a trade-off between short-term costs and long-term benefits. Greenhouse gas emissions reductions induced by environmentally friendly technologies require direct investments in clean technologies and abatement equipment. The benefits of climate change mitigation, however, is not restricted to the lifespan of the physical capital but linked to the lifespan of greenhouse gases. Due to this, it is often argued that investments in emissions reduction technologies should be postponed because the benefits of GHG emissions reduction can only be detected in the distant future. For this reason, climate change policy has to determine a proper balance between future benefits and present day costs.

The most influential greenhouse gas is CO₂. However, methane (CH₄) and nitrous oxide (N₂O) also have strong impacts on climate. Furthermore, a group of industrial gases covering perfluorocarbons (PFCs), hydrofluorocarbons (HFCs) and sulphur hexafluoride (SF₆) together with the already banned chlorofluorocarbons (CFCs) are significant as well. Most studies investigating the economic impacts of climate change cover only CO₂ (McKibbin and Wilcoxon, 1999; Bernstein, Montgomery *et al.*, 1999; Weyant and Hill, 1999; Edmonds, Scott *et al.*, 1999; Kemfert, 2002a; Böhringer and Rutherford, 1999; Babiker, Reilly *et al.*, 2000; Ellerman, 2000; Tietenberg, Grubb *et al.*, 1999; Zhang, 2001). Previous studies that incorporate a multi-gas reduction strategy find that a cost saving multi-gas emissions reduction strategy reduces abatement costs and welfare losses (see Manne and Richels, 2000; 2001, Reilly *et al.*, 2002, 2003). A cost effective control of climate change requires that climate policy strategies need to cover not only CO₂ but also other greenhouse gases. The reason why most of the studies focus primarily on CO₂ emissions is that this gas can relatively easy be measured and monitored by the use of fossil fuels. As each of the greenhouse gases has different lifetimes and impacts on atmospheric chemistry, a comparison of the different effects of each gas is very challenging. A cost effective approach needs to cover reduction methods and impacts of each greenhouse gas.

In this paper, we shed some light on this issue and investigate and compare the impacts of pure CO₂ emissions versus a multi gas emission control. In order to do so, we have to go beyond traditional CO₂ concentration stabilization exercises. At first sight, investigating the stabilization of global mean temperature might be considered a suitable extension. The results, however, would considerably be dependent on the specific climate sensitivity of the selected climate model. In order to exclude the related additional uncertainty, we have selected to investigate the stabilization of radiative forcing, which is – along the chain of causes and effects – the first indicator that aggregates the influences of the different greenhouse gases. The radiative forcing target selected is 4.5 W/m² which corresponds to a CO₂ equivalent concentration of 568 ppm, i.e. a concentration which is approximately twice the pre-industrial level.

We apply the multi-regional, multi-sectoral integrated assessment model WIAGEM (Kemfert, 2002a-b) which is also based on a multi regional trade model GTAP-EL (Burniaux and Truong, 2002; Burniaux, 2002) and coupled with a

Figure 1. Interrelations in WIAGEM

reduced-form climate module that covers all relevant greenhouse gases (ICM, see Bruckner *et al.*, 2003; Hooss *et al.*, 2001; Hooss, 2001; Joos *et al.*, 2001; Meyer *et al.*, 1999). Section two briefly describes the models and section three shows the different scenarios. Section four illustrates the main model outcomes, while the last section concludes.

2. THE APPLIED MODELLING TOOL

Our analysis is performed using the multi-regional WIAGEM model (World Integrated Assessment General Equilibrium Model). This is an integrated economy-energy-climate model that incorporates economic, energy and climatic modules in an integrated assessment approach.¹ The model is based on a multi regional trade model GTAP-EL.² To evaluate market and non-market costs and benefits of climate change, WIAGEM combines an economic approach with a special focus on the international energy market and integrates climate interrelations with temperature changes and sea level rise. The design of the model is focused on multilateral trade flows. The representation of the economic relations is based on an intertemporal general equilibrium approach and contains the international markets for oil, coal and gas. The model incorporates all greenhouse gases (GHG) that influence potential global temperature, sea level rise and the assessed probable impacts in terms of costs and benefits of climate change. Market and non-market damages are evaluated according to the damage costs approaches of Tol (2002). Additionally, this model includes net changes

1. See Kemfert (2002b) for a detailed model description.

2. Burniaux and Truong (2002); Burniaux (2002).

in GHG emissions from sources and removals by sinks resulting from land use change and forest activities.

WIAGEM is an integrated assessment model combining an economy model based on a dynamic intertemporal general equilibrium approach with an energy market model and a climatic sub-model. The model covers a time horizon of 100 years and solves in five-year time increments. The basic idea behind this modelling approach is the evaluation of market and non-market impacts induced by climate change. The economy is represented by 25 world regions which are further aggregated into 11 trading regions for this study (see Figure 1).

The economy of each region is disaggregated into 14 sectors, including five energy sectors: coal, natural gas, crude oil, petroleum and coal products, and electricity. Goods are produced for the domestic and export markets. The output of the non-energy sectors is aggregated into a non-energy macro good. The production function for this macro good incorporates technology through transformation possibilities on the output side and constant elasticity substitution (CES) possibilities on the input side. The CES production structure combines a nested energy composite with a capital-labour-land composite at lower levels. The energy composite is described by a CES function reflecting substitution possibilities for different fossil fuels (i.e. coal, gas, and oil). Fossil fuels are produced from fuel-specific resources. The energy-capital-labour-land composite is combined with material inputs to acquire the total output.

A representative household in each region allocates lifetime income across consumption in different time periods to maximize lifetime utility. In each period, households choose between current consumption and future consumption, which can be purchased via savings. The trade-off between current consumption and savings is given by a constant intertemporal elasticity of substitution. Domestic and imported varieties of the non-energy macro good are imperfect substitutes in each region as specified by a CES Armington aggregation function constrained to constant elasticities of substitution.

Producers invest as long as the marginal return on investment equals the marginal cost of capital formation. The rates of return are determined by a uniform

Table 1. Definitions of Countries and Regions in WIAGEM

	Regions
ASIA	India and other Asia (Republic of Korea, Indonesia, Malaysia, Philippines, Singapore, Thailand, China, Hong Kong, Taiwan)
CHN	China
CNA	Canada, New Zealand and Australia
EU15	European Union
JPN	Japan
LSA	Latin America (Mexico, Argentina, Brazil, Chile, Rest of Latin America)
MIDE	Middle East and North Africa
REC	Russia, Eastern and Central European Countries
ROW	Other Countries
SSA	Sub Saharan Africa
USA	United States of America

and endogenous world interest rate such that the marginal productivity of a unit of investment and a unit of consumption is equalized within and across regions.

Induced technological change is considered as follows: Energy efficiency is improved endogenously by increased expenditures in R&D. This means that, in the CES (constant elasticity of substitution) production function, energy productivity is endogenously influenced by changes in R&D expenditures. The incentives to invest in technology innovations are market-driven. Because energy efficiency is improved by increased R&D expenditures, emissions reduction targets can be met with fewer production drawbacks. Furthermore, investment in R&D and technological innovation give a comparative advantage. The share of R&D expenditures in the total expenditures is endogenously determined by production changes, implying that investment in R&D expenditures competes with other expenditures (crowding out). Spillover effects of technological innovations are reflected through trade effects and capital flows. That means non-R&D-cooperating countries producing technological innovations can benefit from spillover effects through trade of technological innovations and capital flows that can be used for R&D investments. Model calculations show that capital flows increase to non-cooperating countries because of improved competitiveness effects and terms of trade effects. This consequently triggers spillover effects of technological innovations and energy efficiency improvements through increased R&D investments. Figure 1 graphically explains the interrelations of economic activities, energy consumption, climate and ecological impacts in WIAGEM.

In addition to the non-energy macro good, oil, coal and natural gas are traded internationally. The global oil market is characterized by imperfect competition to reflect the ability of the OPEC regions to use their market power to influence market prices. Coal trades in a competitive global market, while natural gas trades in competitive regional markets with prices determined by global or regional supply and demand.

Energy-related greenhouse gas emissions occur as a result of energy consumption and production activities. WIAGEM includes all greenhouse gases covered under the Kyoto Protocol; with carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) considered to have the greatest impact on climate change over the 100-year period covered by the model. Furthermore, the fluorinated gases (CFCs, HFCs, PFCs and SF_6) are considered as well, as described in the next section. The emissions limitation commitments of the Kyoto Protocol Annex B parties are specified as regional emissions limits to reduce coverage of greenhouse gases by the model.

By coupling the economic and climate impact part of WIAGEM with the detailed climate module ICM, we consider the relationship between man-made emissions and atmospheric concentrations and their resulting impact on temperature and sea level. We cover classes of atmospheric greenhouse gas stocks with different atmospheric lifetimes. Energy and non-energy related emissions of CO_2 , CH_4 and N_2O as well as those of halocarbons (CFCs, HFCs, PFCs) and SF_6 alter the concentrations of these substances which in turn influence

radiative forcing. Energy related emissions are calculated according to the energy development of each period. Energy related CO₂ emissions are considered according to the emissions coefficients of the EMF group.

2.1 The ICLIPS Climate Model (ICM)

As part of the ICLIPS (Integrated Assessment of Climate Protection Strategies) project (see Toth *et al.*, 2003, and references therein), a computationally efficient reduced-form multi-forcing climate model was developed at the Potsdam Institute for Climate Impact Research (PIK) in collaboration with the Max-Planck Institute for Meteorology (MPI), Hamburg (Bruckner *et al.*, 2003; Hooss *et al.*, 2001). The ICLIPS climate model (ICM) consists of several modules designed to simulate (a) the atmospheric retention and metabolism of carbon dioxide and other important greenhouse gases (CH₄, N₂O, halocarbons, SF₆, and the aerosol precursor SO₂), (b) the time-dependent contributions of these gases to radiative forcing, and (c) the resulting transient patterns of the anthropogenic climate change signal in terms of selected impact-relevant variables, including: air temperature, cloud cover, precipitation, and sea-level rise. The modules used to form ICM are adaptations of peer-reviewed models that have previously been used individually in a variety of other integrated assessment studies (Harvey *et al.*, 1997; Meyer *et al.*, 1999; Joos *et al.*, 2001; Hooss *et al.*, 2001).

ICM is driven by time-series of the anthropogenic emissions of CO₂, CH₄, N₂O, halocarbons, SF₆ and SO₂. In WIAGEM, total anthropogenic emissions are determined by:

$$TOTEM_{r,t} = E_{r,t} + NonE_{r,t} - S_{r,t} \quad (1)$$

with $TOTEM_{r,t}$ indicating the total anthropogenic *net* emissions per region r and time period t . $E_{r,t}$ and $NonE_{r,t}$ refer, respectively, to energy-related and non-energy-related regional emissions. The enhanced sinks ($S_{r,t}$) reduce total emissions.³

The atmospheric concentration of greenhouse gases may change due to direct emissions, exchange with reservoirs (e.g., ocean, biosphere, pedosphere) and/or chemical reactions (destruction or formation). The biogeochemical sub-modules of ICM take into account these different processes in a gas-specific manner.

The core of ICM contains a modified version of NICCS (Nonlinear Impulse Response Representation of the Coupled Carbon Cycle – Climate System) model (Hooss, 2001; Hooss *et al.*, 2001), developed at MPI, Hamburg. The carbon cycle module of NICCS consists of (a) a differential impulse-response representation of the comprehensive three-dimensional Hamburg Model of the Ocean Carbon Cycle (HAMOCC) combined with an explicit treatment of nonlinear sea water carbon chemistry, and (b) a nonlinear differential impulse-response model of terrestrial biosphere CO₂ fertilization effects. Applying an

3. This means that the emissions reductions targets are also reduced.

inverse calibration technique, the quantitatively unknown CO₂-fertilization factor has been adjusted so as to give a balanced 1980s mean carbon budget, as advised by the IPCC model inter-comparison exercise.

Various components of the MAGICC model (Wigley, 1988; Wigley and Raper, 1992; Wigley, 1994; Osborn and Wigley, 1994; Wigley *et al.*, 1996; Harvey *et al.*, 1997) were adopted in order to simulate the atmospheric chemistry of the major non-CO₂ greenhouse gases. Changes in the concentration of non-CO₂ greenhouse gases (CH₄, N₂O, halocarbons, and SF₆) are calculated by a simple one-box model approach, according to:

$$\frac{dC(t)}{dt} = \frac{1}{b} \sum_r TOTEM_r - \frac{1}{\tau} (C - C_{pre-industrial}) \quad (2)$$

where b is a concentration-to-mass conversion factor and τ is the lifetime of the greenhouse gas under consideration. For N₂O, halocarbons, and SF₆, the lifetime is assumed to be constant (IPCC, 1996; Harvey *et al.*, 1997). CH₄ is removed from the atmosphere by soil uptake and chemical reactions with OH. The lifetime calculation for CH₄ takes into account both processes. As the OH concentration itself is influenced by CH₄, the lifetime attributed to chemical processes is modeled dependent on the CH₄ concentration, in accordance with Osborn and Wigley (1994).

Changes in the atmospheric concentration of different greenhouse gases have the following impact on radiative forcing (IPCC, 1990):

$$\Delta F_{CO_2} = 6.3 \ln \left(\frac{CO_2}{CO_{2|0}} \right) \quad (3)$$

$$\Delta F_{CH_4} = 0.036 (CH_4^{0.5} - CH_4^{0.5|_0}) - f(CH_4, N_2O|_0) + f(CH_4|_0, N_2O|_0) \quad (4)$$

$$\Delta F_{N_2O} = 0.14 (N_2O^{0.5} - N_2O^{0.5|_0}) - f(CH_4|_0, N_2O) + f(CH_4|_0, N_2O|_0) \quad (5)$$

Table 2. Summary Key Assumptions Greenhouse Gases^a

Trace Gas	CO ₂	CH ₄	N ₂ O
Atmospheric Concentration			
Pre- Industrial (ppmv)	278	.789	0.275
1992 (ppmv)	353	1.72	0.310
Energy related Emissions			
1992 (billion tons)	6.0	.08	.0001
growth rate, post 1992			
Non-energy related Emissions			
1992 (billion tons)	.2	.454	.0139
growth rate, post 1992	0	.8	.2

a. Source: IPCC (90) and IPCC (92)

with ΔF measured in Wm^{-2} , concentrations for CH_4 and N_2O given in ppbv and the subscript 0 used to indicate pre-industrial concentration values. The CH_4 - N_2O interaction term, expressed in Wm^{-2} , is determined by:

$$f(\text{CH}_4, \text{N}_2\text{O}) = 0.47 \ln [1 + 2.01 \times 10^{-5} (\text{CH}_4 \times \text{N}_2\text{O})^{0.75} + 5.31 \times 10^{-15} \times \text{CH}_4 \times (\text{CH}_4 \times \text{N}_2\text{O})^{1.52}] \quad (6)$$

where, in accordance with Eq. 4 and 5, CH_4 and N_2O have to be replaced either by actual CH_4 and N_2O concentration values or alternatively by the respective pre-industrial levels.

In addition to Eq. 3–6, the radiative forcing description in ICM takes into account the contributions from SF_6 , tropospheric ozone and stratospheric water vapour (both dependent on CH_4 concentrations), aerosols, and halocarbons, including indirect effects originating from stratospheric ozone depletion.

The time evolution of global mean temperature change and sea-level rise is calculated on the basis of impulse response functions that are calibrated to reproduce the results of a long-term forcing experiment carried out with a sophisticated spatially-resolved Atmosphere-Ocean General Circulation Model at MPI, Hamburg (Voss et al., 1998; Voss and Mikolajewicz, 2001). A detailed description of this approach can be found in Hooss (2001), Hooss *et al.* (2001), Bruckner *et al.* (2003), Joos *et al.* (2001), and Meyer *et al.* (1999).

In order to include the radiative forcing contributions of non CO_2 -greenhouse gases, the carbon dioxide concentration value used in the response function approach of NICCS is replaced by the *equivalent* carbon dioxide concentration C_{Equiv} (measured in ppm) as defined in IPCC (1996a, p.320):

$$C_{\text{Equiv}} = 278 \text{ ppm} \times \exp \left(\frac{\Delta F}{6.3 \frac{\text{W}}{\text{m}_2}} \right) \quad (7)$$

where ΔF denotes the sum of the individual radiative forcing contributions.

ICM calculates the climatic changes due to greenhouse gas emissions and the impact modules estimate the corresponding climate impacts. Market and non-market damages associated with these impacts are assessed by coupling the climate module ICM with WIAGEM. Socio-economic impacts are expressed in terms of changes in regional and global welfare as well as in regional and global GDP losses.

2.2 Scenario Definition

The main aim of this paper is to investigate the economic impacts of the inclusion of all greenhouse gases. Due to this, we compare scenarios where we consider only CO_2 emissions reductions with those where further major

greenhouse gases – methane (CH_4) and nitrous oxide (N_2O) – might be reduced as well. In addition, the combined effect of halocarbons and SF_6 is taken into account. Figure 2 demonstrates the total greenhouse gas emissions until 2100 in the so-called “business as usual” or reference scenario where no climate control takes place. In this scenario, carbon emissions follow the IPCC emissions scenario report (IPCC, 2000).⁴

In order to assess the economic impacts of various emissions reduction options, we compare the following different GHG reduction scenarios:

Reference: no climate control policy takes place, emissions development follows the baseline emissions path.

CO_2 Scenario: in this scenario radiative forcing is not allowed to exceed 4.5 W/m^2 by the end of the model horizon. Emissions mitigation can only be reached by CO_2 emissions reduction.

GHG Scenario: in this multi-gas scenario radiative forcing is also not allowed to exceed 4.5 W/m^2 by the end of the model horizon. However, in addition to CO_2 , CH_4 and N_2O emissions might be reduced as well.

The main reason for differentiating between these scenarios is to investigate the economic impacts of alternative emissions reduction strategies. As in a multi gas reduction case more low cost emission reduction options occur, marginal abatement costs should be lower. Previous studies find substantial lower emissions abatement costs in a multi gas context (Manne and Richels, 2000, 2003), and Reilly *et al.*, 2000, 2002).

3. SCENARIO RESULTS

3.1 Emissions and Carbon Taxes

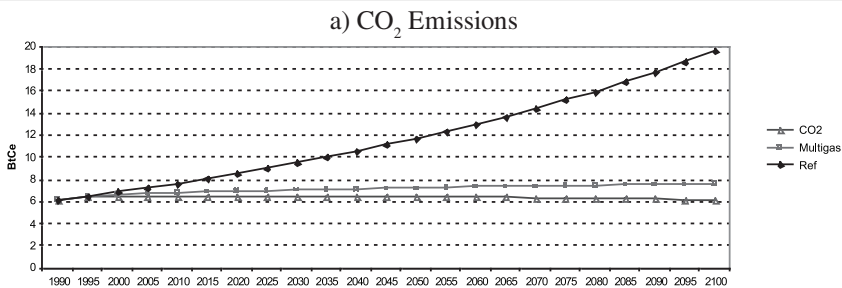
A stabilisation of radiative forcing at a value of 4.5 W/m^2 by the end of the modelling horizon induces substantial emissions reductions. Figure 2 shows the trajectories of the emissions for all gases, and Figure 3 shows the emission reductions relative to the reference case. It can be seen from these Figures that if the above target of radiative forcing stabilisation is to be achieved by CO_2 emissions mitigation alone, then the overall CO_2 emissions will need to be reduced substantially, by about 70 per cent relative to the reference case by 2100, or an average of 7 percent per decade. The figure is improved only slightly

4. IPCC (2000), we follow scenario A1B (1). For non- CO_2 gases, we use EMF21 estimates from the Environmental Protection Agency (EPA 2001): “Non- CO_2 Greenhouse Gas Emissions from Developed Countries: 1990-2010” available at <http://www.epa.gov/methane/pdfs/fulldocumentofdeveloped.pdf> and EPA: “Non- CO_2 Greenhouse Gas Emissions from Developing Countries: 1990-2010.”

if non-CO₂ gases (CH₄ and N₂O) are also to be included, from -70% to -60% (cumulative), or from -7% to -6% (per decade). Despite this small impact on the level of CO₂ emission reductions, the impact on marginal abatement cost (MAC) is substantial (see Figure 4). The MAC reaches a level of about 260 US\$ 1995 per ton of carbon equivalent (\$/TCe) by the year 2100, for the CO₂ alone scenario, but reduced to only about 114 \$/TCe 1995 by the year 2100 if non-CO₂ gases are also included.⁵

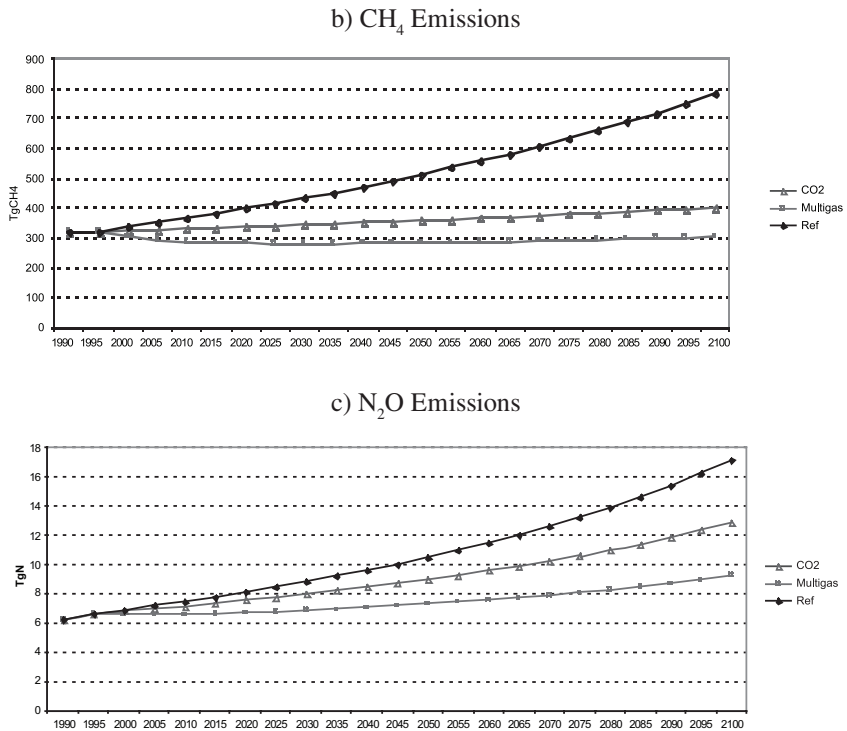
Emissions of CH₄ and N₂O are also reduced substantially (by 50% and 25% respectively relative to the reference case by the year 2100) for the CO₂ alone scenario. This is because all GHGs emissions are linked via production and consumption activities, and hence, the reduction of CO₂ emission reductions will lead to reductions of CH₄ and N₂O emissions - even if the latter are not subject to a target reduction, i.e. not subject to a carbon tax. If CH₄ and N₂O are now also subject to a carbon tax in the same way as CO₂⁶ (the GHG scenario), then the emissions from CH₄ and N₂O will decrease further, and the emissions from CO₂ will increase, as expected (see Figures 2 and 3). The decrease in N₂O emissions is more substantial than the decrease in CH₄ emissions: the percentage reduction in emissions as compared to the reference case for N₂O is now -46% (as compared to -25% for the CO₂ alone scenario), a 20% drop. That for CH₄, is only 12 percentage points (from -49% previously in the CO₂ alone scenario to -61% in the multi-gas case).

Figure 2. Emissions Trajectories of Different Scenarios



5. These figures are quoted for the most optimistic case when all countries participate in emission trading to reduce the cost of emission reductions to a minimum. The opposite (most pessimistic) case when no trading is allowed will increase this cost quite substantially for some regions such as the EU and the USA.

6. The tax is to be based on carbon equivalent unit (Ceq), which is derived using the IPCC Global Warming Potential (GWP) indices (CO₂ = 0.27 Ceq, GWP = 1; CH₄ = 5.73 Ceq, GWP = 21; N₂O = 84.55 Ceq, GWP = 310).

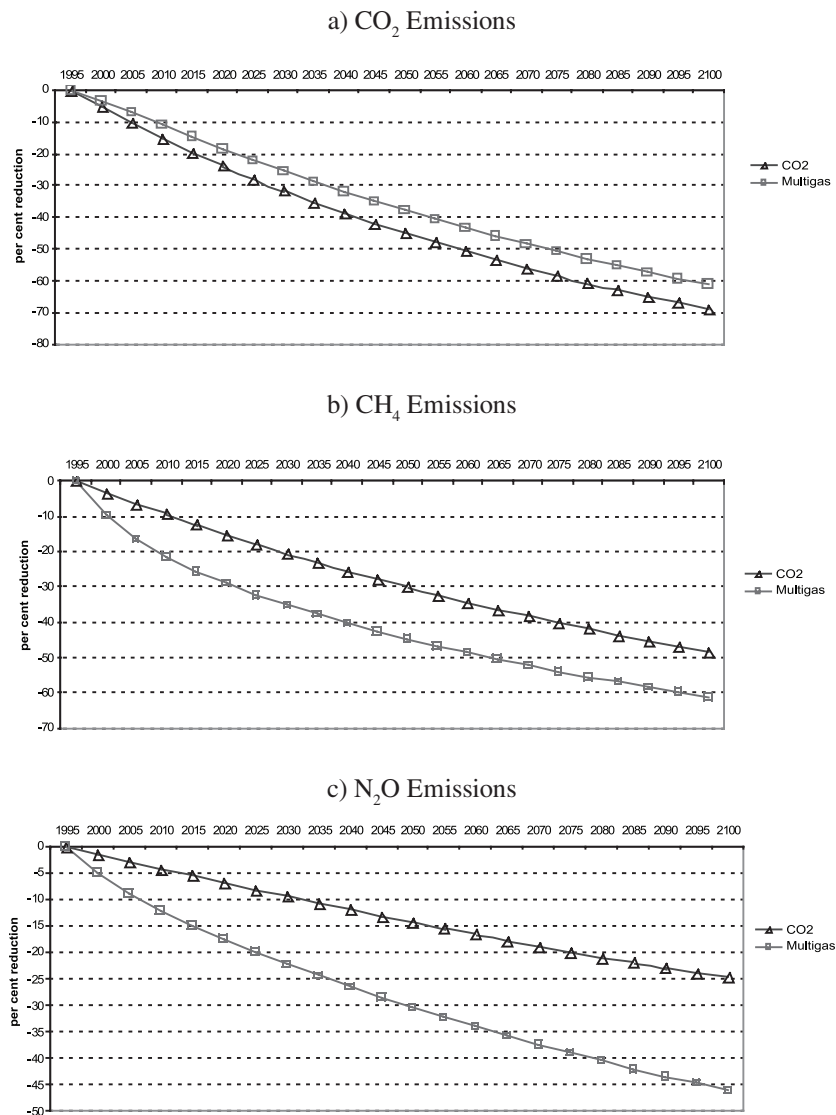
Figure 2. Emissions Trajectories of Different Scenarios

3.2 Sensitivity of the Emissions Results to the Emissions Abatement Elasticities

One important point to note about the emissions paths for various GHGs is that they can be sensitive to the assumptions regarding the values of the abatement elasticities for CH₄ and N₂O as well as assumptions regarding resource growth rates and rates of technological change. In establishing the ‘reference’ scenario for our experiments (from which the CO₂ and the Multi-gas scenarios are then derived), we assume *constant* growth rates for the resource endowments (land, labour, capital and natural resources) over the 100 year period⁷. This

7. The assumed growth rates are: 0.3, 1.0, 1.2, and 1.2 percent per annum respectively for land, labor, capital, and natural resources. These rates are chosen so as to reproduce the reference emission path. The average GDP growth rates generated by these resource endowment growths are on average about 0.85 per cent per annum for all regions, and the average emissions growth rate consistent with these GDP growths is about 1.07 per cent per annum for CO₂, 0.86 per cent per annum for CH₄, and 0.94 per cent per annum for N₂O. These emission growth rates are slightly higher than the GDP growth rate, which implies there is some room for improvements on the rate of emission per GDP, and this is going to be met, partly by the substitution activities following the imposition of the carbon tax, and partly by induced technical change.

Figure 3. Cumulative Emissions Reductions Relative to Reference Case



explains partly for the relatively ‘smooth’ emission growth paths observed in Figure 2. If the resource endowments growth rates (and hence economic activities growth rates) are assumed to be non-uniform over the experimental period, then naturally, the emission growth paths will also be less smooth. Since the main focus of the paper is in investigating the potential contributions of non-CO₂ gases to the overall objective of reaching a particular climate change target in

Figure 4. Cumulative MACs/Carbon Price in US\$ 1995 Per Ton Carbon

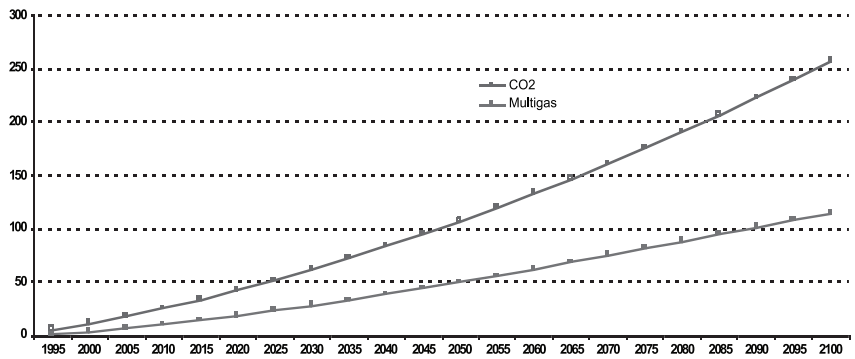
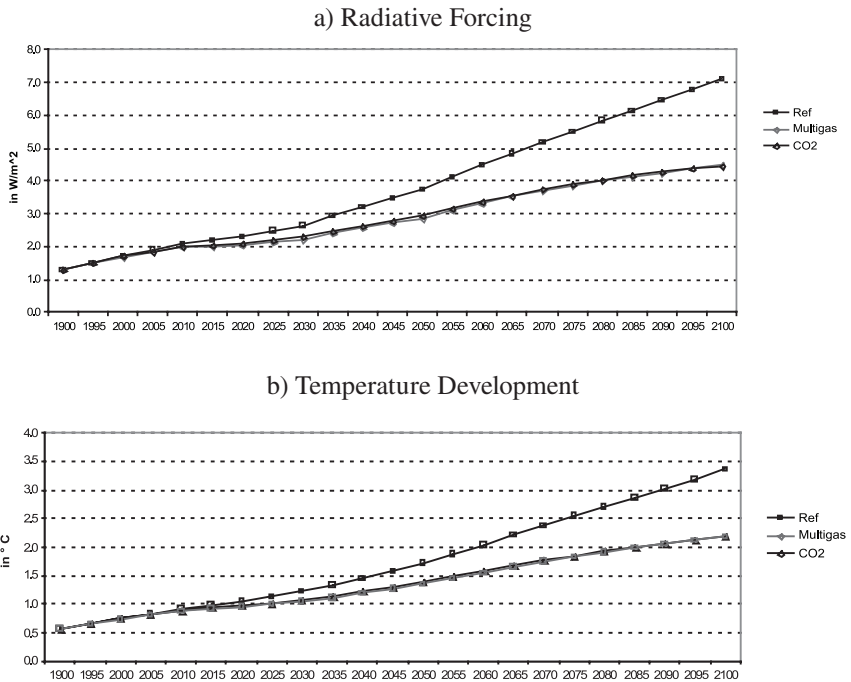


Figure 5. Radiative Forcing and Temperature of Different Scenarios



the final year 2100, the *gaps* in the emission growth paths of the two scenarios (CO_2 alone and Multi-gas) would be more of an interest to us than the shape of the growth paths per se. As a result, although we could have chosen some non-uniform growth rates for the resource endowment growths over the experimental period, we have opted for a simple situation of *constant resource growth* over the

entire period of the experiment⁸, in order to focus on other more important issues. One of these is the question of sensitivity of the emission paths to the assumed abatement elasticities⁹. In choosing the parameters for our experiments, we have chosen these abatement elasticities based on the study by Hyman *et. al* (2002) which are given in Tables 3a, and b.

Table 3a. Values of Substitution Elasticities for CH₄

Sectors\ regions	ASIA	CHN	CAN	EU15	JPN	LSA	Mex	MIDE	REC	RoW	SSA	USA
Rice	0.05	0.05	0.04	0.08	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.05
Crops	0	0	0	0	0	0	0	0	0	0	0	0
Livestock	0.05	0.05	0.04	0.08	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.05
Forestry	0	0	0	0	0	0	0	0	0	0	0	0
Coal	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
OIL	0	0	0	0	0	0	0	0	0	0	0	0
Gas	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
OIL_Pcts	0	0	0	0	0	0	0	0	0	0	0	0
Electricity	0	0	0	0	0	0	0	0	0	0	0	0
Chemicals	0	0	0	0	0	0	0	0	0	0	0	0

Source: Hyman et al. (2002).

Table 3b. Values of Substitution Elasticities for N₂O

Sectors\ regions	ASIA	CHN	CAN	EU15	JPN	LSA	Mex	MIDE	REC	RoW	SSA	USA
Rice	0.02	0.02	0.04	0.04	0.04	0.02	0.02	0.02	0.02	0.02	0.02	0.04
Crops	0.02	0.02	0.04	0.04	0.04	0.02	0.02	0.02	0.02	0.02	0.02	0.04
Livestock	0.02	0.02	0.04	0.04	0.04	0.02	0.02	0.02	0.02	0.02	0.02	0.04
Forestry	0.02	0.02	0.04	0.04	0.04	0.02	0.02	0.02	0.02	0.02	0.02	0.04
Coal	0.02	0.02	0.04	0.04	0.04	0.02	0.02	0.02	0.02	0.02	0.02	0.04
OIL	0.02	0.02	0.04	0.04	0.04	0.02	0.02	0.02	0.02	0.02	0.02	0.04
Gas	0.02	0.02	0.04	0.04	0.04	0.02	0.02	0.02	0.02	0.02	0.02	0.04
OIL_Pcts	0.02	0.02	0.04	0.04	0.04	0.02	0.02	0.02	0.02	0.02	0.02	0.04
Electricity	0.02	0.02	0.04	0.04	0.04	0.02	0.02	0.02	0.02	0.02	0.02	0.04
Chemicals	0.02	0.02	0.04	0.04	0.04	0.02	0.02	0.02	0.02	0.02	0.02	0.04

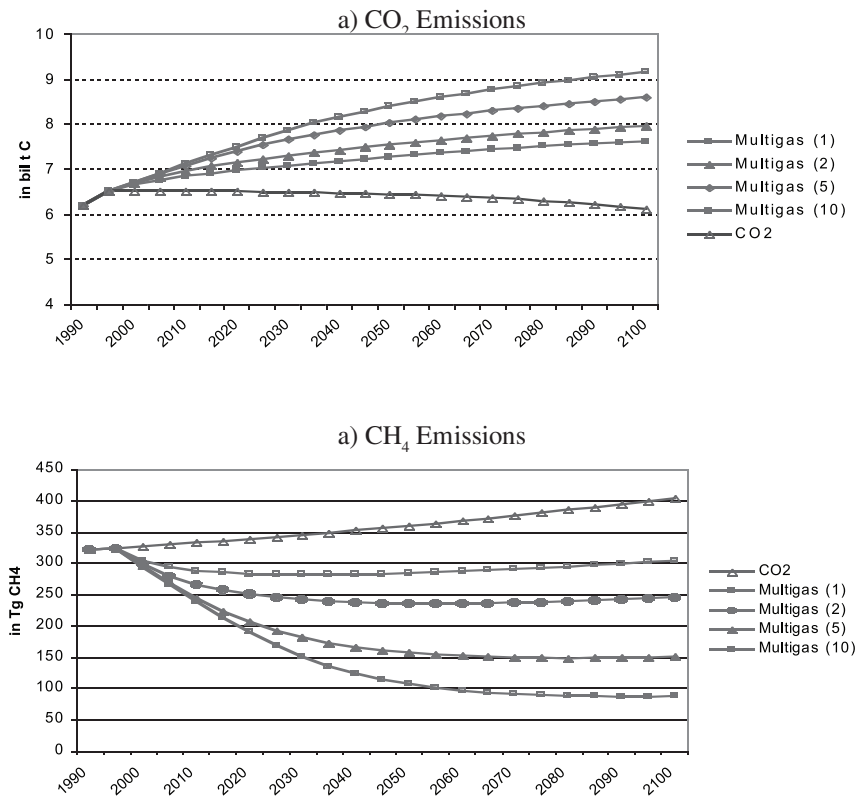
Source: Hyman et al. (2002).

8. Experiments with non-constant growth rates for the resource endowments did not change our main conclusions in any significant sense.

9. The elasticity of substitution between abatement and emission activities.

To test the sensitivity of our results with respect to the values of these substitution parameters, we have repeated the Multi-gas scenario experiments¹⁰ with different values of these abatement elasticities. We call these scenarios Multigas (1), Multigas (2), Multigas (5), and Multigas (10) respectively, which correspond to the cases where these elasticities are 1, 2, 5, and 10 times the benchmark values as given in Tables 3a and b. The results are shown in Figures 6 and 7. It can be seen from these Figures that the shapes of the emission paths (for the Multi-gas case) will be sensitive to the assumed values of the non-CO₂ gas abatement elasticities. This in turn implies the MAC in the Multi-gas scenario is also sensitive to the assumed values of these elasticities, as expected. The greater these elasticities, the greater the contribution of non-CO₂ gases to the achievement of the final target, in terms of a lower abatement cost.

Figure 6. Sensitivity of Emissions Trajectories to CH₄ and N₂O Substitution Elasticities



10. The reference and the CO₂ scenario results are not affected by these substitution elasticities.

Figure 6. Sensitivity of Emissions Trajectories to CH₄ and N₂O Substitution Elasticities

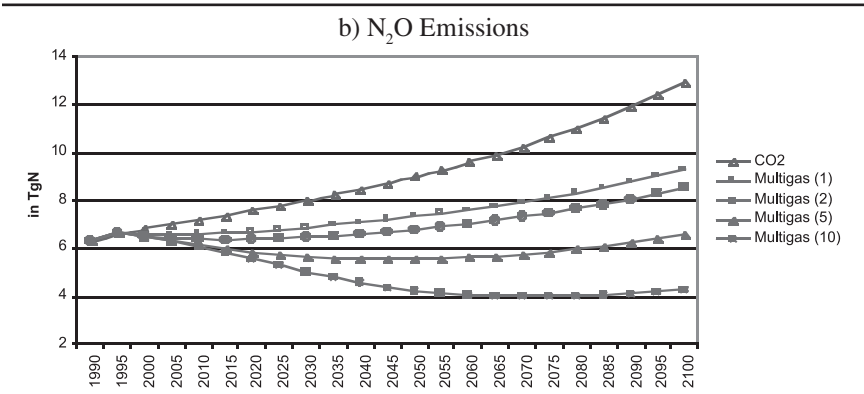
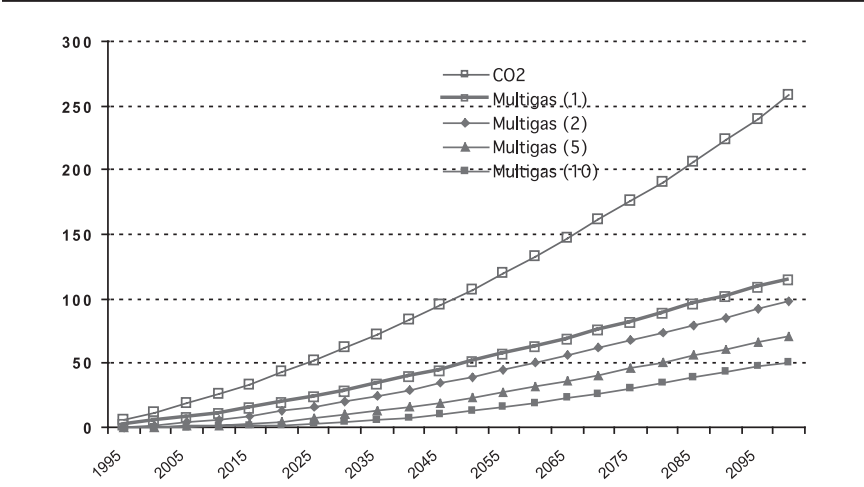


Figure 7. Sensitivity of the Cumulative MACs/Carbon Price with Respect to the Assumed Values of Non-CO₂ Abatement Elasticities



3.3 Economic Effects

Economic efforts to reduce a larger percentage of emissions are higher if we consider only CO₂ emissions and exclude other greenhouse gases. The reason for this is that the inclusion of several gases offers more cost saving opportunities than if we consider only CO₂. A cost minimizing strategy leads to lower permit prices in the case of multi-gas scenario, which in turn also leads to lower production (GDP) losses and lower consumption losses (see Table 4).

We find higher economic losses in terms of GDP mitigation if we only consider CO₂ emissions abatement. Europe and the USA suffer high economic

Table 4. GDP changes (%) from the Reference Case

CON-CO ₂	2010	2050	2100	GDP-Multi Gas	2010	2050	2100
JPN	-3.01	-3.38	-4.07	JPN	-1.38	-2.14	-2.83
CHN	-2.23	-2.74	-3.72	CHN	-1.20	-1.85	-2.10
USA	-3.15	-3.67	-4.02	USA	-1.83	-2.10	-2.49
SSA	-2.09	-2.78	-3.06	SSA	-1.53	-1.85	-2.09
ROW	-1.21	-2.10	-2.53	ROW	-0.56	-1.10	-1.23
CAN	-3.05	-3.76	-4.04	CAN	-1.79	-2.11	-2.53
EU15	-3.98	-4.70	-5.98	EU15	-2.08	-2.81	-3.12
REC	-0.12	-2.25	-4.02	REC	-0.11	-1.13	-2.53
LSA	-2.10	-2.53	-3.08	LSA	-1.13	-1.85	-2.14
ASIA	-2.10	-2.83	-3.77	ASIA	-1.09	-1.85	-2.10
MIDE	-3.08	-4.10	-4.75	MIDE	-1.83	-2.42	-2.79
MEX	-2.10	-2.80	-3.76	MEX	-1.09	-1.85	-2.40

losses because of high abatement costs. These costs are reduced if we consider multi gas emissions reduction options. A pure CO₂ emissions abatement strategy leads to high GDP losses in 2050 and 2100. This results from the fact that meeting the radiative forcing target of 4.5 W/m² leads to significant emissions reductions by 2100. The distribution of regional burden sharing varies over time. Those countries with a very high share of fossil fuel production and consumption have to reduce a substantial amount of CO₂ emissions. Because of substitution and growth assumptions in the model, the share of emissions reduction changes and therefore also economic losses in terms of GDP change. Some developing countries like Asia and China do suffer, not only because of real production cutbacks, but also because of the negative terms of trade effects. Economic losses will be reduced if we consider multi gas options. This is because the economic costs of emission reduction will be lower in this case.

4. CONCLUSION

The main aim of this paper has been to investigate and compare the economic consequences of a pure CO₂ and a multi-gas emission reduction strategy. We have applied a multi-sectoral integrated assessment model WIAGEM based on GTAP-EL coupled with a detailed climate model ICM. The main finding is that a multi-gas mitigation option is a lower cost option leading to a smaller economic burden. Meeting a radiative forcing target of 4.5 W/m² by the end of the model horizon requires a substantial reduction of greenhouse gases. A multi gas reduction strategy leads to a considerable reduction of methane emissions. A pure CO₂ emissions reduction strategy causes significant production and GDP losses in countries with a high share of fossil fuel emissions.

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India's Non-CO₂ GHG Emissions: Development Pathways and Mitigation Flexibility

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This paper analyses the future trends (2000-2030) in Methane and Nitrous Oxide emissions across four scenarios that have been developed for India. The future state of Indian economy in the next 30-years has been broadly visualized under four scenarios proposed as combinations of market integration (extent of liberalization, globalization and integration with the world markets) and nature of governance (centralization vs. decentralization). The methodology chosen for the development of these scenarios draws mainly from the IPCC SRES methodology. The paper presents CH₄ and N₂O emissions for each of the scenarios for all the major emitting sectors. The major sources of Methane emissions are livestock and paddy contributing to about 65% of the total emissions in 2000. The share of emissions from Municipal Solid Waste is also expected to rise with increasing urbanization. Nitrous Oxide emissions arise chiefly from synthetic fertilizer use (contributing 67% of total emissions) and from field burning of agricultural residue. The paper also presents mitigation analysis for CO₂ and CH₄ and long-term, hundred-year analysis for CO₂, CH₄ and N₂O.

1. INTRODUCTION

Traditionally, studies on GHG mitigation have focused on carbon dioxide (CO₂) emissions from energy sources. However each non-CO₂ greenhouse gas is more effective at trapping heat than CO₂. As a result, emissions of these gases contribute significantly to climate change. Global emissions of methane, nitrous oxide, and all of the high GWP gases (including Montreal Protocol Gases such as CFCs and HCFCs, which are not addressed by the UNFCCC) account for approximately 30 percent of the enhanced greenhouse effect since pre-industrial

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times (IPCC 2001). As a contributor to climate change, methane is second only to carbon dioxide. Over the last two centuries, methane concentrations in the atmosphere have more than doubled, largely due to human-related activities.

Indian methane (CH₄) (18.63 Tg) and nitrous oxide (N₂O) emissions (0.31 Tg) in 2000 contributed 27% and 7% respectively to CO₂ equivalent greenhouse gas (GHG) emissions, the remaining being carbon dioxide (CO₂) emissions (928 Tg) (Garg et al., 2003; Garg and Shukla, 2002). The key source categories and main sources for Indian emissions are given in Table 1. Coal (46%) and oil product (15%) consumption together contribute above 60% of the total emissions. The main consumers of these fuels are the industry (including electric power generation) and transport sector. Agriculture, including livestock and other activities, contributes 29%. It is interesting to note that India's GHG emissions are predominantly from urban activities even though the majority of the Indian population (over 70%) live in villages, where agriculture is the main economic activity.

Table 1. Important Contributors to India's CO₂ Equivalent GHG Emissions in 2000

Source categories	Main emissions	Percentage share	Main emission sources
Coal based electricity	CO ₂	29.9	50 large plants
Steel industry	CO ₂	8.8	5 large plants
Cement industry	CO ₂	5.1	50 large plants
Livestock related	CH ₄ , N ₂ O	12.6	Highly dispersed
Paddy cultivation	CH ₄	6.6	Highly dispersed
Biomass consumption	CH ₄ , N ₂ O	5.2	Highly dispersed
Synthetic fertilizer use	N ₂ O	4.1	Highly dispersed
Transport sector	CO ₂	9.5	Highly dispersed and mobile
Waste disposal	CH ₄	3.8	40 large waste dumps
Other sources	CO ₂ , CH ₄ , N ₂ O	14.4	Varied and dispersed
All India (Tg)		1442 ^a	As above

Global warming potentials used for conversion to CO₂ equivalent GHG emissions are CO₂ (1), CH₄ (21) and N₂O (310) as per IPCC (1996).

Source: Garg et al. (2003) and Garg and Shukla (2002).

^a1442=956 (CO₂)+21*18.63(CH₄)+310*0.308 (N₂O), all emissions in Tg.

Many studies have estimated future carbon emissions for India and the related mitigation opportunities (Ghosh et al., 2001; Garg and Shukla, 2002; Nair et al., 2003; Kapshe et al., 2003). However, mitigation flexibility for future Indian CH₄ and N₂O emissions is attracting attention due to the basket of GHG approach and also to utilize the alternate mitigation opportunities for these two gases that offer synergies with sustainable development, especially in developing countries.

A study in Finland has shown that it is profitable to exploit the economic reduction potential of CH₄ and N₂O, and the inclusion of these two gases decreases the annual reduction costs by about 20% in 2010 (Tuhkanen et al. 1999). Innovative technologies offer interesting mitigation opportunities. This paper is an attempt to estimate these trends for India.

2. METHODOLOGY AND SCENARIO DESCRIPTION

The future CH₄ and N₂O emission trends mainly depend upon macro-economic structure, agriculture sector reforms, irrigation development and improved technology penetration. The technology dependence of emissions necessitates disaggregated study of demand and supply projections, environmental performance of various technologies, and detailed assessment of technological progress and future transitions. We, therefore, adopt a bottom-up methodology, which has the modified Enduse component of Asia Pacific Integrated Model (AIM) as the central piece (Kainuma et al., 1999). AIM uses an optimization framework, where total system cost is minimized for each year. Future emission estimation is based on technology shares following the equation;

$$\text{Total emissions} = \sum_{\text{Source}} \sum_{\text{Technology}} (\text{Activity level} * \text{Emission coefficient})$$

This is in line with the recommended Intergovernmental Panel on Climate Change methodology (IPCC, 1996) and follows the same approach as used by Garg et al. (2001).

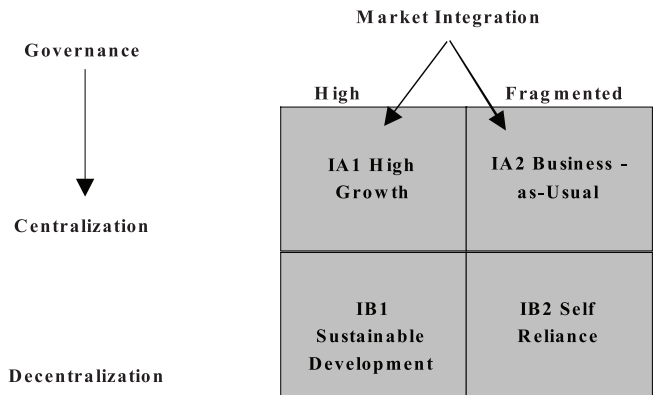
The future CH₄ and N₂O emissions and mitigation flexibility are analyzed for a reference scenario and CH₄ for possible mitigation scenario. The reference scenario reflects the current official policies of the government and forecasts of macro-economic, demographic and agriculture sector indicators. The key driving forces for CH₄ and N₂O emissions projections are economic growth, population (livestock and human), urbanization patterns, land reforms, technological progress and global climate change regimes. Different possible combinations of these key-driving forces would drive the future sectoral technology mix.

2.1 Scenario Description

The future state of the Indian economy in the next 30-years can be broadly visualized under four alternate development pathways proposed as combinations of market integration (extent of liberalization, globalization and integration with the world markets) and nature of governance (centralization vs. decentralization). Market integration can be high on globalization or fragmented to make it more inward looking. Governance could be centralized or with more emphasis on decentralized development. The scenarios are termed as IA1, IA2, IB1 and IB2 (Figure 1). India is currently on a reasonable high-growth path. The economy is

looking to global markets while simultaneously spurred by expanding domestic demands. Market is therefore a critical governing factor. On the other hand, the federal structure of the Indian State, recently initiated reforms in governance at all levels, and continued economic reforms provide the political will for development – thus making governance the other critical driving factor.

Figure 1. Matrix of Indian Emission Scenarios



The four scenarios can be best understood as taking a position in a combination of locus points on the two continuums: extent of market integration and nature of governance. There would be several other scenarios on the continuum, which are also likely but not discussed here, as only the most likely representative sets are presented. One of these, the IA2 scenario comes closest to capturing the existing policy trends and economic dynamics in short to medium-terms and will therefore be referred to as the business-as-usual (BAU) scenario. IA2 considers compounded annual GDP growth of 5.5% over 2000-2030, which is commensurate with current GDP growth trends. IA2 population projections are also in line with the official population projections. This scenario also adheres to the sectoral growth assumptions and projections by various ministries of the Government, and is therefore referred to as the business-as-usual (BAU) scenario.

The storylines differ in factors such as how demographic structure changes with socio-economic conditions, how technological developments and market integration with the global economy drive economic growth, how decentralized economic development activities evolve, and how protection of local and regional environments is implemented. Most of these dynamic forces cannot be defined in strictly quantitative terms. They, however, interact in complex “cause–effect” relationships with quantitative emission drivers (e.g., economic activities and growth, population levels, energy consumption).

There is always the danger of too little differentiation in the scenarios in short to medium-terms, but each storyline has been articulated so that it takes a different direction of future development differing in an increasingly irreversible

way over a longer period of time. The main characteristics of future developments that lead to distinct development paths in the four storylines are

- The extent to which economic liberalization, globalization and increased economic interactions continue over the next three decades
- The rates of national and state-level economic developments and trade patterns in relation to the other characteristics of the storyline
- The nature of the national and regional level demographic developments in relation to the other characteristics of the storyline
- The rates and direction of global and Indian technological change, especially in relation to economic development prospects
- The extent to which national and local environmental concerns shape the direction of future development and environmental controls
- The balance of economic, social, technological, or environmental objectives in the choices made by consumers, governments, enterprises, and other stakeholders.

It is however emphasized here that the IA2 scenario does not represent a preferred or most likely scenario. The analysis is agnostic about the future and all the scenarios are considered equally likely. The three alternate scenarios are called IA1 (high growth), IB1 (sustainable development) and IB2 (self-reliance) (Table 2).

Table 2. Scenarios, Key Drivers and Impact on Model Parameters

Scenario	Key Drivers	Implications on critical parameters of the scenarios and modeling analysis
IA1: High growth	Competition and private participation, Access to global finance and technology, technology R&D, transfer and capacity building, reduced risk perception	Fuel price (↑), technology cost (↓), efficiency (↑), transmission and distribution losses (↓), investment capacity (↑), technology choices (↑), discount rate (↓), earlier penetration of advanced technologies, MSW management (↑), synthetic fertilizer use (↑)
IA2: BAU case	GDP growth, energy efficiency, non-fossil fuels vs. fossil fuels, oil consumption, technological change, movement on the fuel ladder	Sectoral demands (↑↓), investment limits (↑↓), fuel supply (↑↓), range of fossil fuel prices (↑↓), relative fossil fuel price adjustments, efficiencies of technologies using oil and gas
IB1: Sustainable development	Strong environmental awareness and conservationist values, environmental integrity, consumption changes, dematerialization, cooperation, shift away from fossil fuels, local capacity building, rural energy and electricity development	Environmental constraints (↑), energy and materials content of goods/ services (↓), electricity consumption due to efficiency improvements (↓), transmission and distribution losses (↓), penetration of clean and renewable technologies (↑), fossil fuel prices (↑), organic fertilizer use (↑)
IB2: Regional development	GDP growth, population, local emissions, productivity, importance of agriculture, resource intensity, self-reliance	Population growth (↑), sectoral demand (↑↓), investments (↓), penetration of clean and renewable technologies (↑↓), agriculture share (↑), local resource intensive economy, organic fertilizer use (↑)

3. THE REFERENCE (IA2) SCENARIO RESULTS

CO₂ equivalent GHG emissions grow about 2.6 times during 2000-2030, propelled by high CO₂ and N₂O emissions growth. The CO₂ share grows at the expense of CH₄ share, although CH₄ emissions also rise in absolute terms (Table 3).

Table 3. Indian Emission Projections (Tg) IA2

Emissions (Tg)	2000	2010	2020	2030
CO ₂	956	1507	2080	2572
Methane	18.63	20.08	21.73	24.36
N ₂ O	0.308	0.505	0.689	0.807
CO ₂ equivalent GHG ^a	1454	2115	2839	3507

a. Global warming potentials used for conversion to CO₂ equivalent GHG emissions are CO₂ (1), methane (21) and N₂O (310).

3.1 Methane Emissions

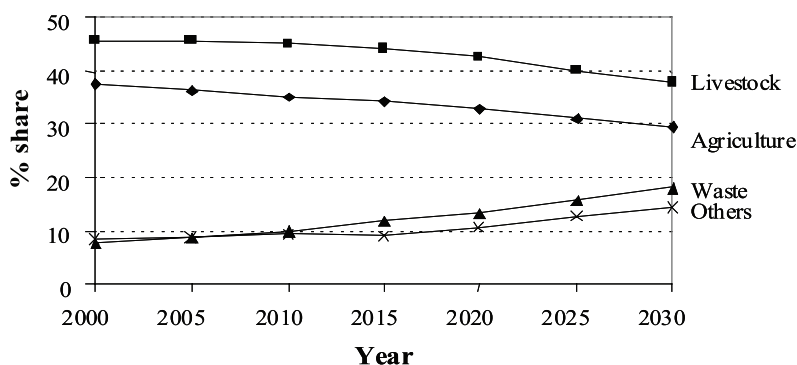
Future CH₄ emissions are shown in Table 4. There is a declining trend for agriculture and livestock related emission shares, while those from waste and coal mining rise gradually (Figure 2).

Table 4. Methane Emission Projections for India under the Reference Scenario

Sources	2000	2010	2020	2030
Agriculture residue	0.10	0.12	0.14	0.16
Biomass consumption	2.91	3.00	3.07	3.11
Coal production	0.72	1.07	1.86	2.89
Oil & natural gas	0.88	0.85	0.50	0.61
Enteric fermentation in animals	7.59	8.04	8.23	8.25
Manure management	0.95	1.00	1.03	1.03
Paddy cultivation	4.00	3.98	3.93	3.87
Municipal solid waste	1.02	1.46	2.30	3.64
Waste water	0.46	0.56	0.67	0.80
Total CH ₄ (Tg)	18.63	20.08	21.73	24.36

3.2 Nitrous Oxide Emissions

Agriculture sector activities account for more than 90% of the total N₂O emissions presently, including 66% from the use of synthetic fertilizers, about 10% each from field burning of agriculture residues and indirect soil emissions, and about 5% from livestock excretions. Use of synthetic fertilizers is the single largest source of N₂O emissions presently and is projected to retain this prominence in future (Table 5).

Figure 2. Changing Contributions for Future Methane Emissions under the Reference Scenario

India consumed 11 Tg of Nitrogen fertilizers in 2000 (FAI 2001). This consumption depends upon the area cultivated and local harvesting practices. The appropriateness and adequacy of fertilizer used can be estimated from food grain production per hectare and fertilizer applied per hectare of gross cropped area. It may however be noted that food grain output depends upon a number of other factors like irrigation, soil, seed variety, pest control etc.

Table 5. Nitrous Oxide Emission Projections for India under the Reference Scenario (Gg)

Sources (Gg)	2000	2010	2020	2030
Coal combustion	9.9	16.8	24.0	28.0
Oil product combustion	2.0	3.6	6.4	10.0
Field burning of agriculture residue	33.9	41.5	42.6	33.4
Biological nitrogen fixation	5.6	6.6	7.8	9.1
Natural gas combustion	0.0	0.0	0.0	0.0
Synthetic fertilizer use	206.1	368.4	524.9	626.8
Livestock	12.2	14.1	16.3	18.8
Industrial processes	12.1	23.0	31.0	38.0
Indirect emissions	26.0	30.7	36.2	42.6
Total N ₂ O (Gg)	307.8	504.6	689.0	806.7

Diverse harvesting practices result in different food grain output per kg of nitrogen fertilizer applied. Analysis indicates that gross food grain production per hectare improves up to a certain level with the quantity of fertilizer applied (FAI 2001). Water availability after fertilizer application plays an important role in reducing N₂O emissions (Kalra and Aggarwal, 1994). Better agriculture practices may result in optimization of synthetic fertilizer use, and further lowering of N₂O emissions. India also uses a lot of organic fertilizers that have much lower N₂O emissions.

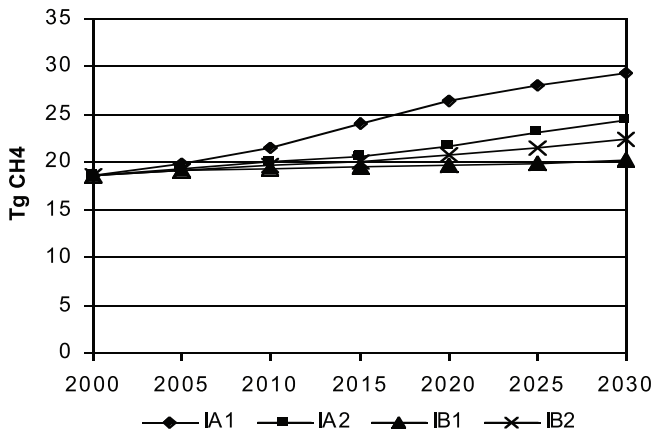
Another important component of N_2O emissions is field burning of agriculture crop residues. The level and extent of the fraction of crop residue that is burnt rather than left on fields in India is a debatable issue. The IPCC default value is 0.45. However, in many parts of the country, farmers preserve agriculture crop residues for feeding their cattle throughout the year. On the other hand, in some advanced and rich states, like Punjab and Haryana, mechanized farming practices are employed that leave almost one-foot high crop residues after harvesting, and these are mostly burnt on the field rather than recovered. However, recent droughts in some states have forced the government to direct these advanced states to provide cattle fodder to the drought prone states. Field burning of agriculture crop residues may therefore be reduced in the future.

4. COMPARING ACROSS SCENARIOS

4.1 Sectoral Methane Emissions under Alternate Scenarios

The future CH_4 emission trends mainly depend upon macro-economic structure, agriculture sector reforms, irrigation development and improved technology penetration. Figure 3 gives the future methane emissions under alternate scenarios. In the BAU (IA2) scenario the emissions increase about one and a half times from about 17 Tg of CH_4 in 2000 to about 25 Tg in 2030. The agriculture sector contributes more than 65% of Indian methane emissions.

Figure 3. Future Methane Emissions under Alternate Scenarios



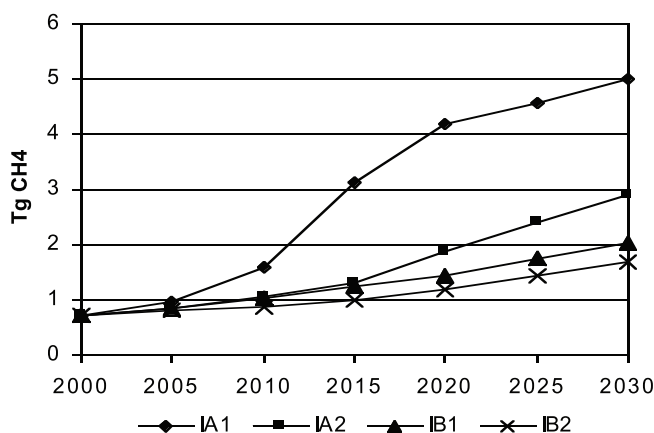
The growth in CH_4 emissions is the highest for the IA1 scenario, which represents the high growth scenario. The emissions increase to about 30 Tg of CH_4 by 2030. The major sectors that contribute to increases in emissions over the base case are the coal-mining sector, livestock and municipal solid waste (MSW). The sustainable development scenario (IB1) has the lowest growth in emissions

mainly due to the increased thrust towards renewable energy sources under this scenario. The sectoral emissions under alternate scenarios are analyzed next.

4.1.1 Coal Mining

In all four scenarios Coal bed methane emissions increase gradually over the years (Figure 4). Initially, the increase is due to the rising level of production mainly from opencast mines, while in later years it is from higher coal production from underground mines as opencast coalmines get exhausted.

Figure 4. Methane Emissions from Coal Mining Across Scenarios



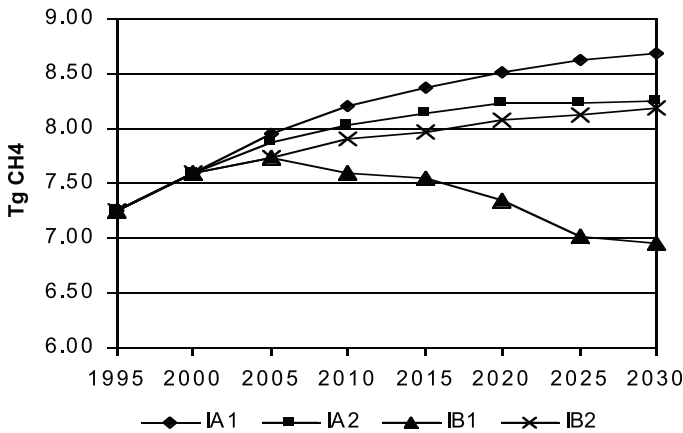
The present economic coal reserves in India are estimated at 76 billion tons, capable of supplying coal for over 100 years at expected demand levels (CMIE Energy, 2004; Garg and Shukla, 2002). As coal demand rises, open cast mining will not be able to meet the requirements and the share of deep coal mining will increase substantially. Higher mechanization is also expected to occur in the future, thereby improving the mine productivity. The growth in emissions is highest in the high growth (IA1) case. The higher growth in the economy leads to greater demand for coal especially in the power sector. This coupled with extraction from deeper mines results in increased domestic coal prices, also prompting increased usage of imported coal (though substitution is not large enough to impact domestic emissions from coal mining). Dependence on underground coal mining results in higher growth in emissions beyond 2015 for scenarios other than the high growth scenario where it occurs at a relatively earlier stage.

Investigation of coal bed methane (CBM) for its commercial exploitation is a comparatively recent development in India and is gaining ground. The government announced in October 2003 that 14 bids for eight blocks had been received under the second round of bidding for CBM exploitation.

4.1.2 Livestock

Almost 90% of methane produced from livestock is from enteric fermentation (Garg et al., 2001). Ruminant animals namely cattle, buffalo, sheep and goats contribute almost the entire methane emissions from this category in India. These emissions steadily increased during the nineties and this trend is expected to continue in all scenarios except the sustainable development scenario (IB1).

Figure 5. Methane Emissions from Livestock Across Scenarios



Following recent trends, the cattle population in the reference scenario is expected to be reduced in many Indian states. However, in cattle sub-categories, there is an increase in crossbred dairy cattle numbers while indigenous cattle population are being reduced. The crossbred dairy cattle have higher per head methane emissions as compared to indigenous cattle. Non-dairy cattle population is also expected to be reduced with an increase in beef consumption and export. In the dairy category, the buffalo share of total milk production in India has increased rapidly (almost 54% in 2000) as compared to about 40% two decades back and this trend is expected to continue. Dairy cattle have the highest methane emissions per head and in this category buffalo related emission coefficients are the highest. Therefore the IA2 trends indicate a marginal increase in methane emissions from enteric fermentation in India even though the livestock population is expected to be decreased.

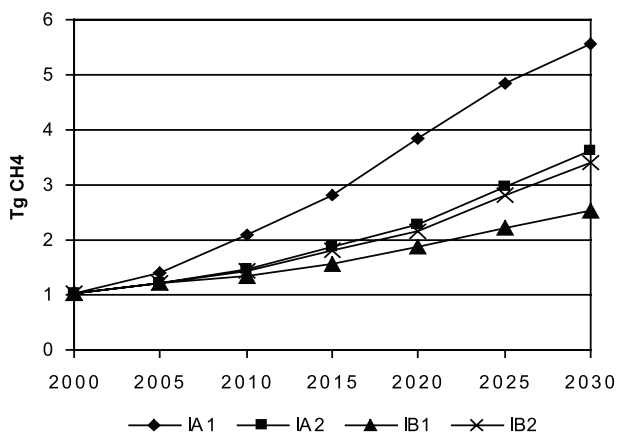
The increasing emissions in the IA1 (Figure 5) scenario results from the high growth in buffalo population required to meet the increasing demand for dairy products. In comparison, the buffalo population decreases, with increase in the population of cows in the IB2 scenario. Though the live stock population does not decrease, emissions from this sector are comparatively lower in the IB2 scenario owing to decreases in the buffalo population.

Livestock feeds in India are not scientifically monitored as they are mostly in the unorganized sector, and agriculture crop residue and common grass form the main animal feeds (Ranjhan, 1993). Mustard oil cakes, (obtained after extracting the oil), are also used by some farmers to add nourishment to animal feed. Improved animal feeds, like Urea Molasses Block (UMB), are slowly being used in some advanced states like Punjab and Gujarat. These coupled with suitable feed digesters; mainly given to enhance milk production, also have the potential to reduce average methane emissions from enteric fermentation. However, due to the large livestock population, lack of awareness and access to improved feed, methane mitigation from this category will require substantial efforts.

4.1.3 Municipal Solid Waste:

The increase in municipal solid waste (MSW) related emissions is due to increasing urban population, higher waste collection and dumping, and deeper waste dumps. These processes increase methane generation rates. Some of these trends are already visible in India and are expected to become stronger in the reference case scenario.

Figure 6. Methane Emissions from MSW Across Scenarios



The highest growth in MSW emissions occurs in the IA1 scenario where the emissions increase about 6 times (Figure 6). This results from the higher growth in the economy and greater urbanization and population living in the urban areas. In both the IA1 and IA2 scenarios there are gradual efforts towards methane recovery from dumpsites. The MSW generation rates in the IA1 scenario are higher than the capture rates and hence the steep growth in emissions. The IB1 scenario however has the best waste management practices and coupled with moderate urbanization and growth in population leads to low emissions from this sector. In the IB2 scenario, waste generation is the lowest. However waste

management and waste to energy conversion technologies are not as developed in the IB1 scenario resulting in larger emissions than the IB1 scenario.

Indian cities are introducing private sector participation in Solid Waste Management. The aim is to attract funding and new technologies for better service delivery. The waste to energy technologies in India include incineration, pelletization and bio-methanation. The incineration plant at Timarpur (Delhi), set up in 1987 using Danish technology, failed to operate properly because the waste fed into the plant did not have sufficient calorific value. In the past cities like Vijayawada, Baroda, Bangalore, Mumbai, and Kalyan tried to set up pelletization facilities. However most of these projects either stalled in development or were eventually shut down due to poor pellet quality. In recent years, there has been much interest in generating power through bio-methanation of MSW. Nagpur, Lucknow, Chennai, Mumbai, Bhopal, and Delhi plan to set up such facilities.

4.1.4 Paddy Cultivation

Methane emissions from paddy cultivation contributed about 21% to the total emissions in the year 2000. In all the scenarios except the IB2 scenario emissions from this sector are expected to decline gradually. Table 6 shows the future emissions from this sector over the next three decades.

Table 6. Future Methane Emissions from Paddy Cultivation Across Scenarios

Year	2000	2010	2020	2030
IA1	4.001	3.964	3.910	3.850
IA2	4.001	3.980	3.930	3.870
IB1	4.001	3.960	3.903	3.840
IB2	4.001	4.016	4.026	4.040

The gradual decline in emissions results from improved irrigation and cultivation practices. Most of these practices involve changing the water management regime to reduce the time over which anaerobic conditions in flooded fields occur, or altering the supplements to the soils to inhibit methanogenesis. These practices are more widespread in the IA1, IA2 and IB1 scenarios. The IA1 scenario adopts the best farming practices, which also includes corporate farm management.

Another major source of methane emissions is biomass consumption. The emissions from this category were about 2.9 Tg CH₄ in the year 2000. This was 16 per cent of the total CH₄ emissions in the country. The emissions are expected to remain stable over the next three decades. While the emissions in the IA1 scenario reach about 3 Tg in 2030, in the IA2 scenario they are slightly higher at about 3.1 Tg of methane. The lower emissions in the IA1 scenario can be attributed to greater and faster penetration of cleaner biomass technologies and switches to cleaner fuels like LPG for residential cooking and heating. The lower

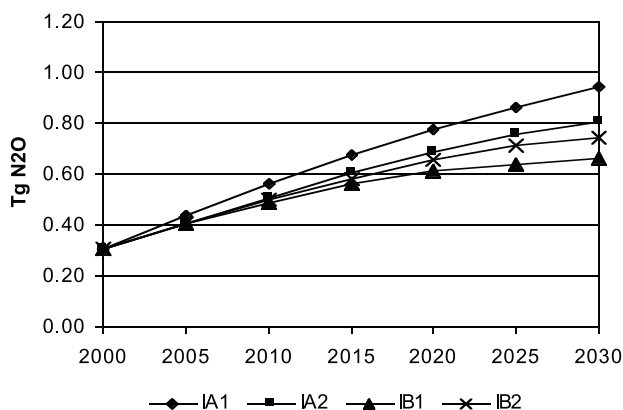
growth in the IB2 scenario ensures that the emissions from this sector remain more or less the same during the thirty-year period. In the IB1 scenario, however, there is a slight decline in emissions, i.e. 2.8 Tg in 2030. This lower emission level results from initiatives to move away from fossil fuels and greater electrification in rural areas.

The other sources of methane emissions include oil and natural gas activities, agriculture residues, manure management and wastewater. These sources together contributed about 13 percent of the total emissions in the year 2000. In the reference case scenario by 2030 the emissions from these sources contribute about 11.5 % of the total emissions. Among these sources the emissions from manure management is the highest in 2030 at about 1 Tg of CH₄.

4.2 Sectoral N₂O Emissions under Alternate Scenarios

The major sectors that contribute to N₂O emissions are the agricultural sector and the industrial processes sector. The sources of emissions in the agriculture sector include use of synthetic fertilizer and the field burning of agricultural residues. The industrial processes include emissions from the production of adipic acid and nitric acid. Figure 7 shows the N₂O emission projections across the scenarios.

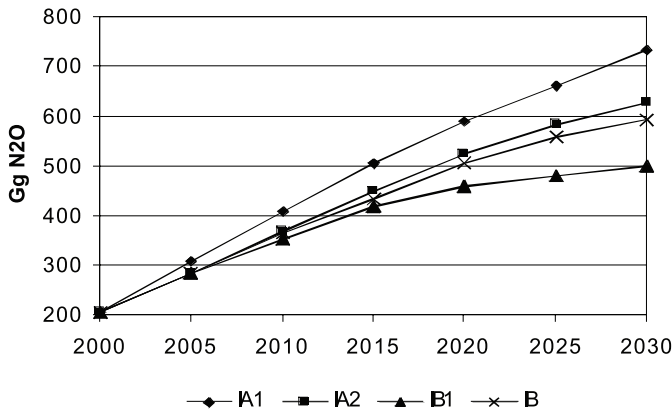
Figure 7. Future Nitrous Oxide Emissions under Alternate Scenarios



4.2.1 Synthetic Fertilizer

Emissions resulting from the use of synthetic fertilizers contribute about 66% of the total N₂O emissions in 2000 (Figure 8). The emissions increase by three times in the reference case scenario and reach 0.63 Tg of N₂O by 2030. The emissions are the lowest in the IB1 scenario owing to the increased use of organic fertilizers.

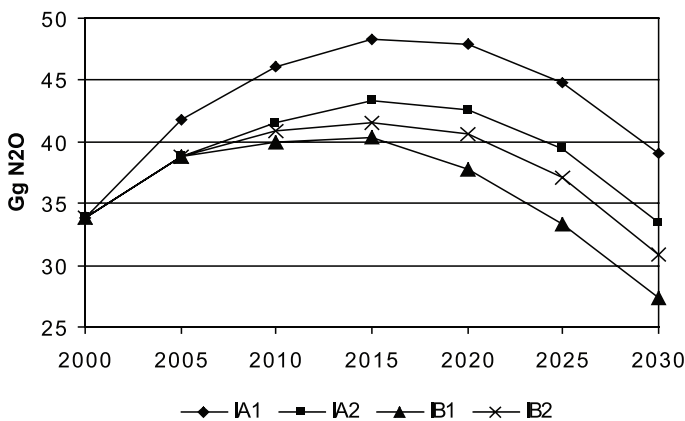
Figure 8. Future Nitrous Oxide Emissions from Synthetic Fertilizer Sector



4.2.2 Field Burning of Agricultural Residues

The second largest contributor to N_2O emissions is the field burning of agricultural residues (Figure 9). However, emissions from this sector do not grow as rapidly as in the synthetic fertilizer sector. In fact, in all four sectors the emissions decline beyond 2015 due to identification of alternate uses of agricultural residues in the future such as incorporation of residues into the soil and offsite uses. Residues not returned to the soil could be used in energy production, as construction materials, in paper and cardboard, as compost and soil additives, as cover for erosion control and landfill, and in several other ways. Currently except for energy production, none of these uses provides a significant market for agricultural residues.

Figure 9. Future N_2O Emissions from Field Burning of Agricultural Residues

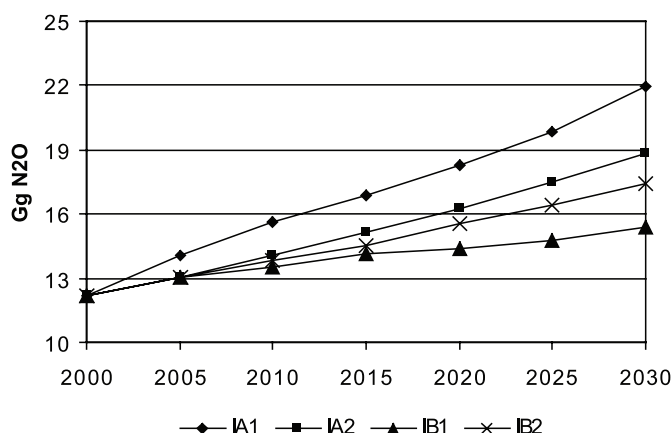


Atmospheric deposition of NH₃ and NO_x (originating from the application of fertilizers) and formation of N₂O in the atmosphere from NH₃ have also been estimated as indirect emissions from nitrogen used in agriculture. These emissions were about 26 Gg in 2000 in the reference case scenario and is expected to grow between 34-40 Gg by 2030 under various scenarios.

4.2.3 Livestock

A majority of the emissions from this sector arise from the grazing animal manure-Nitrogen. These emissions increase about one and half times over 2000-2030 in the IA2 scenario (figure 10). As in the case of methane emissions from the livestock sector, emissions of N₂O are the lowest for the IB1 scenario resulting from a lower buffalo population compared to other scenarios and better dairy management practices.

Figure 10. Future N₂O Emissions from the Livestock Sector

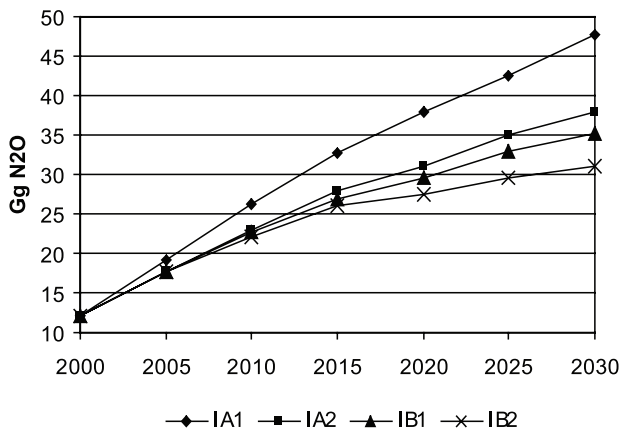


The absence of good dairy management practices in these scenarios, except in IB1, results in higher N₂O emissions.

4.4.4 Industrial Processes

The emissions are chiefly from the production of Nitric acid. The emissions from this sector are therefore correlated with the growth of the economy. The IA1 scenario has the highest emissions while the IB2 scenario has the lowest emissions (Figure 11).

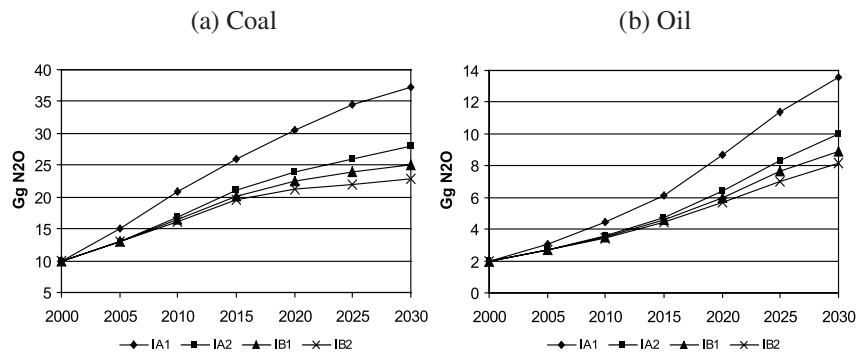
Figure 11. Future N₂O Emissions from Industrial Processes



4.2.5 Fossil Fuel Combustion

The other sources that contribute to N₂O emissions include emissions from coal, oil and natural gas combustion. The emissions from natural gas combustion are negligible. Among the fossil fuels, the emissions are the highest from the coal sector (Figure 12). In the reference case, the emissions from this sector were about 10 Gg of N₂O in year 2000, reaching about 28 Gg in 2030.

Figure 12. N₂O Emissions from Coal and Oil Combustion



The IB2 scenario has the lowest growth in emissions because of the increased thrust towards renewable energy sources, which results in a shift away from coal and oil consumption. The highest growth in emissions from the coal and oil sectors is in the IA1 scenario (figures 12). Higher economic growth results from greater consumption of fossil fuels in this scenario.

5. LONG TERM ANALYSIS

This section presents results of hundred-year projections for CO₂, CH₄ and N₂O emissions for the reference case scenario. The base case storyline construction depends on an understanding of how the energy sector dynamics, specifically the power and transportation sectors for CO₂ and the agricultural sector dynamics for CH₄ and N₂O emissions have been evolving in the past as well as an analysis of the present situation and most likely future trajectories. Each scenario construction incorporates changes in the economic growth rates and structural changes in the economy. The key driving forces for these changes are economic growth, population, domestic energy resource supply, energy prices, local environmental concerns and global climate change regimes. These will drive the future technology-fuel mix for the Indian energy and environment systems.

5.1 Long Term CO₂ Emissions

The CO₂ emissions increase by about six times in the hundred-year period - from 956 million tonnes CO₂ in 2000 to about 6087 million tonnes CO₂ in 2100 under the reference scenario (figure13). A sector wise break up of CO₂ emissions shows the share of the power sector to be the highest, which remains around 45% during the hundred-year period. This is because of the continued dominance of coal technologies in the energy mix. Industry and transport are the next major contributors. Though the share of industry goes down from 32% to about 28%, the share of the transport sector increases from 15% to about 22%. The share of the agriculture and residential & commercial sectors are relatively low compared to other sectors (about 1.5 % and 2 % respectively).

Figure 13. Long Term Carbon Emissions for India

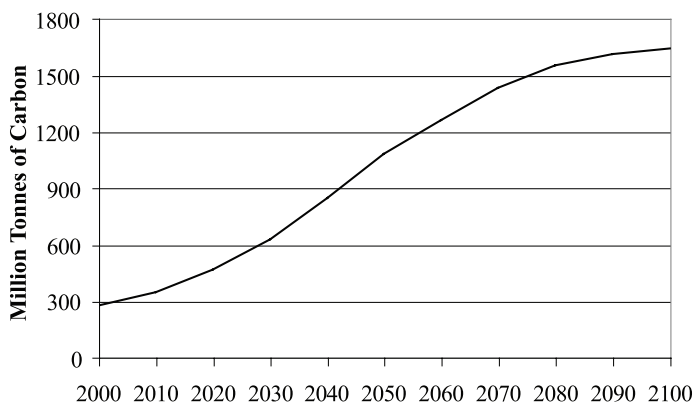
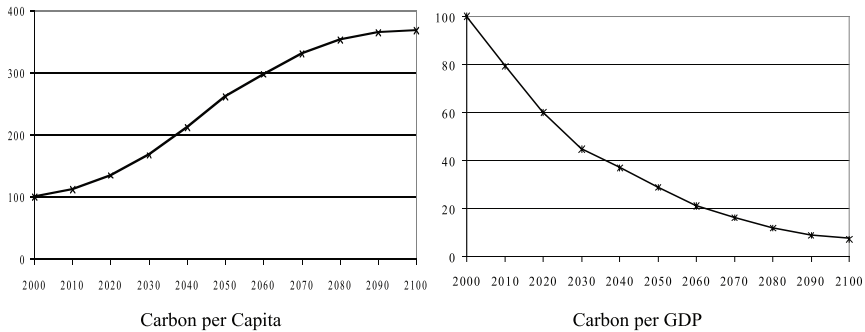


Figure 14. Future Intensity Trends for India (Indexed 2000=100)

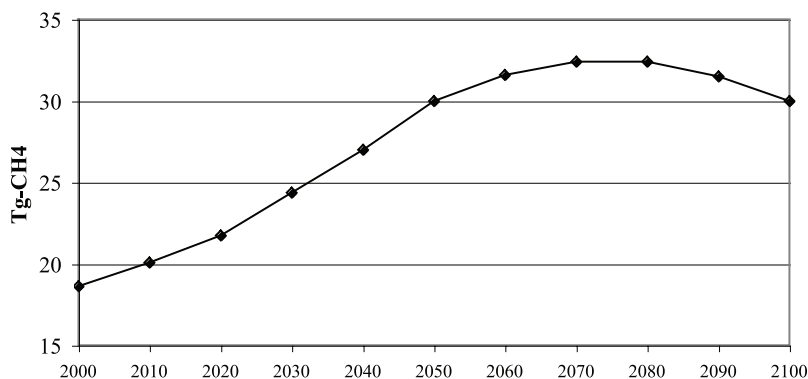
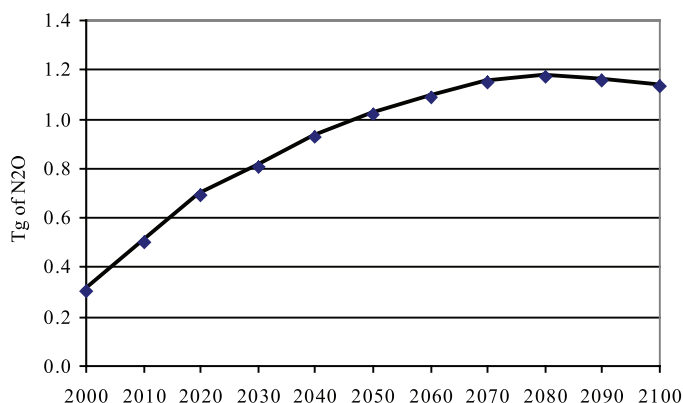
The per capita carbon emissions increases about 3.6 times and reaches 1.01 tonnes of carbon per person by the end of the century (Figure 14). However this is below the present per capita emissions of developed countries and still below the world average per capita emissions as per the majority range of IPCC scenarios (Nakicenovic et al., 2000). The carbon to GDP ratio in 2100 is approximately one tenth of that in 2000. Indian economy becomes carbon efficient. There is decoupling between GDP growth and carbon emissions.

5.2 Long Term CH₄ and N₂O Emissions

Methane emissions are expected to increase steadily during the first half of the present century owing to the dominance of the agricultural sector in the economy. The emissions increase to about 30 Tg of CH₄ in 2050 (figure 15), reach about 32 Tg in 2070 and then decline to 29.4 Tg in 2100 under the reference scenario. The major sources of emissions in 2050 are live stock (contributing about 34% of total methane emissions), paddy cultivation (14%), Municipal Solid Waste sector (22%), and biomass (12%). The percentage of emissions from the paddy cultivation continues to decrease beyond 2050 (from about 22% in 2000 to 10% in 2100) mainly due to the development of better methods of cultivation and the decreasing reliance of the economy on the agricultural sector. It may also be noted that certain methane mitigation policies do become a part of the reference case scenario in the long run.

The contribution of emissions from livestock remains more or less constant beyond 2050. The contribution of emissions from the waste sector is, however, much greater in 2050 compared to 2000 (22% in 2050 as opposed to about 5% in 2000). This is due to increasing urbanization and higher waste disposal in managed dumpsites. However beyond 2050, the contribution remains more or less constant reaching about 20% in 2100.

N₂O emissions increase from about 0.3 Tg in 2000 to about 1.1 Tg by 2060 (Figure 16). The growth in emissions is mainly due to the increasing use of synthetic fertilizer in agriculture. However beyond 2050 as the economy becomes

Figure 15. Long Term CH₄ Emissions for India**Figure 16. Long Term N₂O Emissions for India**

less dependent on the agricultural sector and with increasing use of organic fertilizers, emissions stabilize and beyond 2070 show a declining trend and reach 1.13 Tg by 2100.

The agricultural sector (synthetic fertilizer use, biological N₂ fixation, field burning of agricultural residues) and the livestock sector together contribute about 70% of total N₂O emissions in 2060. However the percentage contribution of this sector is reduced to about 55% in the next forty years, with increasing emissions from the industrial processes sector.

6. MITIGATION OPTIONS

The earlier sections discussed the methane and nitrous oxide emission trends for different growth scenarios. An attempt was also made to analyze

the impact of methane removal processes on the reference case scenario. This analysis was carried out using the AIM/Enduse (India) model, which offers a technology selection framework for analysis of country-level policies related to greenhouse gas emissions mitigation and local air pollution control (Hibino et al 2003). The development of bottom up non-CO₂ gas mitigation options database is based on the framework of AIM/Enduse database. The major source for technical information on removal processes has been EPA reports (USEPA 1999, 2001, 2001a) and consultation with sector experts (see Table 7).

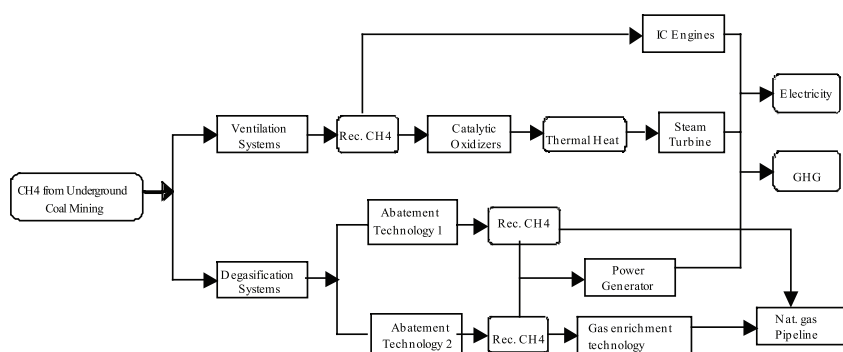
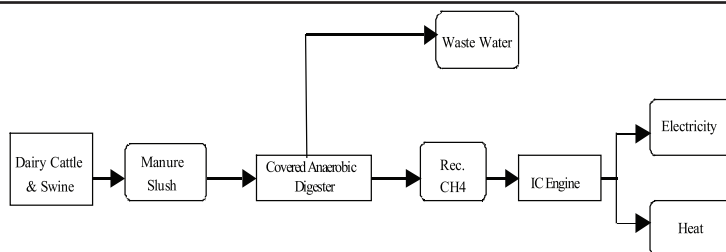
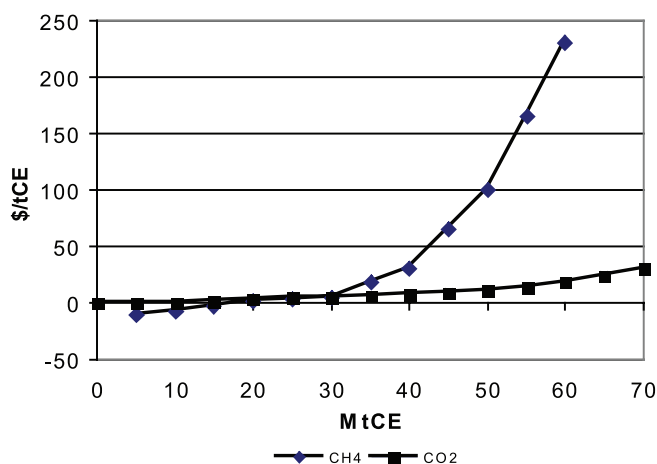
Table 7. Methane Emission Sources and Abatement Technologies Considered for Modeling

Source	Sector	Abatement technologies
Coal Production	Energy – Fugitive Emissions (solids)	Degasification techniques for electricity generation and degasification, ventilation for electricity and oxidizer for heat.
Livestock (manure)	Agriculture	Covered anaerobic digester, plug flow digester, and complete mix digester
Livestock (Enteric)	Agriculture	Partial replacement of roughages with concentrates
Gas production and distribution	Energy- Fugitive Emissions (oil and gas)	Low bleed pneumatic devices and Instrument Air
Paddy	Agriculture- Rice cultivation	Mid season drainage, replace urea with AS and alternate flooding/drainage
Waste Sector	Waste - Solid Waste Disposal on Land	Converting methane to electricity and as a direct source for gas.

As a starting point these linkages are kept simple for modeling purposes. Figures 17 and 18 give examples of the coal and manure management sector linkages with the removal processes as modeled (*Rec. CH₄* indicates *recovered methane*).

Most of the above technologies are under various stages of use and development in developed countries like the US and several of the EU countries. For India, it is assumed that these technologies would become available for application on a large enough scale by 2005. Using the AIM/Enduse (India) model, the Marginal Abatement Cost (MAC) curves for Methane for 2010 illustrates the amount of reductions possible at various values. Methane and CO₂ abatement results are presented together for 2010 in Figure 19.

The above figure illustrates that CH₄ emission reductions can be cost effectively achieved at energy market prices with no additional emission reduction values (i.e. even at \$0/TCE). It is also interesting to note that CH₄ and CO₂ mitigation options will compete till about 5 US\$ per ton of carbon equivalent. Thereafter it is much cheaper to mitigate CO₂ than CH₄. Above \$110/TCE the CH₄ MAC starts to become inelastic. However the development of new mitigation options in the future may result in an increase in cumulative emission reductions at higher levels of taxes.

Figure 17. Emission from Coal Sector and Linkages to Removal Processes**Figure 18. Emission from Manure Management Sector and Linkages to Removal Processes****Figure 19. Marginal Abatement Cost Curves for CH₄ and CO₂ for India in 2010**

7. CONCLUSIONS

This paper highlighted the emission trends of greenhouse gases like CO₂, CH₄ and N₂O in India for short to medium, and long terms. The sector most prominently contributing to total CH₄ and N₂O emissions is the agricultural sector. The present dominance of this sector ensures a steady rise in these emissions under the reference case scenario in the short to medium run. However, a more environmentally conscious society (as depicted by the IB2 scenario) can help reduce the growth in these emissions while not compromising the economic growth. Reducing the growth rates of these emissions depend as much on policy initiatives to move towards a more sustainable society as on the expected declining contribution of the agricultural sector to the country's GDP in the long term. Developing countries like India may also be coupled with competing mitigation options for different greenhouse gases and scarce resources. Policy initiatives to introduce technology options for utilizing gases like methane as an energy source in India can provide much-needed flexibility in the GHG mitigation program.

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Costs Savings of a Flexible Multi-Gas Climate Policy

Asbjørn Aaheim*, Jan S. Fuglestvedt* and Odd Godal**

Current climate policies are based on the use of Global Warming Potentials (GWPs) to compare emissions of various greenhouse gases. Yet, from an economic point of view, more efficient methods exist. We compare the potential costs of implementing some long-term goal for stabilization of the climate in three cases: Reduce CO₂ emissions only, reduce emissions of the four greenhouse gases CO₂, CH₄, N₂O and SF₆ using the standard IPCC GWPs and reduce emissions of the same four gases with efficient and flexible, time dependent metrics. A multi-gas approach with GWPs reduces the costs by 8 percent when compared with CO₂ reductions only, whereas the costs may be reduced by an additional 2 percent if using flexible metrics. If compared with the use of GWPs, we find that efficient weights increase the cost savings of including non-CO₂ gases in climate policy by 15-40%, depending on the stabilization goal.

1. INTRODUCTION

Many of the gases emitted from human activities enhance the greenhouse effect, yet they do so in quite different manners. The responses to a perturbation of some gases, like carbon dioxide (CO₂), lasts for hundreds of years, while for others, like methane (CH₄), the perturbation degrades within a decade or two. When designing policies to stabilize the climate, it is important to ask not only how much the various greenhouse gases (GHGs) should be reduced, but also *when* it should be done.

These questions have puzzled many researchers from different disciplines the last couple of decades. In an attempt to give some guidance to the first question, Lashof and Ahuja (1990) and Rodhe (1990) provided a first order assessment of the

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impact on climate from emissions of the various gases. Building on these studies the Intergovernmental Panel on Climate Change (IPCC) introduced the Global Warming Potential (GWP) index (IPCC, 1990), which later was adopted in the Kyoto Protocol. The index compares the radiative forcing from a pulse emission of a gas integrated over a given time horizon to that of CO₂. Multiplication of the emissions of various non-CO₂ gases by their respective GWP values translate these into a common unit; the so-called “CO₂ equivalents”.

Subsequently, various studies of the importance of the various gases from an economic perspective that recognized the dynamic nature of the climate problem started to appear in the literature. By now, this collection of studies is quite extensive, and they all implicitly or explicitly criticize the GWP approach. The methodology common in these studies is to estimate the optimal mix of abatement of various gases, given some economic criterion. From this, the efficient prices, and hence the efficient gas tradeoffs or weights are derived. Two approaches to this problem prevail in the economic literature. One, which we shall adopt, is the *cost-effective approach*, where some pre-specified climate constraint is taken as given, and costs subject to that constraint are minimized (Eckaus, 1992; Michaelis, 1992; 1999; Aaheim, 1999; Manne and Richels, 2001; and O'Neill, 2003). The other, the so-called *cost-benefit approach*, determines the optimal mix of abatement of various gases based on the balancing of climate damages and abatement costs¹ (see Fuglestad et al., 2003 for an overview of relevant studies).

Two conclusions can be drawn from the economic analyses of efficient greenhouse gas tradeoffs. First, the weights for how emissions of various GHGs could be guided efficiently today may be quite different from those given by the GWP index. However, whether a particular gas is given a weight that is too small or too large in the GWP index seems to depend particularly on the assumptions made in the economic model, where the chosen objective for reducing emissions from a general perspective typically plays a key role. The second finding, which is only evident from those studies solving the intertemporal optimization problem, is that the weights change over time, not only for climatic reasons as is true also for the GWP index, but also for economic reasons. For instance, it follows from Manne and Richels (2001) that if the objective is to stabilize the long-term climate, reducing emissions of methane today is practically worthless from an economic point of view. This is reflected in a weight close to zero for this gas for several of the upcoming decades. Towards the end of the century, however, methane emissions reductions are much more valuable than reflected by the GWP index. However, if the rate of climate change is of greater concern, these results may be at least in part reversed, illustrating the importance of the relationship between how gases can be compared efficiently and what the purpose of emissions reductions generally are.

1. It may be added that the cost-effective approach essentially is a specific case of the cost-benefit approach, namely the one where damages are assumed to be zero below a specific level of climate change, and infinitely high above this level.

It is clear that the use of the GWPs for policy making is fixed for the period of the Kyoto Protocol, 2008-2012. And, even though the Intergovernmental Panel on Climate Change so far has not assessed other more promising ways to compare GHGs (Godal, 2003), that issue may appear on the agenda when designing policies for combating climate change after the year 2012, especially as the principle of comprehensiveness is embedded in the UNFCCC.² Since a wide range of studies conclude that using the GWP index may lead to inefficiencies (Fuglestad et al., 2003), we shall address the following problem:

How Large Could Efficiency Gains Be if GWPs are Replaced by Economically Efficient Weights?

Few studies have addressed this issue. Godal and Fuglestad (2002) examined the effects of using different indices on the composition of least cost abatement of various gases in Norway. The effects were found to be relatively small. However, since the impact on climate beyond emissions in terms of CO₂ equivalents was not modeled, the actual costs of using one particular index as compared to another were not investigated for a more comprehensive climate measure (say radiative forcing or temperature change). Also, due to its limited regional relevance, the study begged for a broader analysis where the costs of using the GWP index could be more properly assessed in a global long-term framework.

This broader analysis was accomplished by O'Neill (2003), who provided a first order estimate of the issue addressed here. The study used a cost-effectiveness framework and included two gases (CO₂ and CH₄), and it was found that the cost of climate policy over the next 100 years was reduced by 2% if the flexible approach was used rather than an approach with fixed GWPs. From this it was concluded that the flexible framework would not substantially decrease the total costs of climate policy for a given constraint on the level of radiative forcing, as compared to a case when the GWPs were used, although it could have a substantial effect on the least cost mix of reductions of the various gases.

We follow O'Neill (2003) in the sense that we apply a cost-effectiveness dynamic framework. Our analysis differs from O'Neill (2003) in several ways. For instance, we do not rely on abatement cost functions for CO₂ that are derived from a computable general equilibrium model, but rather explicitly model the intertemporal production, consumption and investment decisions. We also include additional gases. Together with O'Neill (2003), our analysis may give some guidance to policy makers as to whether or not they would want to implement a different index than GWPs for future climate agreements.

In section 2 we outline the main characteristics of the model. We first spell out the problem of the free, flexible case, and then turn to the additional constraint for the cases when using GWPs and when only CO₂ emissions are

2. According to Article 3.3. "... policies and measures should ... cover all relevant sources, sinks and reservoirs of greenhouse gases..."

targeted. Section 3 provides a brief summary of the choice of functions and parameters. The numerical results appear in section 4, while section 5 discusses some limitations and concludes.

2. MODEL

2.1 A Flexible Multi-Gas Climate Policy

The model is highly stylized, just detailed enough to capture some important features of the issues addressed here. It should be clear from the outset that it is deterministic. There is one global region where households at any time $t \in [0, T]$ derive utility from consuming energy $x_u(t)$ and “other goods” $x_c(t)$. The objective is to maximize the total welfare over the given time horizon, that is,

$$W = \text{Max} \int_{t=0}^T V(x_c(t), x_u(t)) e^{-\delta t} dt, \quad (1)$$

where $V(x_c(t), x_u(t))$ measures the instantaneous welfare at time t , and δ is the consumers' pure rate of time preference.

There are two production sectors, $i = 1, 2$. Sector 2 produces energy – sector 1, other goods (and services). Both sectors demand energy and capital, such that the production function in sector i is given by $f^i(u_i(t), k_i(t))$, where $u_i(t)$ is the use of energy and $k_i(t)$ the use of capital in sector i at time t .

The total capital stock of the economy, $k(t)$, is divided between the two production sectors

$$k(t) = k_1(t) + k_2(t). \quad (2)$$

Capital goods are produced in sector 1, “other goods”, only. In addition to providing capital goods, sector 1 also provides consumption goods, x_c , and input to the abatement of GHG emissions. Denote by a_j the use of products from sector 1 to the abatement of the gas $j = 1, \dots, n$. The growth in the total stock of capital of the economy is then given by

$$\dot{k}(t) = f^1(u_1(t), k_1(t)) - x_c(t) - \sum_{j=1}^n a_j(t). \quad (3)$$

Note that the depreciation term for sectors 1 and 2 is omitted to facilitate the presentation. The differential equation (3) clears the market for “other goods”: The output from this sector is partly spent on consumption and abatement. The remaining is saved and invested to increase the total stock of capital.

Moreover, equilibrium in the energy market requires that at any time t it has to hold that

$$f^2(u_2(t), k_2(t)) = x_u(t) + u_1(t) + u_2(t). \quad (4)$$

Emissions stem from the use of energy.³ Thus, there is an emission coefficient attached to energy use for each greenhouse gas, $j = 1, \dots, n$ which we denote by $b_{i,j} \geq 0$, to account for the fact that the emissions coefficient varies across sectors, i , including households that we denote as sector $i = 3$. The emissions can be reduced by reducing energy use, or by spending amount $a_j(t)$ on direct abatement of gas j . The abatement $a_j(t)$ reduces emissions of gas j by $G^j(a_j(t))$, where $\partial G^j / \partial a_j > 0$ and $\partial^2 G^j / \partial a_j^2 < 0$.

Emissions increase the atmospheric concentrations by the constant β_j . We can then redefine the emission coefficients and the reductions from direct abatement in order to express them in terms of concentrations units to $\beta_{i,j} = \beta_j b_{i,j}$ and $g^j(a_j) = \beta_j G^j(a_j)$, respectively.

For a given flow of emissions of the various gases, the concentration of each gas evolves according to a specific process. For CO_2 ($j = 1$) this is a rather complicated process, which we shall simplify considerably for programming reasons. Hasselmann et al. (1997) provides a simplified representation of results from the more advanced general circulations models, consisting of a weighted sum of five exponential terms with different but constant decay rates. We simplify the relation from Hasselmann et al. further by dividing the CO_2 concentration into two components only. One part, $\psi \in (0,1)$, accumulates totally in the atmosphere, while the remaining part, $(1-\psi)$, declines naturally at the constant rate $1/\tau_j$, $j = 1$, where τ_j is what is usually referred to as the lifetime of gas j .⁴

Thus, the degrading part of the CO_2 concentrations, $S_1^D(t)$, evolves according to

$$\dot{S}_1^D(t) = -\frac{1}{\tau_1} S_1^D(t) + (1-\psi) \left(\beta_{3,1} x_u(t) + \sum_{i=1,2} \beta_{i,1} u_i(t) - g^1(a_1(t)) \right), \quad (5)$$

whereas, the perfectly accumulating part develop according to

$$\dot{S}_1^A(t) = \psi \left(\beta_{3,1} x_u(t) + \sum_{i=1,2} \beta_{i,1} u_i(t) - g^1(a_1(t)) \right), \quad (6)$$

The total amount of CO_2 concentration at any time is therefore given by

$$S_1(t) = S_1^D(t) + S_1^A(t). \quad (7)$$

The concentrations of all the other gases $S_j(t)$, $j = 2, \dots, n$, evolves according to

$$\dot{S}_j(t) = -\frac{1}{\tau_j} S_j(t) + \beta_{3,j} x_u(t) + \sum_{i=1,2} \beta_{i,j} u_i(t) - g^j(a_j(t)), \quad j = 2, \dots, n, \quad (8)$$

which has the same form as the variable part of the CO_2 response (5).

3. The numerical calculations include also exogenous emissions, which we omit in this description.

4. The lifetime of a gas is defined as the time it takes for some amount of concentration to decrease to $1/e$ of its initial level, where $e = 2.718\dots$

By definition, changed concentrations of GHGs contribute to radiative forcing, denoted $\Phi(S_1(t), \dots, S_n(t))$, although in quite different manners. It is therefore convenient to make further specification of the index j . Denote CH_4 by $j = 2$, nitrous oxide (N_2O) by $j = 3$ and sulfur hexafluoride (SF_6) by $j = 4$. We shall restrict our analysis to these four gases.⁵ The relationship between the concentrations of the various gases and the total radiative forcing function is based on IPCC, (2001), that is,

$$\begin{aligned} \Phi(t) = & \alpha_1 \ln(S_1(t)/S_1^0) + (1 + \mu) \alpha_2 (\sqrt{S_2(t)} - \sqrt{S_2^0}) + \alpha_3 (\sqrt{S_3(t)} - \sqrt{S_3^0}) \\ & + \alpha_4 (S_4(t) - S_4^0) \end{aligned} \quad (9)$$

where $\alpha_j, j = 1 \dots 4$, are constant scaling parameters that transform the concentration function of gas j into radiative forcing. $S_j^0 = S_j(0)$ is the initial concentration of gas j , which is year 2000 in the numerical model. The parameter μ , encapsulates what is known as the indirect effects of methane, and is set to 0.3 in accordance with IPCC (2001). The so-called “overlap term” which accounts for the interactions between N_2O and CH_4 on radiative forcing, has thus been omitted here.

Finally, our approach is such that radiative forcing in the last period cannot exceed a specific level $\bar{\Phi}$, that is,

$$\Phi(T) \leq \bar{\Phi}. \quad (10)$$

A more common formulation is to assume that the target should not be exceeded at any instant $t \in [0, T]$. However, to simplify computations, we apply (10). It is worth stating that the only motivation for positive abatement in this optimal control problem is due to the constraint on the level of radiative forcing in year T as given in (10), a so-called transversality condition.

What remains for the specification of the model is a transversality condition for real capital to avoid the stock of capital to be consumed towards the last period. We require that the present value of real capital not be lower in the terminal year $t = T$, than at $t = 0$, that is,

$$r_1(T)K(T) \geq r_1(0)K(0) \quad (11)$$

where $r_1(T)$ is the user price of capital in the terminal year. The user price is endogenous, and (11) can be interpreted as a conditional requirement for

5. CO_2 , CH_4 , and N_2O are currently the main contributors to radiative forcing among the gases targeted in the Kyoto Protocol, and are likely to remain so in the future. We have included the industrial gas SF_6 mainly because of its long life-time, to see how the control of this gas changes when GWPs are replaced by a long-term target on forcing. The contributions to radiative forcing from the remaining gases in the Kyoto Protocol, PFCs and HFCs, are similar to that of SF_6 – i.e. very small. They may, of course, be important for the implementation of climate policy in specific sectors of the economy, and even to a country in some cases. With the world perspective, they may be left out without loss of principal insight.

sustainability, related to the present productivity of the capital stock. The initial quantities of the stock variables, $K(0)$ and $S_j(0)$, including the share of constant and variable concentrations of CO_2 , ψ , are known at $t = 0$. The description of the objective and the constraints is now complete. The solution is given in the Appendix of Aaheim et al. (2004). What follows below is a brief economic interpretation of the optimum conditions.

The conventional condition applies for the household's demand, namely that the marginal utility of energy equals the marginal utility of other goods in equilibrium. The price of "other goods" reflects the marginal private cost of production, while the energy price includes, in addition to the private cost of production, a shadow price on the emissions of households' energy use. This shadow price corresponds to the optimal charge on emissions associated with the energy consumption.

Capital is allocated to the two production sectors under the condition that the marginal productivity of capital is equal in both production sectors at each point in time. The same condition applies for the input of energy and "other goods" to production, but the optimal charge (shadow cost) of the associated emissions is deducted when measuring the productivity of energy use.

The choice between energy savings and direct abatement, a_j , $j = 1, \dots, 4$, is governed by the social cost of emitting gas j . This cost is due solely to the target on radiative forcing in the terminal year, T . Thus, the marginal cost of abatement for a particular gas equals the social cost of greenhouse gas emissions, while the emissions charge on energy use equals the social cost of the composite of emissions from the energy use in each sector of the economy. The marginal abatement cost may, in other words, be interpreted as the efficient emissions charge on the various gases under a tax regime. Also the composition of abatement is governed by the contribution to radiative forcing at T , that is, the last euro spent on abatement is to reduce radiative forcing at T equally much regardless of whether emissions of CO_2 , methane, nitrous oxide or SF_6 is abated.

In essence, the optimal weighting of different greenhouse gas emissions implies that the composition of abatement at each point in time is evaluated from the terminal year $t = T$, and then looking "backwards" to $t = 0$ in order to minimize the total cost of achieving the terminal target as if there was perfect foresight. This leads to an individual abatement profile for each gas, expressed in terms of the optimal rate of increase in the direct abatement cost. This rate of increase can be read out of the intertemporal first-order conditions, which connects the abatement profile directly to the life-time of that gas. A short life-time implies a rapid rate of increase in abatement costs, and if the abatement costs are to increase at a high rate, the initial abatement level will have to be correspondingly low.

Low initial abatement of short-living gases follows intuitively from the fact that early abatement has little impact on the radiative forcing in the terminal year. "Early" abatement of long-lived gases seems, on the other hand, to be relatively more effective, since it may have a notable impact on the radiative forcing also in the terminal year. In addition to the life-time of each gas, the abatement profile

also depends on the curvature of the abatement cost curves for the different gases. The optimal abatement is to be advanced the more strongly curved the abatement cost curve is. In other words, the relative contribution to radiative forcing from two gases is not constant over time, as assumed when using GWP, but must be considered flexible in the sense that it should reflect the dynamic properties of the gas as well as the costs of abatement. Hence, the notation “flexible weights” as opposed to the fixed weights when using GWP in cases studied below.

The consumption-saving decision in the model follows the so-called Ramsey rule (see e.g. Blanchard and Fisher, 1989), which says that at each point in time the rate of social return on investments should be equal to the marginal welfare loss by abstaining from consumption “now”. In technical terms, this welfare loss can be divided into two terms: the pure rate of time preference and the marginal effect on welfare from consumption growth expressed by the intertemporal elasticity of substitution.

In this model, climate policy becomes very focused on the terminal year, which is when the composition of abatement on the different gases is determined. In order to better reflect damages from climate change, one might also impose targets for the rate of change in radiative forcing or temperature change, and indeed several analysts have calculated optimal climate policy with such constraints (see e.g. Michaelis, 1999).

2.2 The Fixed GWP and the CO₂ Control Only Cases

To compare the use of “flexible weights” with the use of GWPs, it is necessary to formalize an additional constraint that encapsulates such a framework. We do this by replacing the optimum condition for the composition of abatement with the constraint that relative marginal abatement cost between the various gases should equal the values of the GWP index at all instances. Then, we have⁶

$$\frac{\partial G^1(a_1(t))/\partial a_1(t)}{\partial G^j(a_j(t))/\partial a_j(t)} = GWP_j \text{ for } j = 2, \dots, n \quad (12)$$

One might interpret the two alternatives as the difference in looking “forward” without knowledge about abatement costs and dynamic properties of various gases in the GWP case, and looking “backwards” from some future point in time and utilizing these properties that we know about today for each gas in the flexible case. Thus, the savings of using flexible weights is the value of this information.

In the “CO₂ control only” case, we simply set the abatement of the other gases exogenously to zero. Recall, however, that the emissions of these gases may still be reduced under emissions targets because of reductions in the energy use.

6. Recall that $G(a_j)$ is the emissions reductions obtained by spending a_j on abatement. Thus the inverse of the abatement cost functions that are more commonplace in the literature.

3. PARAMETERS

The model was calibrated with data for economic activity, energy use, emissions and abatement costs applied on the world total. Data were provided by the Energy Modeling Forum (EMF), and abatement cost data for non-CO₂ gases were provided by the United States Environmental Protection Agency (EPA) through EMF (see Delhotal et al., 2004). Direct abatement costs for CO₂ are very difficult to obtain. The figures used in our numerical analysis must be considered only as qualified guesses. Household consumption was calibrated to a linear expenditure system, and both production sectors are represented by a CES production technology.

In calibrating the model, initial consumption, production and emissions would have to correspond to the optimal solution. The simple structure of the model, plus the constraints on the terminal capital stock and concentrations applied to the world total suggest that the initial optimized level of the control variables may deviate substantially from the observed values. In the numerical model, consumption of non-energy goods exceeded the observed by 8 percent, total energy use by 10 percent and emissions by ± 10 percent for the different gases. Generally, energy use is somewhat overestimated. In order to attain a reasonable level and growth rate for consumption, the pure rate of time preference, δ , was set as low as $\frac{1}{2}$ percent.

The data for the abatement cost functions were adapted by log-linear functions, $g^j(a_j) = A_j a_j^{\theta_j}$, where A_j and θ_j are constants. This functional form did not fit the estimated costs very well for all the gases. For N₂O, in particular, the potential for direct emissions reductions is much larger in the model than indicated by the abatement data, which suggest a very low cost up to 30% reductions, but infinitely high above 40%. The EPA emphasizes, however, the uncertainties in these estimates, especially for non-developed countries. Table 1 provides some of the gas-specific parameters used in the numerical analysis.⁷

Regarding the parameterization of the climate module, we have relied on formulation and values provided by the IPCC (2001), with the exception of the response function for CO₂, as explained in the previous section. We assume that 30% of the CO₂ emissions accumulates totally and that the remaining degrades at an annual rate of 5% (τ_1 is 20 years). How our response function compares to the single lifetime approach often applied in similar optimal control problems (e.g. by Michaelis (1992;1999)) and with the IPCC CO₂ response functions, is shown in Aaheim et al. (2004).

It should be pointed out that we have applied the GWPs reported in IPCC (1996) when these are forced onto the optimization problem, since this is consistent with the GWPs that are to be used in the Kyoto Protocol.

7. Mt are million metric tons; Gt is giga metric ton; C is carbon; N is nitrogen; ppmv, ppbv and pptv are parts per million, billion and trillion volume respectively; yr is year; and USD are United States (2000) dollars.

Table 1. Some Parameter Values*

Parameter	Symbol	CO ₂	CH ₄	N ₂ O	SF ₆
Abatement cost function parameters	A_j	0.6	61.18	0.46	0.0038
	θ_j	0.35	0.23	0.12	0.17
Global Warming Potential	GWP	1	21	310	23 900
Lifetime	τ_j		12	120	3 200
Radiative forcing	α_j	5.35	1.3	0.12	0.52
Initial concentration	S_j^0	368	1 759	316	4.2

* Units are: A_j , θ_j are such that productivity of abatement is measured in terms of GtC, MtCH₄, MtN and MtSF₆ all per trillion USD; GWPs in tonne CH₄, N₂O and SF₆ per tonne CO₂ respectively; lifetimes, τ_j , in years; α_j are such that radiative forcing is given by W/m²; initial concentrations in ppmv (CO₂), ppbv (CH₄ and N₂O) and pptv (SF₆).

The time horizon of our model is 100 years (i.e. it runs to the year 2100), and we have employed a constraint on the level of radiative forcing of 4.5 W/m² as compared to pre-industrial levels. Our numerical analysis considers three different policy scenarios on the no-abatement reference case: The flexible multi-gas case, the fixed GWPs multi-gas case, and CO₂ only case.

4. RESULTS

4.1 Emissions and Radiative Forcing

The optimal emissions trajectories for the two most important gases, CO₂ and CH₄ for the various cases are given below.

Figure 1 yields some intuitive and some surprising results. First of all, and as commonly known, stabilizing the level of radiative forcing to 4.5 W/m² or below requires strong abatement policies towards the last half of the century. As is intuitive, the GWP case allows for more emissions of CO₂ throughout the period as compared to the CO₂-only case. However, in the flexible multi-gas case, the path yields more emissions until around 2090, after which emissions are reduced even below the CO₂ control only case. This is mainly because cutting energy use is also a means of reducing emissions of methane, which turns out to be of great value towards the end of the time horizon. Reductions in the emissions of CO₂ then follow as a consequence.

Figure 2 also contains some surprises and some trivialities. First of all, we see that in the flexible case, the emissions of CH₄ are lower than in the other cases towards the end of the time horizon. This is quite intuitive since the remaining time until the cap is to be met is short, which encourages abatement of short-lived gases such as CH₄. We also observe that the methane emissions are always lower when GWPs are used as compared to a CO₂ control only policy. However, it is interesting to note that methane emissions are reduced quite substantially even in the CO₂ only control scenario when no direct abatement of methane is carried out.

Figure 1. Optimal Emissions Profiles of CO₂ in the Three Policy Scenarios and in the Reference Case

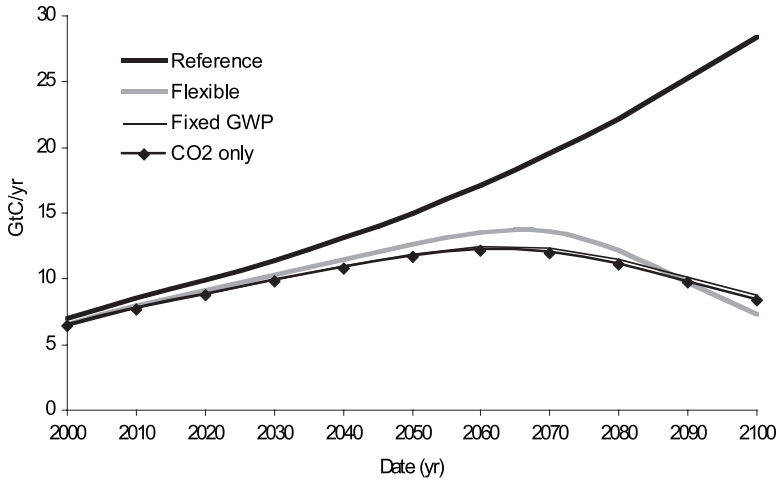
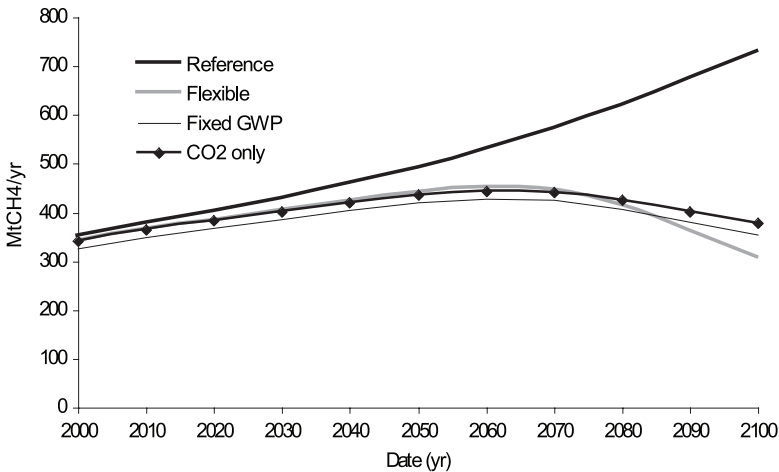
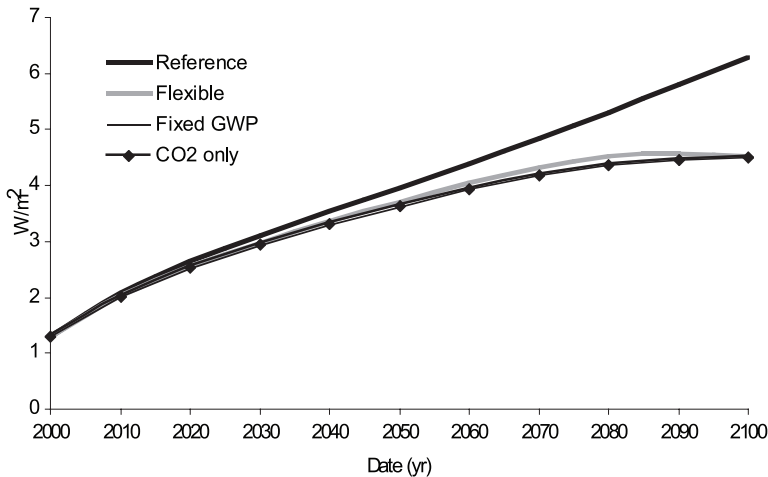


Figure 2. Optimal Emissions Profiles of CH₄ in the Three Policy Scenarios and in the Reference Case



The reason for this is that a large source of methane emissions is related to the use of energy, which is reduced from a CO₂ perspective.

Together with the other gases, these optimal emissions profiles give rise to concentrations, which again contribute to the more relevant and common measure, radiative forcing. In Figure 3, it should be noted that the radiative forcing in the CO₂ only control strategy is almost an exact superimposition of the GWP case.

Figure 3. Development of Radiative Forcing as Compared to the Pre-Industrial Level in the Various Cases

Since the reference case yields a higher level of radiative forcing than the imposed constraint, emissions must be reduced in the various scenarios to satisfy the constraint. The first observation from Figure 3 is that in the fixed GWP and in the CO₂ only cases, the radiative forcing trajectory is below the corresponding flexible one. Basically this means that the flexibility in the tradeoffs between the various gases allows for a higher path.

It is also clear (from the underlying figures) that in the flexible case, radiative forcing slightly exceeds the cap before the terminal year, hence declining in the last decade to meet the target. Had the constraint been applied over the whole time horizon, that would obviously not have been feasible.

4.2 Prices and Flexible Weights

When comparing various climate policies, a common measure used in the literature is the price of carbon. This measure is of course interesting because of the role that activities leading to such emissions play in the production and consumption of key economic goods.

When comparing the development of the carbon prices, we see from Figure 4 that prices are about 20% higher in the GWP case and about 40% higher in the CO₂ control only case, both as compared to the flexible case. Thus, using different approaches towards the multi-gas issue yields quite different results in terms of carbon prices.

How the prices of the non-CO₂ gases compare to that of CO₂ (that is, the flexible weights) and how these compare to GWPs is depicted in Figure 5.

More specifically Figure 5 shows the graphs of the functions $h_j(t)$ given by

Figure 4. The Price of Carbon Emissions in the Three Policy Scenarios

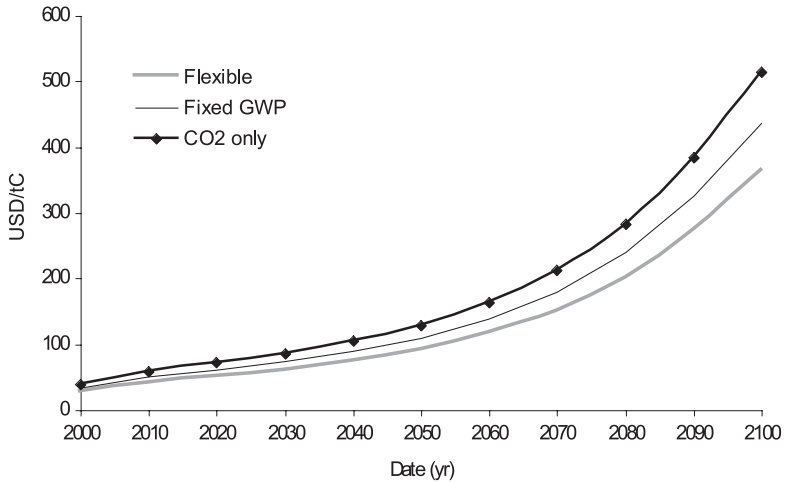
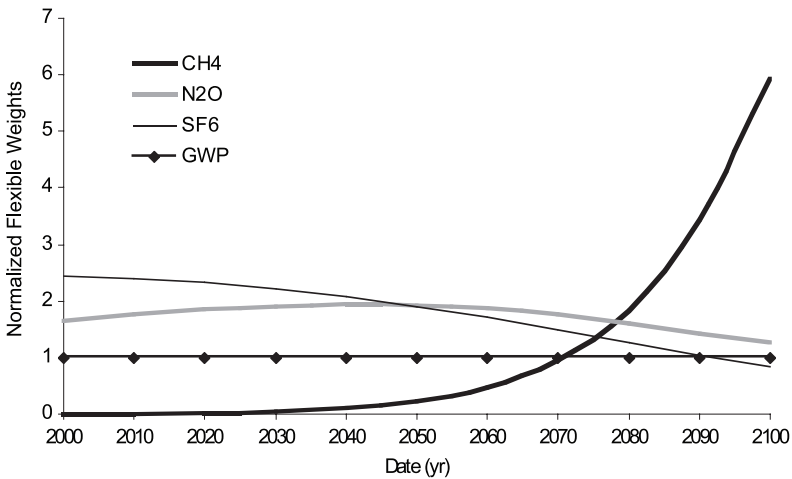


Figure 5. Optimal Flexible Weights Normalized to GWPs



$$h_j(t) = \frac{\partial G^1(a_1(t))/\partial a_1(t)}{\partial G^j(a_j(t))/\partial a_j(t)} \frac{1}{GWP_j} \text{ for } j = 2, 3, 4. \quad (13)$$

evaluated at the optimal path. In words, and recalling that $G^j(a_j(t))$ is the emissions reduction obtained by spending a_j on abating gas j (confer footnote 6), the first part of the right hand side of (13) gives the price of a non- CO_2 gas at each instant in the flexible case, divided by the price of CO_2 (measured per ton CO_2) in the same flexible case for the same instant. We call these optimal weights that could then be used as an index to guide cost-minimizing agents in a quota regime in an

efficient manner. In order to compare with GWPs, the weights were then divided by the GWP value for the gas at hand (recall also that the GWP value for CO_2 by definition equals 1). Hence, Figure 5 gives valuable information in terms of how the efficient prices of the non- CO_2 gases compare both to that of CO_2 and to the GWP value for each of the gases.

We see from Figure 5 that optimal weights would guide the emitting agents towards focusing more on methane later, relative to CO_2 , as compared to the (constant) GWP index. The opposite is true for SF_6 . Our results support the findings of Michaelis (1992) and Manne and Richels (2001) in the case when there is no constraint on the growth rate of radiative forcing.

We also observe that the final optimal weight for methane (compared to CO_2) is about six times higher than the GWP value for methane, the value of each being 125 and 21 respectively. At a first glance the value 125 seems unreasonably high keeping in mind that the instantaneous effect on radiative forcing by methane emissions is well below 100 times that of CO_2 with today's chemical composition of the atmosphere. However, in the terminal year, when we only care for the instantaneous effect on radiative forcing, this composition is significantly different from what it is today. The non-linear relations between concentrations and forcing for these gases, then drives this particular result.

4.3 Welfare Effects

The results presented thus far are well in line with and supports the existing literature, in particular Manne and Richels (2001) and Michaelis (1992). Now, we turn to the issues that motivated this study, namely the welfare effects of using a flexible approach. Or in other words, what are the costs of using the GWP weights compared to a flexible approach in the implementation of a multi-gas policy?

Although changes in welfare is taken care of by the welfare function *per se*, a comparison of the numerical value of W in the different alternatives does not give a good conception as to whether the cost of using GWP is large or small. To provide a more intuitive measure, we compare the alternatives by means of what we call a "constant annual consumption equivalent", or $\bar{x}_c$ for short, defined such that the following holds

$$W^* = \int_{t=2000}^{2100} V(\bar{x}_c, x_u^*(t)) e^{-\delta t} dt, \quad (14)$$

In (14) W^* is the welfare attained by consuming the optimal $x_u^*(t)$ and $x_c^*(t)$. The measure $\bar{x}_c$ is therefore the constant level of consumption over the 100-year period that would give the same total welfare W^* as the total welfare attained by the consumption path in the alternative. Hence, $\bar{x}_c$ varies for the alternative scenarios and is highest in the flexible case.

The figures displayed in Table 2 are calculated on the basis of the constant annual consumption equivalent. From upper part of Table 2, we see that climate policy costs are about 1.5 trillion USD per year, or about 3% of the value

Table 2. The Costs of Climate Policy; and the Cost Savings of Multigas Policy with Fixed GWPs and with Flexible Weights

	Units	Flexible	Fixed GWP	CO ₂ only
Costs of climate policy	Billion USD/yr	1 454	1 488	1 614
	Percent	2.9 %	3.0 %	3.2 %
Cost savings compared to CO ₂ only	Billion USD/yr	160	126	0
	Percent	9.9 %	7.8 %	0.0 %

of the constant annual consumption equivalent in the reference case. Most of these costs occur towards the last half of the century, since that is when the major cuts in emissions take place.

If we use the CO₂ only case as a basis for comparison, the cost savings of the two alternative policies are as shown in the lower part of Table 2. When including the non-CO₂ gases, costs decrease with about 126 billion USD per year as compared to the CO₂ only case, which is about 7.8% of the costs of climate policy when only CO₂ be targeted. When flexible weights are applied, costs fall by about 160 billion USD per year as compared to the CO₂ only case. Hence the additional cost savings of applying flexible weights rather than using GWPs amount to $160 - 126 = 34$ billion USD per year. In other words, the cost savings that stem from including non-CO₂ gases may be increased by $34/126 = 27\%$ if using flexible weights.

4.4 Two Alternative Scenarios

We also solved a slightly modified model under the hypothesis that radiative forcing could not exceed 5.3 and 3.9 W/m² as compared to pre-industrial levels rather than the 4.5 W/m² simulation discussed above. We found that the cost savings of using flexible weights rather than fixed GWPs were 16 and 106 billion USD per year for the two cases respectively. Moreover, the cost savings of a multigas approach using GWPs as compared to a CO₂ only strategy, were increased by 15 and 40% respectively, if applying flexible weights. Hence, it appears as the more ambitious the climate policy chosen, the more important becomes the choice of method to compare GHGs, which seems quite reasonable.⁸

5. SOME LIMITATIONS AND CONCLUDING REMARKS

We have compared a climate policy that is flexible in terms of the timing and abatement of the various GHGs with two alternatives: climate policies that use fixed GWPs, and targeting CO₂ emissions only. It is clear that the study has evident general shortcomings, as any deterministic model forecasting climate and

8. For more detailed description of the results on the alternative scenarios, see Aaheim et al. (2004).

economic activities a hundred years into the future would have. In particular, the motivation for mitigating emissions given by constraining radiative forcing in the year 2100 cannot be claimed to be a very realistic representation of the climate problem. It is also clear that more detailed numerical models exist, models that include more gases, sources and sinks, have a better description of the economic and climate system, and so on. We think, however, that the main characteristics for optimal policy following a shift from fixed to flexible weights of greenhouse gas emissions is captured in the simple model applied here.

Some more specific areas of improvement to the current analysis deserve attention. First, in the cause-effect chain from emissions to climate change and impacts, we stopped at radiative forcing. Moving on to temperature would make sense, but adds complexity to programming significantly. Second, we assumed that the GWPs used in the non-flexible case remained fixed throughout the period. Since GWPs depend on the composition of the atmosphere, these values are likely to change for chemical and radiative (not economic) reasons that will be reflected in updates in the literature and by the IPCC. Such scenario-dependent changes were ignored. The important choice of the time horizon was somewhat arbitrary and may be seen as a compromise between the time scales of the climate system and those of meaningful long-term economic forecasting. Lastly, no constraint on the rate of change of radiative forcing was applied. Other studies show that if the objective is to slow the rate of change in the near term, short-lived gases like methane could play an important role at the beginning of the period. The weight to assign to emissions of short-lived gases under the flexible alternative very much depend on these assumptions. To some extent, it might be correct to claim that flexible weights solve the problem of choosing time horizon for the calculation of GWPs, but creates the problem of choosing a time frame for the comprehensive analysis.

Given our approach, two conclusions from the numerical simulations deserve particular mention. First, CO₂ is the main problem. By including non-CO₂ gases and using GWPs, the costs of climate policy decrease only by around 8%. Second, the additional cost savings from the flexible refinement as compared to using fixed GWPs is about 2%, which is very similar to what reported by O'Neill (2003). In monetary terms, this amounts to somewhere in the range of 16 to 106 billion USD per year (on a global basis) depending on the level of the climate constraint. Hence, although most cost savings that stem from including non-CO₂ greenhouse gases in climate policy are realized through the use of GWPs, these gains may be further increased by somewhere in the range of 15-40% if applying flexible weights rather than GWPs.

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The Role of Non-CO₂ GHGs in Climate Policy: Analysis Using the MIT IGSM

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First steps toward a broad climate agreement, such as the Kyoto Protocol, have focused on less than global geographic coverage. We consider instead a policy that is less comprehensive in term of greenhouse gases (GHGs), including only the non-CO₂ GHGs, but is geographically comprehensive. Abating non-CO₂ GHGs may be seen as less of a threat to economic development and therefore it may be possible to involve developing countries in such a policy even though they have resisted limits on CO₂ emissions. The policy we consider involves a GHG price of about \$15 per ton carbon-equivalent (tce) levied only on the non-CO₂ GHGs and held at that level through the century. We estimate that such a policy would reduce the global mean surface temperature in 2100 by about 0.55° C; if only methane is covered that alone would achieve a reduction of 0.3° to 0.4° C. We estimate the Kyoto Protocol in its current form would achieve a 0.25° C reduction in 2100 if Parties to it maintained it as is through the century. Furthermore, we estimate the costs of the non-CO₂ policies to be a small fraction of the Kyoto policy. Whether as a next step to expand the Kyoto Protocol, or as a separate initiative running parallel to it, the world could well make substantial progress on limiting climate change by pursuing an agreement to abate the low cost non-CO₂ GHGs. The results suggest that it would be useful to proceed on global abatement of non-CO₂ GHGs so that lack of progress on negotiations to limit CO₂ does not allow these abatement opportunities to slip away.

1. INTRODUCTION

It seems unlikely that the world will soon negotiate a comprehensive global agreement to abate all greenhouse gases (GHGs). First steps toward a broader agreement, such as the Kyoto Protocol, have focused on less than

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global geographic coverage. A notable exception was a proposal by Hansen et al. (2000) that focused on scenarios of global abatement of methane and black carbon emissions but included no formal economic analysis. In this paper we examine less than comprehensive coverage of the significant GHGs but consider that it may be possible to achieve global geographic coverage. We examine the implications of leaving CO₂ out of a global cap, as CO₂ emissions are arguably the most expensive to reduce substantially of all the major GHGs. We suppose a modest policy with a GHG price of about \$15 per ton carbon-equivalent (tce) throughout the century, and we look at the resulting emissions reductions and their implications for climate change and economic welfare. We compare that to what we would get if we had a comprehensive cap including CO₂, at that same price, and to the climate benefits of the Kyoto Protocol in its current form, assuming its current participants would hold to the Protocol's caps through 2100. The simulation experiments are not meant to suggest that this is all that should be done to reduce GHGs over the next century, or that CO₂ from fossil energy should be ignored. Our intent is to show what we can get in terms of climate change mitigation benefit if it is possible to achieve nearly global coverage of the non-CO₂ gases. Broader negotiations on climate change currently appear stalemated and in the meantime it may be worthwhile to at least pursue an agreement to limit the non-CO₂ GHGs. We use the MIT Integrated Global System Model (IGSM) for this analysis.

The next section provides a brief discussion of the past and future contribution of the non-CO₂ GHGs. In section III we discuss briefly the case for a non-comprehensive GHG cap, and why there may be more room for global agreement on non-CO₂ GHGs than on CO₂. Section IV describes the MIT IGSM that we use to simulate these scenarios, focusing our attention on the Emissions Prediction and Policy Analysis (EPPA) component as it is key to the economic policy results we present. Section V describes the specific scenarios and results, and Section VI offers our overall conclusions.

2. PAST AND FUTURE CONTRIBUTIONS OF NON- CO₂ GHGS

Among the greenhouse gases, methane (CH₄) is the most important direct anthropogenic source of increased radiative forcing after CO₂. The Intergovernmental Panel on Climate Change (IPCC) estimated its contribution to increased radiative forcing between 1750 to 2000 to be 0.48 watts per meter squared (Wm⁻²), nearly 1/3 the contribution from CO₂ (Ramaswamy et al., 2001). These calculations do not include the full contribution of CH₄. One product of CH₄ oxidation in the atmosphere is CO₂, and so part of the CO₂ increase, albeit a small part, is the result of oxidation of methane. CH₄ is also a contributor to tropospheric ozone (O₃) formation, which also is a warming gas. The IPCC estimated that increases in tropospheric O₃ between 1750 and 2000 contributed 0.35± 0.15 Wm⁻². CH₄ is likely not the most important contributor to past increases in O₃, and clearly identifying its contribution is difficult because the chemistry of O₃

formation in the troposphere is complex and non-linear in precursor emissions.

Existing projections suggest that the relative contribution of CH₄ to radiative forcing may decrease somewhat in the future. Webster et al. (2003) estimated that CH₄ might contribute another 0.6 (-0.17 to 1.71) Wm⁻² of radiative forcing by 2100 (95% error bars in parentheses), compared to an additional forcing from CO₂ of 4.2 (2.1 to 7.5) Wm⁻². At the median values the additional CH₄ contribution drops to about 15% of CO₂, from the historical share of 1/3. CO₂ and CH₄ are produced, in part, by the related processes (fossil fuel production) and in part by separate processes (e.g., agriculture, biomass burning, land fills and other waste disposal) and CH₄ emissions from both fossil and non-fossil sources are subject to uncertainties independent from those affecting CO₂ emissions (Webster et al. 2002). Thus, low and high levels of the two gases are correlated to some degree but it is possible to have relatively high levels of CH₄ and low levels of CO₂. This work can thus not rule out cases where the CH₄ contribution remains high or even increases relative to CO₂.

The historical contribution of nitrous oxide (N₂O), hydrofluorocarbons (HFCs), sulfur hexafluoride (SF₆), and perfluorocarbons (PFCs) together are on the order of CH₄ (Ramaswamy et al., 2001). Much of the historical forcing is due to the CFCs, whose emissions have largely been phased out because of their ozone depleting effects. HFCs have been rapidly replacing them. PFC use was growing rapidly because of its use in computer chip manufacture, but more recently has slowed. The mix of these substances, and the source of them, has changed dramatically in the past decade or so, and could change further still in the future (Reilly et al., 1999; US EPA 1999, 2001a,b,c; Reilly et al. 2000; Mayer, et al., 2001; Reilly et al., 2002; Reilly et al. 2003). Forecasts are highly uncertain (Harnisch, et al., 2000; Mayer et al., 2001), in part, because these new chemicals may find new uses. As the automobile fleet continues to grow, particularly in tropical developing countries, HFC use in mobile air conditioning could grow dramatically. As the climate effects of these substances have become more widely known, some firms are already taking actions to prevent the release of the substances, to recycle them, or to switch to those with less powerful effects on climate. In some cases, the potential development of new products and new uses for them is being shelved, recognizing that the investment in development may not be worth it if soon after introduction a climate agreement would mean they would need to be phased out. All of this adds to uncertainty. A true “no-policy” case, ignoring actions that already appear to be built into decisions because of the expectation of climate policy, can lead to very large projections of industrial GHG emissions (US EPA, 2001b). These considerations add further to uncertainty and make it difficult to establish a true no-policy reference. Webster et al. (2003) estimated the additional contribution from N₂O by 2100 to be 0.50 (0.16 to 1.0) Wm⁻² and the combined additional forcing from PFCs, SF₆, and HFC to be 0.34 (0.27 to 0.54) Wm⁻². Even though emissions are more uncertain for these substances than for methane, there is somewhat less uncertainty in their atmospheric concentrations because of their very long lifetimes.

3. POLICY CONSIDERATIONS

Global climate policy is currently at a stalemate. The Kyoto Protocol may or may not enter into force, and in any case the US, the world's largest emitter of GHGs, is not part of it, nor do developing countries such as India and China have commitments under the Protocol. The Protocol had many features that in principle made it desirable from a cost-effectiveness standpoint. It started with more or less comprehensive inclusion of GHGs¹ and it allowed emissions trading (UNFCCC, 1997) which under some conditions can lead to efficient reductions among different substances and different regions.² But the fact that it did not include all regions meant that, at best, emissions trading could equalize marginal cost among the participating countries but not between developed and developing countries, except to the extent the Clean Development Mechanism (CDM) could work. Experience has shown that crediting features of cap and trade systems, of which CDM is an example, are usually not very effective at getting reductions from the creditable sources. These credit systems get bogged down in the bureaucracy of defining the baseline against which a credit is allowed. So while there was much effort at including market mechanisms in the Protocol that would reduce the cost of achieving its targets, the problem it could not overcome was limited regional coverage. It started with relatively deep cuts in developed countries and no cuts in developing countries, and so the cost-effectiveness within the capped countries was destroyed by the lack of geographical comprehensiveness. Now that the US has withdrawn from Kyoto, the cap is far less binding if all of the flexibility mechanisms are used, and in that case the cuts look not deep at all, and if achieved cost effectively most of the reductions in the first commitment period would likely come from reductions of non-CO₂ GHGs (Babiker, et al. 2002). The Protocol was intended to be only a start toward a comprehensive policy, and any inefficiency of narrow regional coverage would decrease if more regions gradually joined as planned.

If Kyoto doesn't get very far, or we look for ways to expand its coverage, is there another way to make a start on climate policy rather than a gradual regional expansion? The Kyoto Protocol approach imagines more countries joining and accepting a comprehensive GHG cap. This is unlikely to be cost effective for many years because it will continue to have a price gap between those under a cap, and those not yet capped. While the Kyoto cap is not a very deep cut in the first commitment period, it likely will gradually become tighter with economic growth in the participating countries. Efficiency of the trading mechanism will be gradually compromised if the Protocol is unable to get other big emitters to join. Cost effectiveness would go for the least costly reductions first, and only tackle the

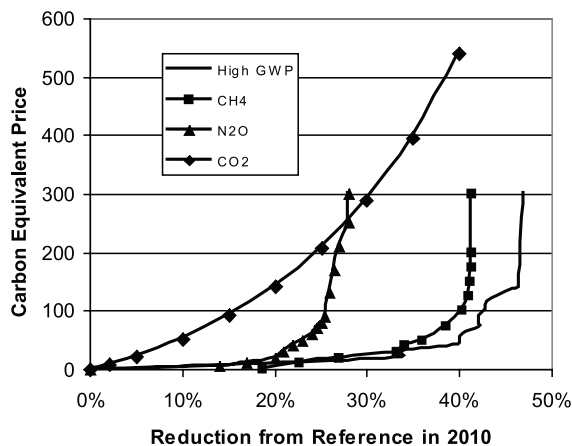
1. Although it did not include tropospheric ozone or aerosols that also have important effects on the radiative balance of the atmosphere, and it also limited the contribution from sinks. Including these specifically within the GWP weighted caps presents some difficult problems, see Reilly et al. 2003.

2. Babiker et al., 2004 show that given existing tax distortions in energy markets, emissions trading can easily increase the economic cost of a policy compared to the case without emissions trading.

more costly reductions as needed. One of the most important results of analyses of the non-CO₂ GHGs abatement possibilities is that considerable reductions can be achieved at a quite low cost per ton of carbon equivalent. Figure 1 illustrates the broad picture for these gases by showing, in percentage terms, the reductions that can be achieved for a given cost/tce (using 100-year Global Warming Potential indices to convert to carbon equivalent). Figure 1 shows abatement curves for the US, but the picture is not vastly different for other countries. The implication of this basic picture is that in the first-step of comprehensive and cap and trade scenarios, a disproportionate amount of the reductions come from the non-CO₂ GHGs. For example, Hyman et al., 2003 show that with a cap of 10% below a 2010 reference for all GHGs including CO₂, the non-CO₂ GHGs make up 30 to 70 percent across countries of the cost effective reduction in 2010 which is far above their share of emissions.

Of course it would be desirable to have a comprehensive cap on all substances set at just the right level, but that has proved politically infeasible. The above reasoning suggests, however, that if we could get agreement on the non-CO₂ gases we would get the majority of the most cost effective reductions that a modest comprehensive cap would get. Therefore, if a comprehensive cap is infeasible, leaving out CO₂ initially might be a reasonable start to a policy that would not lead to excessive cost inefficiency. Why might it be possible to get global agreement on the non-CO₂ GHGs when it has been impossible to get such agreement on CO₂? The simple answer is that there are a lot of abatement opportunities that are not very expensive. Given that CO₂ emissions are closely

Figure 1. Marginal Abatement Curves (MACs) for the High-GWP Industrial Gases (Hydrofluorocarbons, Perfluorocarbons, Sulfur Hexafluoride), Methane, Nitrous Oxide, and Carbon Dioxide



Sources: Figure from Reilly, et al. (2003). Original data: Methane: U.S. EPA, 1999; High-GWP Industrial gases: U.S. EPA, 2001b; nitrous oxide: Jochen Harnisch, 2001, personal communication; CO₂ calculations based on EPPA model simulations.

linked to energy which is quite fundamental to the economy, and given the existing price of fuels, people have already exhausted many of the easy ways to reduce fuel use. A small additional carbon charge which would produce a small increase in the price of fuels would only yield marginal reductions in fuel use and carbon emissions. In contrast, venting of the non-CO₂ GHGs as a means of disposing of them is unpriced and little attention has been paid to preventing this release. To be sure, many have some price: CH₄ is an energy source and venting it means the opportunity value of the energy is lost, and the produced chemicals (SF₆, HFCs) have a production cost, and the cost of venting them is the cost of purchasing replacements. But, because of the high GWPs of these gases, the opportunity costs of venting are on the order of pennies per carbon-equivalent ton when using 100-year GWP or any other reasonable index of their climate effects. Looked at another way, a \$15 per ton carbon-equivalent incentive would be several multiples of the opportunity cost of not venting these substances (e.g. Reilly et al., 2003).

Detailed studies suggest that preventing release of these substances may even be economic in some cases, given the opportunity cost of purchasing the replacements (US EPA, 2002). Such no regrets options have been likened to finding \$50 bills on the sidewalk, and if they existed many argue that most would have been spotted and picked up already. But abatement opportunities for the non-CO₂ GHGs, if they are no regrets, are comparatively nickels, dimes, and quarters on the sidewalk. Yet, if we recognize that in climate terms they are worth several dollars that may make it worthwhile to stoop, pocket the change, and make substantial progress in slowing climate change. Even if the spare change does not fully compensate for the bother of stooping, we still have the climate benefits. Developing countries looking for energy without having to spend hard currency may find it particularly attractive to recover CH₄. Similarly, recycling the industrial gases, if it saves their purchase, may be desirable. A further consideration is that at this point, very little of the industrial gases (PFCs, SF₆, and HFCs) are emitted in developing countries. Therefore agreement here would focus on prevention, establishing best practice in developed countries, and assuring that these practices are used elsewhere when the products and production moves there. This may be easier to agree on than cutting back on something on which a poor country already depends. As noted above, either because reducing emissions of these substances is actually cost-effective or in anticipation of carbon-equivalent penalty for emitting them, many firms are reducing them. Creating a global agreement on these substances would consolidate these actions, and in many cases act as a preventative measure against developing practices that would lead to their release.

Not all is completely without pain, however. Cutting agricultural sources of N₂O and CH₄, tied as they are to food production, are potentially as big a threat as limits on CO₂ and energy use. The good news is that it appears that substantial mitigation of CH₄ from paddy rice is possible with mid-season drainage, and this appears to also increase yield. The practice has thus spread widely in China quite apart from any concern about CH₄ emissions. CH₄ from ruminants is by

comparison not an easily solved problem. Manure handling, however, need not develop into the manure pit operations prevalent in the US that, due to the anaerobic conditions, generate large amounts of CH₄. Alternatively, building in the capacity to collect and use the methane from these pits as an energy source could be cost-effective. We discuss how we deal with these issues below.

4. THE MIT IGSM

The MIT Integrated Global System Model (IGSM) (Prinn et al., 1999) includes the Emissions Prediction and Policy Analysis (EPPA) model, designed to project emissions of greenhouse-relevant gases (Babiker et al., 2001) and the economic consequences of policies to limit them (e.g., Paltsev, et al., 2003, Reilly et al., 1999; Jacoby et al., 1997); a chemistry and climate model that includes a two-dimensional (2D) land-ocean (LO) resolving climate model (Sokolov & Stone, 1998), coupled to a 2D model of atmospheric chemistry (Wang et al., 1998; Wang & Prinn, 1999; Mayer et al., 2000), and a 2D or three-dimensional (3D) model of ocean circulations (Kamenkovich et al., 2002). The TEM model of the Marine Biological Laboratory (Melillo et al., 1993; Tian et al., 1999; Xiao et al., 1997, 1998) simulates carbon and nitrogen dynamics of terrestrial ecosystems. With regard to the simulations reported here, the particularly important aspects of the earth system components of the model are those that represent atmospheric chemistry. Atmospheric chemistry is resolved separately for polluted conditions, i.e., emissions in urban airsheds, and background conditions. Urban conditions are resolved at low, medium and high levels of pollution (Mayer et al., 2001). This is important because the formation of tropospheric O₃ has a highly non-linear dependence on levels of NO_x, volatile organic compounds (VOCs) including CH₄, and CO as they vary from background levels to concentrations observed in different types of urban environments. The hydroxyl radical (OH) is key to the oxidation of CO and CH₄. For example, if levels of CO are high then oxidation of it will use up much of the OH and therefore extend the lifetime of CH₄. In turn, production of OH is driven by O₃ and NO_x (which also produces O₃). Too much NO_x however, will deplete OH through HNO₃ formation. Correctly resolving the atmospheric chemistry is thus important both for estimating the concentrations of CH₄ (as its lifetime endogenously changes with changes in OH) and levels of tropospheric O₃ as they affect warming.

The EPPA component of the IGSM model is a computable general equilibrium (CGE) model. The main advantage of CGE models is their ability to capture the influence of a sector-specific (e.g. energy, fiscal, or agricultural) policy on other industry sectors, on consumption, and also on international trade. EPPA is a recursive-dynamic and multi-regional model covering the entire the world economy (Babiker et al, 2001). It is built on the economic and energy data from the GTAP dataset (Dimaranan and McDugall, 2002; Hertel, 1997) and additional data for the greenhouse gases (CO₂, CH₄, N₂O, HFCs, PFCs and SF₆) and urban gas emissions (CO, VOC, NO_x, SO₂, black carbon (BC), organic

carbon (OC), and ammonia (NH₃) (Mayer et al., 2001; Hyman et al. 2003). GHG inventory data and projections of abatement opportunities are based largely on US EPA data (US EPA 2001a-c; 2002 a-b). It has been used extensively for the study of climate policy. (Jacoby et al, 1997; Babiker, et al, 2000, 2002; Viguier et al, 2001; Bernard et al, 2003; Paltsev et al, 2003; Reilly et al, 2002; McFarland et al, 2003), climate-multigas interactions (Reilly et al, 1999; Felzer et al. 2003), and to study uncertainty in emissions and climate projections for climate models (Webster et al, 2002, 2003). Table 1 provides an overview of the basic elements of the model, with greater details in Babiker et al. (2001) and Paltsev et al. (2003, 2004), and for the non-CO₂ GHGs Hyman et al. (2003).

Inventories for non-CO₂ GHGs were updated for this study to be consistent with US EPA data made available for the EMF study. The approach for inclusion of these gases is detailed in Hyman, et al. (2003) and Webster et al. (2002), with greater details on the methods of developing emissions coefficients that change over time for aggregate EPPA sectors in Mayer et al., (2001). Briefly, the method is to introduce each separate GHG emission as an input into a separate nest of the constant elasticity of substitution (CES) production function of the relevant sectors. For example, CH₄ emissions are modeled as coming from agriculture (paddy rice, ruminant, manure, and biomass combustion related to deforestation); other industry (food processing waste); energy intensive industry (waste from paper and chemical industries); household consumption (land fills); coal production (coal seam gas); oil production (venting from production); and gas consumption (leakage from pipelines). Similar detail for each of the substances is modeled based on the various emissions sources. This allows us to specify separate abatement opportunities for each sector, and, for example, to distinguish between emissions that come from production of oil and coal from those that result from consumption/transmission as in the case of CH₄ from natural gas.

We estimate an elasticity of substitution for each sector's emissions such that the partial equilibrium production function response to changing price of the substance matches bottom-up abatement curves constructed based on a technology-by-technology assessment as in EPA (2001a,b,c). Agriculture is relatively aggregated and here we combine bottom-up abatement curves for different agricultural sources into a single abatement curve for agriculture. We assume no feasible abatement possibilities for ruminant emissions, and very restrictive opportunities for abatement of N₂O from agriculture in developing countries. In developed countries we include somewhat more abatement of N₂O because studies show the potential for reducing nitrogen fertilizer use without reducing yield by, for example, soil testing and better crediting of nitrogen in manure. Similarly, there is more opportunity for CH₄ abatement from agriculture in the US because more of it is emitted from large confined cattle operations where opportunities for abatement have been identified. Little or none of the CH₄ emissions in developing countries comes from livestock operations of this type. There are consequently much lower emissions per head from livestock compared to the US, nearly all of what is emitted is from ruminants, and there is no abatement

Table 1. Countries, Regions, and Sectors in the EPPA Model

Country or Regions	Sectors	Factors
Developed	Non-Energy	Capital
United States (USA)	Services (SERV)	Labor
Canada (CAN)	Energy Intensive products (EINT)	Land
Japan (JPN)	Other Industries products (OTHR)	Crude Oil Resources
European Union+ ^a (EUR)	Transportation (TRAN)	Natural Gas Resources
Australia/New Zealand (ANZ)	Agriculture (AGRI)	Coal Resources
Former Soviet Union ^b (FSU)	Energy	Hydro Resources
Eastern Europe (EET)	Coal (COAL)	Shale Oil Resources
Developing	Crude Oil (OIL)	Nuclear Resources
Africa (AFR)	Refined Oil (ROIL)	Wind/Solar Resources
India (IND)	Natural Gas (GAS)	
China (CHN)	Electric: Fossil (ELEC)	
Indonesia (IDZ)	Electric: Hydro (HYDR)	
Higher Income East Asia ^c (ASI)	Electric: Nuclear (NUCL)	
Mexico (MEX)	Electric: Solar and Wind (SOLW)	
Central and South America (LAM)	Electric: Biomass (BIOM)	
Middle East (MES)	Electric: Natural Gas Combined Cycle (NGCC)	
Rest of World ^d (ROW)	Electric: NGCC with Sequestration (NGCAP)	
	Electric: Integrated Combined Cycle Coal Gasification, Sequestration (IGCAP)	
	Oil from Shale (SYNO)	
	Synthetic Gas (SYNG)	
Emissions of Climate Relevant Substances		
Substances		
CO ₂ , CH ₄ , N ₂ O, HFCs, SF ₆ , PFCs, CFCs, CO, NOx, SOx, VOCs, BC, OC, NH ₃		
Sources		
Combustion of refined oil, coal, gas, biofuels and biomass burning, manure, soils, paddy rice, cement, land fills, and industrial production.		

a. The European Union (EU-15) plus countries of the European Free Trade Area (Norway, Switzerland, Iceland).

b. Russia and Ukraine, Latvia, Lithuania, Estonia, Azerbaijan, Armenia, Belarus, Georgia, Kyrgyzstan, Kazakhstan, Moldova, Tajikistan, Turkmenistan, and Uzbekistan.

c. South Korea, Malaysia, Phillipines, Singapore, Taiwan, Thailand

d. All countries not included elsewhere: Turkey, and mostly Asian countries.

possibility for these regions that we represent as feasible in the model.

If we imagined the development of manure handling operations in the developing countries of the type in the US, our baseline emissions of CH₄ would be higher. In that regard, our simulations may underestimate the importance of focusing on preventative measures. Similarly, we do not simulate in our baseline a large transition to landfills in developing countries that create large amounts of CH₄. Reduction of agricultural methane from livestock production in developing countries would need to come from reduced agricultural production, but that is

negligible because the value of food is high relative to the GHG cost share in production, particularly for the low GHG prices we simulate here. We include abatement from rice paddies based on drainage studies done by International Energy Agency (IEA), as discussed in Hyman et al., 2003. The IEA data estimated a cost to this practice. Recent observations that mid-season drainage may actually increase yields could mean it is, on net, economically beneficial apart from the CH_4 abatement.

By reflecting abatement opportunities as they differ in developing versus developed countries and among different sources, the EPPA model is well-designed to consider the questions we address in this paper. A related aspect of the approach is that, as previously discussed, many of the detailed bottom-up estimates suggest no regrets, or economically beneficial actions that would reduce GHG emissions. As discussed in Hyman et al. (2003) one could treat this information in a model of our type by removing them from abatement opportunities and building the reductions into the reference scenario. Another approach, and the one we use, is to assume that because these abatement activities have not occurred implies that there is some unmeasured cost or barrier that is preventing them from being implemented. We thus include these emissions in the reference, and assume that they require a low carbon-equivalent price in order to be realized.

5. SCENARIOS CONSTRUCTION AND RESULTS

We construct the following cases:

1. *Ref*: A case with no explicit climate policy.
2. *CH₄-only*: All abatement options for CH_4 below \$15/tce(100-yr GWPs)
3. *All Non-CO₂*: As (2) expanded to N_2O , SF_6 , PFCs, and HFCs
4. *All GHGs*: As in (3) expanded to include CO_2 .
5. *All GHGs=cap*: Cap and trade is expanded to CO_2 , but total GWP weighted emissions reductions is equal to the GWP-weighted emissions reduction resulting from the \$15/tce in (3).
6. *Kyoto*: Kyoto with current participants, i.e. without the US, and with sink allowances agreed at Marrakesh, and full trading among Parties (assuming Russia ratifies) including non- CO_2 GHG emissions of the participating Parties with no Clean Development Mechanism (CDM) credits.
7. *Kyoto-CO₂*: As in (6) but excluding non- CO_2 GHGs from the policy. However, reductions in emissions of non- CO_2 gases because of reductions in fossil fuels (e.g. reduced coal bed methane emissions because of reduced coal use) are included in the IGSM runs.

The reference case serves as a basis of comparison to allow us to estimate the net present value of the welfare loss (discounted at 5% per annum)

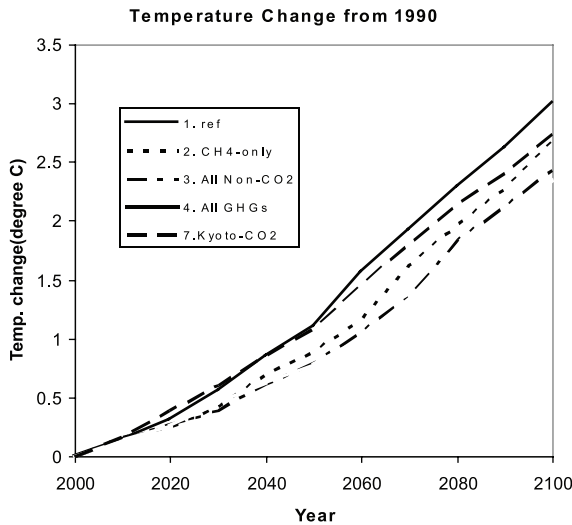
under the different scenarios and to see the climate benefits of the policy cases. Cases 2-4 are normalized on the carbon-equivalent price, and so we expect more climate mitigation benefit as we include more GHGs, but we also expect the cost in terms of welfare loss to increase because of the greater GHG coverage. Case 5 is designed to show the economic cost of limiting ourselves to the non-CO₂ GHGs by contrasting Case 3 with a scenario where the GWP weighted emissions reductions are the same but spread over all gases to equilibrate the carbon-equivalent price. These cases are all done in place of Kyoto; i.e., assuming the Protocol does not enter into force and the Parties that have ratified it abandon that approach and pursue the non-CO₂ GHG approach. This is not meant to represent the realistic intentions of the Parties that have already ratified but to show clearly the difference between the Kyoto approach and non-CO₂ GHG approach for making a start on global climate policy. Finally, the last two cases are Kyoto targets but Case 7, by excluding the non-CO₂ GHGs is designed to separately identify the non-CO₂ GHG contribution to the Kyoto Protocol, and is not meant to suggest that the Kyoto Parties do not intend to control these emissions.

Climate Results. Figure 2 shows the simulated change in global mean surface temperature for five of the seven simulations. We omit case 5, *All GHGs=cap*, because this has the same GWP weighted reduction in emissions as case 4, and we are interested in it solely for the economic comparison.³ We also do not graph Case 6 because it is nearly indistinguishable from Case 7. The climate results show that the *CH₄-only* policy has a substantial effect on temperature, particularly in the nearer term. The reduction in the temperature increase reaches about .3° to .4° C by 2050-2060 and remains at about that level through 2100. In comparison the *Kyoto-CO₂* warming reduction only approaches this level by 2100 (the temperature reduction in 2100 is about .26° C). This reflects mostly the fact that the effective lifetime of CH₄ is quite short (on the order of 12 years allowing for OH effects) compared with CO₂ which remains in the atmosphere much longer. Thus, the climate benefits of reductions in CH₄ are seen mostly within the time horizon of the simulation, whereas the lifetime of CO₂ is on the order of 100 years, and thus the climate benefits of CO₂ reductions in the latter half of the century are mostly not realized until after 2100.⁴ Sarofim et al. (2005) conduct very long run model integrations with the MIT IGSM and show that it can take more than 200 years for similar reductions in emissions of CO₂ and other GWP-weighted GHGs to show similar temperature reductions. Similar to this paper,

3. However, as shown elsewhere (Reilly et al. 1999, Sarofim et al. 2005) the GWP weights do not correctly weight the GHGs and so the temperature effects are different depending on which gases are reduced. This issue has been explored thoroughly in the above papers and elsewhere. Here we want to focus on the economic differences of policies that would be viewed as identical given the agreement to use GWPs.

4. Here we use lifetimes frequently used in the literature only to provide an order-of-magnitude idea of the difference. Because carbon is partitioned in different reservoirs, a single lifetime is not truly appropriate, and as noted, the calculation of the lifetime of CH₄ in the MIT IGSM is endogenous but it is not straightforward to extract its lifetime as it changes over time.

Figure 2. Climate Change Results Expressed as Decadal Average Mean Surface Temperature Change from Year 200 for the Reference and for Policy Scenarios



they show greater near term benefits of CH₄ abatement, compared to CO₂. The *All Non-CO₂* case shows, of course, greater climate mitigation benefit than the *CH₄-only* case. The benefit rises to over .5° C reduction in warming by 2100. These gases include N₂O with a similar lifetime as CO₂, HFCs which have on average a shorter lifetime (~30-50 years) and the very long-lived PFCs and SF₆ which have lifetimes of 1000's of years. So this is a mixed group of gases, but much of the additional benefit we see through the year 2100 simulation horizon likely comes from N₂O reductions and the shorter-lived HFCs. The *All GHGs* case, where we further extend the \$15/tce policy to CO₂, has small additional climate benefits, about .1° C warming reduction. This reflects the fact that the \$15/tce is a marginal increase in fuel prices and spurs on only small reductions in energy use. The case 6 (*Kyoto*) climate results, not plotted because they are indistinguishable when graphed from *Kyoto-CO₂*, show a small (.05° C) reduction in warming compared with case 7. This warming reduction also starts much earlier and the difference with *Kyoto-CO₂* and holds steady for most of the century, reflecting the effects of including CH₄ abatement and the relatively short lifetime of CH₄.

As discussed at the beginning of the paper, we are not proposing that any of these policies represents a sufficient response to the risks posed by climate change. Rather we are considering possible next steps in what appears to be a stalled global climate negotiation. In that regard, it is of interest given the high costs often associated with the Kyoto Protocol, where projections quickly rise to \$100's/tce, that a global policy focused particularly on the non-CO₂ GHGs

where the price is on the order of \$15/tce could achieve, at least in the 2100 time horizon, greater climate benefits than a CO₂-only version of the Kyoto Protocol extended to 2100. If we failed to deal with CO₂ the accumulating atmospheric concentrations would, of course, become a greater burden over time. But, if we could make progress to make sure that the very inexpensive abatement options are in place to prevent the releases of the non-CO₂ GHGs these results show substantial climate benefits.

Economic Costs. We have standardized the non-CO₂ scenarios around a \$15/tce price, but the coverage varies and so the macroeconomic cost in terms of lost consumption differs. Climate policy can also interact with other pre-existing taxes in the economy and so carbon price is a poor indicator of the cost of a policy (Paltsev, et al, 2004). Table 2 shows the Net Present Value (NPV) cost, using a 5% discount rate, of these policy cases through 2100. The NPV welfare cost of the CH₄-only case is \$57.6 billion (1997\$), or about .005% of the NPV of total consumption over the century. The cost of the *All Non-CO₂* case is \$181.6 billion, and if we expand this policy to CO₂ the costs more than double to \$430 billion. The CH₄-only policy cost is about 13% of the *All GHG* case but it achieves more than ½ the climate mitigation benefits. The increased cost from adding N₂O, HFCs, PFCs, and SF₆ to the policy is nearly 30% of the *All GHG* case costs, and it contributes about 30% of the climate benefit. The cost increase of expanding the \$15 tax to CO₂ is 58%, but this addition contributes only 15% of the climate mitigation benefit realized in 2100. Of course these less comprehensive policies are more expensive than a comprehensive global policy covering all gases designed to achieve the same GWP-weighted reduction. The *All GHGs=cap* case with a cap on all gases including CO₂ costs about ½ as much as the *All Non-CO₂* case. The amount of CO₂ reductions that result from a \$15 price are small but adding this flexibility further reduces the policy cost. The problem is that the negotiations to put policies in place to achieve this appears stalemated because countries are concerned that current policy approaches using a fixed cap would become too costly. We see this in the Kyoto scenarios (6 and 7) which are measured in trillions of dollars rather than billions (Table 2). And, with narrow regional coverage they achieve less climate benefit.

Interactions. There are a number of interactions that come into play in the estimate of cost and climate mitigation benefit. To the extent that CO₂ policies reduce coal use, they can also reduce sulfate aerosols, and this reduction has a

Table 2. Economic Costs of Mitigation Policies

Scenario	2	3	4	5	6	7
	CH ₄ -only	All Non-CO ₂	All GHGs	All GHGs=cap	Kyoto	Kyoto-CO ₂
NPV welfare loss (billions of 1997\$)	57.6	181.6	429.9	95.5	6663.1	8941.5
Welfare loss (% of NPV of total consumption)	0.005	0.017	0.039	0.009	0.606	0.813

warming effect that offsets the cooling from CO₂ reductions. CO₂ also enhances growth of vegetation and carbon storage, and thus policies that reduce CO₂ also reduce uptake by vegetation in the IGSM runs, and as a result the reductions in emissions are not quite as effective as if this did not occur. Changes in energy use also affect emissions of many O₃ precursors. Specifically, CH₄ and NO_x and CO produced in combustion of fossil fuels are all O₃ precursors. We find that scenarios 2-4 with larger reductions in CH₄ reduce tropospheric O₃ levels about 5% on average by the end of the century compared to the reference. In comparison, the Kyoto scenarios reduce O₃ by about 3% due to reduced NO_x and CO only. While a small effect, O₃ is a warming substance and thus this makes the CH₄ policies somewhat more effective than CO₂ policies in reducing temperature. A further effect of methane abatement is a lower CO₂ concentration because the CH₄ would have been oxidized. If the CH₄ emissions reductions from fossil energy sources (coal mining, petroleum production, and leakages from natural gas transmission and distribution) that we estimated for cases 2-4 are used for fuel in order to displace other natural gas use, the displaced natural gas would have oxidized into about 14 GtC, or about 2-3 years of current annual fossil carbon emissions. So abating these emissions also reduces atmospheric CO₂.

We do not include in the above calculation oxidation of the CH₄ involved in abatement from biogenic sources because we assume the biomass material that produced this CH₄ was atmospheric CO₂ before it was taken up by the vegetation. The agricultural activities leading to these emissions are cycling the carbon on fairly rapid timescales, and so we assume that avoiding the formation of CH₄ under anaerobic conditions leaves this vegetation to instead decay directly into CO₂. This would be the case for paddy rice for example.⁵ On the cost side, many countries have existing fuel taxes, and climate policy directed toward fuels interacts with these existing taxes to raise the cost of the climate policy. Paltsev et al. (2004) show that the extra cost due to this tax interaction effect can be several times the direct cost of the carbon policy itself. This fact likely explains why expanding the \$15/tce policy to CO₂ increases the costs as much as it does (Table 2).

6. CONCLUSIONS

The current policy challenge is to make a start toward stabilizing greenhouse gases in the atmosphere. An idealized policy would be comprehensive geographically, and would include all substances that affect the radiative balance of the atmosphere. There are technical, scientific, and policy-related reasons why it has not been possible to jump-start a fully comprehensive policy. Issues of measuring carbon sinks have limited how this potential CO₂ reduction source has been included in climate policies. Aerosols have important radiative effects; sulfates cool the surface whereas other aerosols like BC have more complex

5. If CH₄ from manure is collected and used as an energy source to offset a fossil source this would through the offset lead to a reduction in carbon.

warming and cooling effects on climate. Tropospheric O₃ has been a major contributor to historical forcing but the complex and non-linear interactions among its precursors makes it difficult to confidently identify reductions in emissions of specific substances that would in all circumstances lead to reductions of O₃. Moreover, aerosols and ozone are short-lived and not well-mixed in the atmosphere and so their climate effects display a different geographic pattern, and may differentially affect cooling, warming, and precipitation compared with the longer-lived GHGs (Reilly, et al., 2003). Even among the GHGs, their differing nature has made it impossible to find the correct index by which to compare them, and so policies that use 100-year GWPs poorly represent the relative climatic effects (Reilly et al., 1999; Sarofim, et al., 2005). On the policy side, developing countries have resisted joining the group of countries in the Kyoto Protocol that have taken on caps, at least for the present. Recognizing these many difficulties, to get started one would like to find the less than comprehensive set of policies that would be effective, have a chance of broad acceptance among most countries, and would not be highly inefficient. Fortunately, these last two conditions, cheap and acceptable, often go hand in hand.

We have considered here policies that are global in nature but focused on the non-CO₂ GHGs. The radiative effects of the non-CO₂ GHGs are well-known, and so there is no scientific doubt that reducing them will lead to climate mitigation benefit. On the cost side, it has become ever clearer with more study and attention that there are many ways to abate these non-CO₂ emissions at low cost, or possibly with economic benefit. Whereas reducing CO₂ emissions from energy has been seen as a threat to economic growth among developing countries, the non-CO₂ GHGs are less fundamental to an economy and so reducing them does not pose that large a threat. We estimate that abatement opportunities for CH₄ that could be achieved at less than \$15/tce would over the next century reduce warming by .3° to .4° C. Expanding this to other non-CO₂ GHGs would reduce warming by another .2° C, for a total reduction of about 0.55° C. This is substantially more than the .25° C reduction we estimate the Kyoto Protocol in its current form would achieve if Parties to it maintained it as is through 2100. Furthermore, we estimate the costs of the non-CO₂ policies to be a fraction of the Kyoto policy.

Stabilization of greenhouse gases in the atmosphere will require that carbon emissions from fossil energy be reduced. Unfortunately, we are stuck in a policy stalemate of how to proceed on carbon dioxide. Non-CO₂ GHG abatement would occur through the Kyoto Protocol and even abatement in developing countries could be achieved under it through the CDM. However, the opportunities to avoid these emissions may slip away as we wait for ratification of the Kyoto Protocol. Even if ratified the CDM itself may be ineffective at getting the reductions in developing countries. Whether as a next step to expand Kyoto, or as a separate initiative running parallel to it, the world could well make substantial progress on limiting climate change by pursuing an agreement to abate the low cost non-CO₂ GHGs.

While we simulated control with an emissions tax and/or cap and trade system, other policy approaches may be equally effective. Abatement of these substances may be easily controlled by establishing best practice measures, or through regulatory standards without being highly inefficient. Policies might simply be established to not use landfills as a waste disposal method, or to create them such that methane would be collected and used as an energy source. Methods that capture rather than vent SF₆ from electrical switchgear testing, already used by many companies, could simply be mandated. As long as we are focused on methods that are relatively low cost, it is not obvious that great inefficiencies arise from less than ideal market incentive mechanisms. And given the existence of other pre-existing distortions in the economy and the inability to establish accurate indices by which to establish equivalent multi-substance taxes (or the rate at which different substances would trade) the idealized instruments may not work ideally. The bottom line is that there appear to be low cost abatement options that we should act on as soon as we can, and through whatever policies or measures different countries find acceptable to their circumstances, and thus hopefully make it possible to get broad country participation.

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