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Multiple Gas Control Under the Kyoto Agreement

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This report is one of a series intended to communicate research results and improve public understanding of climate issues, thereby contributing to informed debate about the climate issue, the uncertainties, and the economic and social implications of policy alternatives. Titles in the Report Series to date are listed on the inside back cover.

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Multiple Gas Control Under the Kyoto Agreement

John Reilly, Monika Mayer and Jochen Harnisch*

Abstract†

Under the Kyoto Protocol, reductions in emissions of several radiative gases can be credited against a carbon equivalent emissions cap. We investigate the economic implications of including other greenhouse gases and sinks in the climate change control policy using our revised and updated version of the Emissions Prediction and Policy Analysis (EPPA) model. In addition we amended our methane abatement curves based on different interpretations of estimates that substantial abatement of methane can be obtained at no cost. The inclusion of other greenhouse gases and CO_2 sinks reduces the costs of achieving CO_2 emissions reductions specified under the agreement.

Contents

1. Introduction

The Kyoto Protocol includes carbon dioxide (CO_2) emissions from fossil fuels, methane (CH_4), nitrous oxide (N_2O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), and sulfur hexafluoride (SF_6) (FCCC, 1998). The Protocol also allows credit for carbon sinks resulting from direct, human-induced afforestation and reforestation measures occurring after 1990. Integrated economic studies have only begun to include evaluation of the costs of multi-gas control strategies (Hourcade, 1996; Wigley, Richels, and Edmonds, 1996; Nordhaus, 1994). Most still include only CO_2 emissions from fossil fuels (*e.g.*, Weyant and Hill, 1999). In previous work with the MIT Integrated Global Systems Model we have evaluated the economic, atmospheric, climate, and ecosystem implications of a multigas agreement including all of the "Kyoto" gases listed above and forest sinks (Reilly *et al.*, 1999a,b). In this paper we investigate the economic implications of including other greenhouse gases and sinks in the climate change control policy, updating our previous analysis in several ways. The most important change is that we have revised and updated our Emissions Prediction and Policy Analysis (EPPA) model. We also have revised our methane abatement curves based on revised estimates of methane abatement costs,

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and present estimates of abatement cost curves for methane based on different interpretations of estimates that substantial abatement of methane can be obtained at no cost. Our previous work was reported in 1985 $US owing to the fact that our previous version of EPPA was based on a 1985 data. Our new model is based on a 1995 data and we therefore report estimates in 1995 $US. For comparison purposes one therefore must multiply all prices and costs in the previous work by 1.43. We do not address here some of the implications for climate and ecosystems and what these imply about the usefulness of Global Warming Potentials (GWPs) for comparing gases. For this analysis, see in particular Reilly *et al.* (1999b).

2. Multigas Assessment Using the EPPA Model

The EPPA model is a recursive dynamic multi-regional general equilibrium model of the world economy. The current version of EPPA is built on a comprehensive energy-economy data set that accommodates a consistent representation of energy markets in physical units as well as detailed accounts of regional production and bilateral trade flows. The base year for the model is 1995 and the model is solved recursively through time at 5-year intervals. There are eight commodity groupings and 12 regions in the basic version of EPPA used here although the underlying GTAP data provides us with the flexibility to disaggregate regions and sectors in greater detail. Description of the specific regions and commodities included in the model is provided on **Table 1**. Nested CES functions are used to describe technologies and preferences. For more details see Babiker *et al.* (2000).

Emissions of CO_2, CH_4, N_2O, PFCs, HFCs, and SF_6 are associated with various activities that are projected in the model (**Table 2**). SO_x, NO_x, and CO are also projected for purposes of linking with an atmosphere/climate model. The non-CO_2 gas component of the revised version of EPPA is still being tested and reformulated. For analysis purposes here, we use the emissions projections and feed-back relationships for these gases as in Reilly *et al.* (1999a,b).

Costs of reductions in emissions of CO_2 from fossil fuels are computed by introducing a constraint in EPPA (*e.g.*, the emissions limitation agreed to in the Kyoto Protocol) on emissions.

Table 1. Countries, Region, and Sectors in the General Equilibrium Model

Country or Region		**Commodities**	
USA	United States	AGRIC	Agriculture
JPN	Japan	COAL	Coal
EEC	Europe	OIL	Crude Oil
OOE	Other OECD	GAS	Natural Gas
FSU	Former Soviet Union	REFOIL	Refined Oil
EET	East European Associates	ELEC	Electricity
IND	India	ENERINT	Energy Intensive products
BRA	Brazil	OTHERIND	Other Industries products
CHN	China (including Hong Kong + Taiwan)		
EEX	Energy Exporting Economies		
DAE	Dynamic Asian Economies		
ROW	Rest of world		

Table 2. Reference Projections of Trace Gases and EPPA Activities*

Gas	Anthropogenic Emission Sources	EPPA Activities
CH_4	Rice production, livestock waste, enteric fermentation, land fill waste, natural gas venting and distribution losses, coal seam gas, biomass burning	Agricultural production, natural gas production, coal production, exogenous biomass burning from deforestation
N_2O	Fertilized soils, Adipic and nitric acid production, catalytic converters in vehicles, biomass burning	Agriculture production, other industry production, refined oil production, exogenous biomass burning from deforestation
PFCs	Aluminum and semiconductors production, solvent use, other	GDP
HFCs	Refrigeration and air conditioning, solvent and foaming agent use, by-product of HCFC production	GDP
SF_6	High voltage switch gears, magnesium production and semiconductor production, other	Electricity use, GDP

*SO_x, NO_x, and CO are also projected for purposes of linking with an atmosphere/climate model.

The production and consumption relationships within the model result in fuel switching and reduction in energy use so that the emissions constraint is met. The same approach could be applied for other gases in the model but, given the fixed coefficient nature of the relationship between emissions and activity levels, the implication would be that emissions reductions could only occur through reductions in the activity levels that emitted these gases. In fact, there are a variety of technological solutions for reducing these gases that are less costly than doing away with the activity. We have summarized these abatement opportunities as marginal abatement curves (MACs), constructed by ordering the abatement options from lowest cost to highest cost. We have also generated marginal abatement curves for reductions in emissions of CO_2 from fossil fuels based by running the EPPA model with successively tighter emissions restrictions (*e.g.*, 10, 20, …, 60 percent reductions from reference in 2010).

Greater detail on our abatement opportunities for other greenhouse gases (GHGs) and sinks is contained in Reilly *et al*. (1999a,b). **Figure 1** presents our revised marginal abatement curves for methane. A difference from our previous work is that we exactly fit the data points using a piecewise linear estimation process and, for this paper, have done the same for the CO_2 marginal abatement curves. For methane, we fit the abatement curve to the share of emissions reduction from the

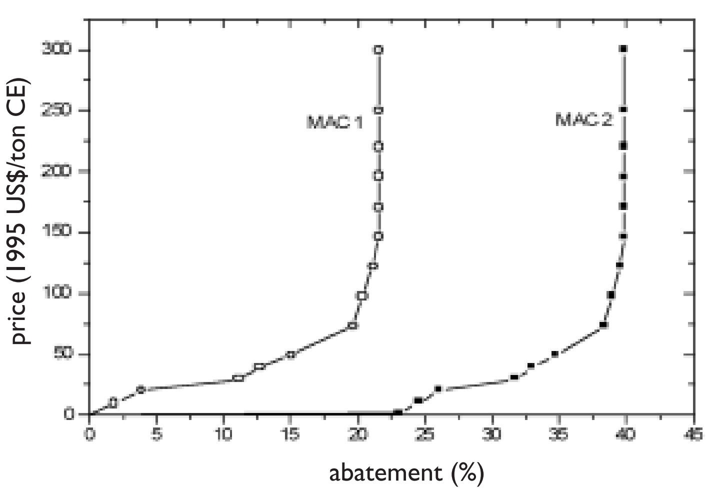

Figure 1. Marginal Abatement Curves for Methane in 2010

2010 reference based on data from a study by Gibbs (1998) for the United States and assume the same abatement cost schedule applies to other Annex B regions. The Gibbs (1998) estimate indicates that over 20% of US methane emissions can be eliminated at zero cost or less, represented in MAC 2. We also consider an alternative cost relationship (MAC 1) that assumes zero cost abatement opportunities are already reflected in the reference scenario. We use these abatement curves to estimate a market-clearing price for abatement across gases and sinks using the 100-year GWPs specified in the Kyoto Protocol (see Reilly *et al*., 1999a,b). One aspect of this approach is that, as a result of the carbon constraint imposed on the EPPA model, activities such as coal, oil, and gas production and fuel use are reduced and consequently other GHG emissions associated with these activities (CH_4, N_2O) are also reduced. We refer to these as "free reductions" because, as we have modeled them, they occur without any additional abatement cost beyond that associated with reducing carbon emissions. Costly abatement (as reflected in our abatement curves) applies to the remaining emissions.

3. Policy Cases

Our economic analysis is limited to provisions directed at Annex B countries. In our model these countries are represented in as the United States (USA), the 15 countries that are currently members of the European Union (EEC), Japan (JPN), the remainder of the OECD (OOE), the regions of the former Soviet Union (FSU) and Central and Eastern Europe (EET). We consider only cases without emissions trading among countries. In addition to a future reference case with no emissions controls, we develop four basic policy cases to test the economic importance of including non-CO_2 gases in the Kyoto Protocol.

Case 1: Fossil CO_2 Target and Control. Only CO_2 is included in determining allowable emissions, unlike the requirements in the Kyoto Protocol that require consideration of multiple gases, and only CO_2 emissions abatement options are considered.

Case 2: Multi-Gas Target with Control on CO_2 Emissions Only. A multi-gas target (using GWPs) as described in the Kyoto Protocol is used, but only carbon emissions from fossil fuels are controlled.

Case 3: Multi-Gas Target and Controls. The multi-gas Kyoto target applies and parties seek the least cost control across all gases and carbon sinks, using methane MAC 2.

Case 4: Same as Case 3, except using methane MAC 1.

We also create an alternative scenario for the EEC based an EEC-only assessment of other gases. In this scenario, labeled EEC 1, we use our marginal abatement costs curves but use the reference emissions projections and base emissions estimated by de Jager *et al*. (1999).

4. 2010 Reference Emissions and Abatement Costs of Meeting the Kyoto Protocol

Percentage changes in emissions for all gases are given in **Table 3**. The economic results are presented in **Table 4** and the gas-by-gas abatement contributions are given in **Tables 5** and **6**. The overall result is that inclusion of all of the gases in the Kyoto agreement has a significant effect on the shadow price of carbon and on total costs. The combination of including 1990 emissions of all GHGs in the base and increasing emissions of other GHGs through 2010 means that the required reduction is greater in Cases 2, 3, and 4 compared with Case 1. The error in costs estimates based only on CO_2 is substantial. The shadow price is between \$55/ton and \$171/ton lower for the US, EEC, JPN, and OOE under the multigas case than under the carbon only case (comparing Cases 1 and 3). Total costs across all Annex B regions are lower under the multigas Case 3 by over 30% compared with Case 1. The constraint is not binding for the FSU and only binds for the EET with a multigas target.

Table 3. Reference Emissions for year 2010, percentage growth from 1990

Gas	USA	JPN	EEC	OOE	EET	FSU	EEC 1
CO_2	37.7	28.2	27.9	37.8	-9.6	-10.1	8
CH_4	8.2	21.1	10.9	21.3	27.3	34.8	-27.1
N_2O	31.1	47.3	28.7	36.3	19.1	25.7	7.9
SF_6	21	40	23.4	27.3	60	9.4	-13.2
HFC	124.4	152.2	132.9	144	240	187.5	75.2
PFC	-32.4	-76.9	-31.7	-29.2	-18.2	-14.5	-26.3
Total	**34.7**	**29.8**	**26.5**	**34.2**	**-1.3**	**-3**	**4.5**
***Required reductions**, percentage reduction from 2010 reference*							
CO_2-only, Case 1	32.5	26.7	28	31.4	-2.9	-9	12.7
Multi-gas, Cases 2-4	31	27.6	27.3	29.6	5.8	-1	11.7

EEC 1 is an alternative scenario for the EEC based on de Jager *et al*. (1999) projections.

Table 4. Shadow Prices and Total Cost of Abatement

	USA	JPN	EEC	OOE	EET	EEC 1
	Shadow Price (US\$/ton CE)					
Case 1	258	305	210	271		49
Case 2	360	386	281	465	22	56
Case 3	156	250	151	100	11	23
Case 4	176	260	175	131	2	31
	Total Costs (US\$ x 10^9)					
Case 1	61	14	29	12	0	3
Case 2	86	19	45	24	0.2	4
Case 3	38	12	22	5	0.02	1
Case 4	43	13	27	7	0.1	2

EEC 1 is the alternative scenario for the EEC based on de Jager *et al*. (1999) projections.

Table 5. Abatement by GHG, percentage of total abatement, Case 3

Gas	USA	JPN	EEC	OOE	EET	EEC 1
CH_4	9.8	3.2	13.5	21	79.8	26.8
free CH_4	3	0.4	2.6	5.1	2.1	2
N_2O	6.3	3.2	6.3	5.3	1.5	10.4
free N_2O	1.8	1.8	1.4	0.8	0.1	1.1
SF_6	1.3	3	1.4	1.8	0.5	2.3
HFC	3.6	8.2	4	2.1	0.1	2.7
PFC	0.5	0.2	0.5	2.1	0	0.5
Total Other GHGs	26.2	18.8	27.1	48.4	81.9	42.7
Sinks	4.6	1	1.5	16.1	0	0
Carbon	69.1	79	68.9	45.7	16	54.2

Table 6. Abatement by GHG, percentage of total abatement, Case 4

Gas	USA	JPN	EEC	OOE	EET	EEC 1
CH_4	4.2	1.3	5.6	8.9	7.2	8.5
free CH_4	3.2	0.4	2.8	5.9	9.3	2.6
N_2O	6.7	3.2	6.5	5.6	6.7	11.7
free N_2O	2	1.9	1.5	1	0.4	1.4
SF_6	1.4	3	1.4	1.9	3.1	2.6
HFC	3.6	8.2	4	2.4	0.4	4.1
PFC	0.6	0.2	0.5	2.4	0.2	0.6
Total Other GHGs	21.2	17	19.7	39.4	17.6	27.6
Sinks	4.8	1	1.6	18.2	0	0
Carbon	73.5	80.7	75.9	53.7	72.8	68.5

Given that the Kyoto agreement includes other gases in the 1990 base but only allows the flexibility to reduce other gas emissions we ask: How much more would the agreement cost if this flexibility was not exercised? This answer is obtained by comparing Case 2 with Case 3 (or Case 4). If one must reach the Kyoto target only through reductions in CO_2 emissions (Case 2) the costs for Annex B about twice as much than in Cases 3 or 4 where the flexibility of including other gases is fully exercised. The reductions in costs between these cases are quite different for different regions. A multigas assessment of trading would therefore being considerably different than an CO_2-only analysis of trading.

The difference in how to interpret zero cost abatement options (Case 3 and Case 4) has a measurable effect. We only evaluated methane abatement with respect to this uncertainty. If similar issues exist for other gases, the effect would be larger. The difference between EEC and EEC 1 also reflect differences in projecting the reference level of emissions. The very optimistic view in EEC1, that combined reference emissions will increase very slowly, results in much lower costs than for the reference case we project. Projected gas-by-gas abatement levels (Tables 5 and 6) show substantial “free reductions” of CH_4 and also sizable “free reductions” for

N_2O. Apart from these "free reductions," CH_4, N_2O, sinks, and the combination of the other three GHGs are of roughly equal magnitude for most regions. While any one of the other gases or sinks may be small by itself, in combination they contribute across the regions between 18 and 60% of the abatement needed to meet the Kyoto target. Sinks make no contribution in EET or EEC 1 because the carbon price is less than our estimated minimum cost of establishing a forest. The overall conclusion is that failure to take advantage of the flexibility accorded by the inclusion of other gases would raise the cost of meeting the objectives of any climate policy.

5. References

Babiker, M., J. Reilly, I. Sue-Wing, and R. Eckaus, 2000, The MIT Emissions Prediction and Policy Analysis (EPPA) Model, Joint Program on the Science and Policy of Climate Change, MIT (forthcoming).

de Jager, D., C.A. Hendriks, H.A.M. Heijnes, and K. Blok, 1999, Emissions Reduction Potential for Non-CO_2 Greenhouse Gases in the EU-15, in: *Greenhouse Gas Control Technologies*, P. Reimer, B. Eliasson and A. Wokaun (eds.), Elsevier Science Ltd., Oxford, UK.

Gibbs, Michael J. (ed.), 1998, *Costs of Reducing Methane Emissions in the United States*, Preliminary Report, ICF Incorporated, Methane and Utilities Branch, Atmospheric Pollution Prevention Division, Office of Air and Radiation, U.S. Environmental Protection Agency, Washington, D.C., (Revised Draft) July 31.

Hourcade, J.C., *et al*., 1996, A review of mitigation cost studies, in: *Climate Change 1995: Economic and Social Dimensions of Climate Change*, J.P. Bruce *et al*. (eds.), Cambridge Univ. Press, Cambridge, UK, pp. 297-366.

Nordhaus, W.D., 1994, *Managing the global commons*, The MIT Press, Cambridge, MA.

Reilly, J., R. Prinn, J. Harnisch, J. Fitzmaurice, H. Jacoby, D. Kicklighter, P. Stone, A. Sokolov, C. Wang, 1999a, Multigas Assessment of the Kyoto Protocol, MIT Joint Program on the Science and Policy of Climate Change, Report No. 45, MIT, Cambridge, MA, January 1999.

Reilly, J., R. Prinn, J. Harnisch, J. Fitzmaurice, H. Jacoby, D. Kicklighter, P. Stone, A. Sokolov, C. Wang, 1999b, Multigas Assessment of the Kyoto Protocol, submitted to *Nature*.

Wigley, T.M., R. Richels and J.A. Edmonds, 1996, Economic and environmental choices in the stabilization of climate, *Nature*, **379**: 240-243.

Weyant, J. and J.N. Hill, 1999, Introduction and Overview, *Energy Journal* Special Issue, The Costs of the Kyoto Protocol: A Multi-Model Evaluation, pp. *vii-xliv*.