

MIT Joint Program on the Science and Policy of Global Change



Modeling Non-CO₂ Greenhouse Gas Abatement

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To inform processes of policy development and implementation, climate change research needs to focus on improving the prediction of those variables that are most relevant to economic, social, and environmental effects. In turn, the greenhouse gas and atmospheric aerosol assumptions underlying climate analysis need to be related to the economic, technological, and political forces that drive emissions, and to the results of international agreements and mitigation. Further, assessments of possible societal and ecosystem impacts, and analysis of mitigation strategies, need to be based on realistic evaluation of the uncertainties of climate science.

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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Abstract

Although emissions of CO₂ are the largest anthropogenic contributor to the risks of climate change, other substances are important in the formulation of a cost-effective response. To provide improved facilities for addressing their role, we develop an approach for endogenizing control of these other greenhouse gases within a computable general equilibrium (CGE) model of the world economy. The calculation is consistent with underlying economic production theory. For parameterization it is able to draw on marginal abatement cost (MAC) functions for these gases based on detailed technological descriptions of control options. We apply the method to the gases identified in the Kyoto Protocol: methane (CH₄), nitrous oxide (N₂O), sulfur hexafluoride (SF₆), the perfluorocarbons (PFCs), and the hydrofluorocarbons (HFCs). Complete and consistent estimates are provided of the costs of meeting greenhouse-gas reduction targets with a focus on “what” flexibility—*i.e.*, the ability to abate the most cost-effective mix of gases in any period. We find that non-CO₂ gases are a crucial component of a cost-effective policy. Because of their high GWPs under current international agreements they would contribute a substantial share of early abatement.

Contents

1. Introduction	1
2. Representing the Non-CO ₂ Gases in a CGE Model.....	3
2.1 Alternative Formulations of Emissions Control.....	3
2.2 Details of Implementation.....	4
3. Implementation in the MIT EPPA Model.....	9
3.1 National Cost Curves for the US and China.....	11
4. A Sample Application.....	13
4.1 The Relative Role of the Non-CO ₂ Gases	14
4.2 The Importance of Multi-Gas Coordination.....	14
4.3 Regional Contributions of Non-CO ₂ Gases to a Cost Effective Climate Policy.....	16
5. How Important Is Endogenous Representation of GHGs?.....	17
6. Summary and Conclusions	20
7. References	21

1. INTRODUCTION

Human activities are contributing a complex mix of greenhouse gases (GHGs) to the atmosphere, perturbing the radiation balance of the Earth and very likely modifying its climate. Carbon dioxide (CO₂) from fossil fuel burning and human land use change is the most important single anthropogenic influence. Also of critical importance, however, are emissions of non-CO₂ gases including methane (CH₄) and nitrous oxide (N₂O) that are naturally present in the atmosphere, and a group of industrial gases including perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), and sulfur hexafluoride (SF₆). Taken together with the already banned chlorofluorocarbons (CFCs), they are of significance roughly equivalent to CO₂ (Reilly, Jacoby and Prinn, 2003). To effectively limit climate change, and to do so in a cost-effective manner, climate policies need to deal with all of them.

Previous studies have explored the degree to which abatement opportunities among these non-CO₂ GHGs could substantially reduce the cost of meeting an emissions target. The savings found, compared with a CO₂-only policy, were more than proportional to the emission contribution of these non-CO₂ sources (Hayhoe *et al.*, 1999; Manne and Richels, 2001; Reilly *et al.*, 1999; Reilly, Mayer and Harnisch, 2003). At the time most of these earlier studies were done, however, the non-CO₂ gases had not been fully incorporated within the underlying analytic models.¹ Instead, exogenous marginal abatement curve (MAC) functions for these gases were combined with economic model results for fossil carbon emissions (*e.g.*, Reilly *et al.*, 1999; Hayhoe *et al.* 1999).

An important disadvantage of analysis using exogenous MAC functions is their inability to capture many of the interactions that would result from a GHG constraint. For instance, there are spillover effects of the control of one gas onto emissions of others that are not easily captured using an exogenous abatement curve approach. Gases such as CH₄, N₂O, and SF₆ will be affected by a carbon restriction because some of their emissions sources are closely tied to energy production and use. Methane is emitted from energy transport activities and N₂O is produced in fossil fuel combustion. Reduced electricity production that might result from restrictions on fossil fuels would reduce SF₆ emissions because of its use in electrical switchgear. Also omitted are effects on prices of exports and imports of energy and other goods, and the terms of trade, and on investment in and depletion of fossil fuel resources. Endogenizing abatement of GHGs within a CGE model, which includes these mechanisms, allows the interactions between controls of different gases to be consistently assessed.

A further issue concerns welfare analysis. Economic costs estimated as areas under a MAC function are not consistent with the equivalent variation measure of welfare most commonly used in assessing policy costs in CGE models. Explicit representation of these abatement opportunities within the CGE production structure allows consistent costing of controls applied across several gases, and ensures comparability among studies using different analytical models.

In Section 2 we describe an approach for incorporating non-CO₂ GHGs in a CGE model, along with a method for estimating the necessary parameters. Functions representing the abatement costs of these gases are fit to results from detailed, bottom-up studies of cost. Avoiding the often shrill debate between “top-down” and “bottom-up” models of energy, the approach allows the assessment to be consistent with partial-equilibrium bottom-up studies while taking account of the economy-wide interactions that any control action will stimulate. The analytic approach is introduced using CH₄ as an example. In Section 3 we describe its implementation in the MIT EPPA model (Babiker *et al.*, 2001) and extension to all the non-CO₂ gases. Section 4 presents a sample calculation, showing the relative importance of the non-CO₂ gases among countries and as function of time and stringency of policy. The differences in results from this all-gas CGE approach, as compared with analysis using MAC curves, is explored in Section 5. Section 6 concludes with thoughts about next steps in multi-gas policy and its assessment.

¹ Manne and Richels (2001) introduced abatement costs as an endogenous component of their model, but did not consider the industrial gases (HFCs, PFCs, and SF₆).

2. REPRESENTING THE NON-CO₂ GASES IN A CGE MODEL

2.1 Alternative Formulations of Emissions Control

The common approach to modeling the control of CO₂ from fossil energy combustion is, in general, not applicable to the other GHGs. Modeling CO₂ control is simplified by the fact that it is emitted in fixed proportions with the burning of oil, coal, and natural gas. The modeled activity of energy-using sectors—like agriculture, industrial production or provision of household services—may involve a number of energy inputs, some of them from fossil sources. Abatement of CO₂ emissions results from some combination of changed demands for energy services, increased efficiency in their use, or substitution among energy sources. However achieved, reduction of CO₂ emissions is synonymous with lower overall fossil fuel use or a shift to less carbon-intensive sources.² In a CGE model, these emissions can be estimated in proportion to the activity levels of the coal, oil and gas industries.

Emissions of the other GHGs cannot, in general, be tied in fixed proportions to activity in the sectors that produce them, because actions can be taken to reduce emissions per unit of activity. Given this fact, there are a number of avenues for endogenizing pollution control that are consistent with production theory and the restrictions of CGE modeling. One is to create a clean-up sector that removes the pollution, using capital, labor, and other inputs. In such an approach, emitting sectors would purchase abatement services from the clean-up sector and this clean-up service would be another input into the production of, for example, agriculture, coal mining, or natural gas distribution. Such an approach would provide flexibility to represent the factor shares of the clean-up activity. Adequate representation of available opportunities would, however, require many clean-up sectors because (to take just one example) the technology for abating CH₄ emissions from agriculture, coal-mining, and landfills all differ from one another.

A second approach would be to create an alternative production process that is “cleaner” than conventional technology, and that includes a cost structure reflecting the extra cost. For example, an agricultural production function might be added that produces agricultural goods but with less CH₄ than existing agricultural practice. Production from the alternative activity would cost more than the conventional one, the premium in cost reflecting the additional inputs needed to reduce emissions. Again, the limit to this approach is that there are many alternative production activities that produce different levels of each of the GHGs, so many different production functions would have to be created to represent the ways that production costs and emissions might change under different combinations of GHG control. Failure to introduce a wide range of combinations for each gas and sector of origin would give the unrealistic “bang-bang” solutions characteristic of this type of activity analysis.

We have chosen a simpler approach, modeling the GHG directly as an input into the production function. We thus are able to compactly introduce GHG control by introducing such an input for each GHG in each sector from which the gas is emitted. As shown below, we then

² An exception is carbon sequestration technologies that, at a cost, divert the carbon from the fuel or the smokestack to some form of storage, and thus change the relationship between fuel use and carbon. For an approach that can be used to model sequestration parallel the approaches discussed here see McFarland, Herzog, and Reilly (2002).

require only an emissions coefficient and an elasticity of substitution between the GHG and other inputs.³

2.2 Details of Implementation

Representing emissions as an input is common in analytical general equilibrium models of pollution control (*e.g.*, Fullerton and Metcalf, 2001; Babiker *et al.*, 2003a). A couple of practical considerations arise, however, in using this approach in CGE modeling. Many CGE models, including the one applied here, use Constant Elasticity of Substitution (CES) production functions, and a feature of this family of relations 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. We overcome this problem by positing a very low initial price (\$1/ton of carbon equivalent) for each GHG. In fact, this procedure is not particularly unrealistic because for many of these gases there is currently a small incentive to collect or recycle the gas (Reilly, Jacoby, and Prinn, 2003). Introducing a small initial cost requires rebalancing the social accounting matrix underlying the model (Babiker *et al.*, 2001), but because these costs are a very small percentage of any production sector ($\ll 1\%$) this correction does not introduce significant changes in the base year conditions.

A second limitation 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.⁴ The practical task in modeling the non-CO₂ gases is to decide how to structure the GHG nest while avoiding needless complexity. We have chosen to place these GHGs at the top of the nest, as illustrated in **Figure 1** for the CH₄ emitted from agricultural production. This formulation implies, other things equal, that a rise in the price of the GHG (as a result of a tighter emissions constraint) leads to a substitution away from it by means of a proportional increase in the use of all other inputs.

Detailed data on technological options for controlling other GHGs might be developed that suggest a different set of input usage than implied by this assumption. In practice, it is difficult to make a close translation between inputs as represented in engineering studies and as estimated and represented in production functions. The distinction between capital and material inputs is blurred, and engineering studies typically do not allocate management, insurance, bookkeeping, and other such overhead expenses to a small add-on emissions control technology. Thus it is not clear exactly how to allocate such expenses in a consistent way in the conversion to a more elaborate production function format. Moreover, what is often available is a single engineering cost estimate that refers to a single technology. So, even if a true representation of a particular technology could be constructed, it might not apply at different levels of abatement. Thus,

³ In fact, this approach would not be that dissimilar from CGE modeling of CO₂ control if, instead of evaluating the fossil fuel input as energy, it was treated as a carbon (disposal) input. With this change in treatment the ability to gradually substitute away from carbon use would be represented by an elasticity of substitution between carbon and other inputs, but this is just the set of elasticities of substitution that describe the demand for fuels and energy.

⁴ For the details of the nesting structure of the model applied here, see Babiker *et al.* (2001).

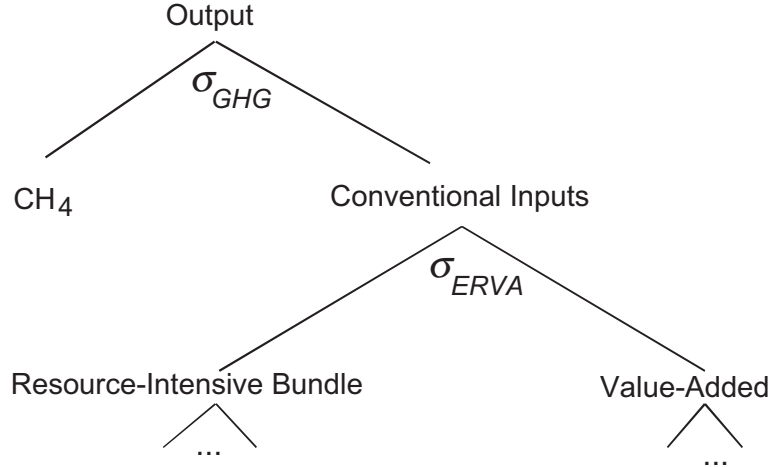


Figure 1. The Agriculture Production Structure with Methane as Input to Production

locating GHG disposal at the top of the nest, and the implications of doing so, represent in our judgment a good first approximation of input demand resulting from emissions control.

A third practical task is the estimation of the elasticity of substitution, σ_{GHG} in Figure 1. Here we make 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. Such MAC functions are often developed as a summary description of detailed process models that evaluate abatement options (*e.g.*, Brown *et al.*, 1998; US EPA, 1999, 2001). The input demand function can be derived directly from the CES production function, and the demand elasticity is directly related to the substitution elasticity. We can thus fit an inverse input demand function to a MAC and estimate an elasticity of substitution that fits the underlying bottom-up data.

The mathematics of this relationship, using CH_4 as an example, is as follows. A constant elasticity of substitution (CES) function is of the form:

$$P_o = \left[\theta [P_{i1}]^{1-\sigma} + (1-\theta)[P_{i2}]^{1-\sigma} \right]^{\frac{1}{1-\sigma}} \quad (1)$$

Where:

P_o = Price of the output of the CH_4 -emitting sector,

P_{i1} = Price of CH_4

P_{i2} = Price of all other inputs to the production process, itself the result of the sector production nest representing these inputs.

θ = CH_4 input share,

σ = Substitution elasticity between CH_4 and the other input aggregate.

By differentiating this function with respect to P_{i1} , the unit demand function (*i.e.* the quantity of methane demanded to produce one unit of output) is obtained. If X_1 is the input quantity of methane, this unit demand function is:

$$X_1 = \theta \left(\frac{P_o}{P_{il}} \right)^\sigma. \quad (2)$$

The price elasticity of demand can be derived by taking the derivative of (2) with respect to P_{il} :

$$\frac{\partial X_1}{\partial P_{il}} = -\frac{\theta\sigma}{P_{il}} \left(\frac{P_o}{P_{il}} \right)^\sigma + \frac{\theta\sigma}{P_o} \left(\frac{P_o}{P_{il}} \right)^\sigma. \quad (3)$$

To derive the elasticity of input demand ε_{di} , we multiply Expression 3 by P_{il}/X_1 and substitute for X_1 from above, yielding:

$$\varepsilon_{di} = \frac{\frac{\partial X_1}{\partial P_{il}}}{\frac{X_1}{P_{il}}} = -\sigma \left(1 - \frac{P_i}{P_o} \right). \quad (4)$$

If we let α equal the cost share of methane in production costs, *i.e.*:

$$\alpha = \frac{P_i}{P_o}, \quad (5)$$

we can rearrange terms to see that the elasticity of substitution σ is equal to:

$$\sigma = -\frac{\varepsilon_{di}}{1 - \alpha}. \quad (6)$$

In fact, control costs for methane are a small share of total production costs, especially for the level of aggregation typical in CGE models so that $1 - \alpha$ is essentially equal to one. Therefore, the substitution elasticity is virtually the same as the price elasticity of demand. Methane marginal abatement curves can be thus generated by the following equation:

$$Abatement = 1 - X_1 = 1 - \theta \left(\frac{P_o}{P_{il}} \right)^\sigma, \quad (7)$$

where α is estimated to match a MAC from detailed bottom-up studies. In this form, baseline emissions are assumed to be equal to 1.0, so that abatement is expressed here as a percentage of baseline emissions. For our purposes, we may substitute into Equation 7 the values $\theta = 1.0$ (*i.e.*, baseline emissions = 100%) and that $P_o = 1$ (the initial price index for output for that sector), yielding:

$$Abatement = 1 - \left(\frac{1}{P_{GHG}} \right)^\sigma, \quad (8)$$

where $P_{il} = P_{GHG}$ is the emissions price applied to CH_4 in this case. Note that the choice of this function imposes a key restriction on the functions. ‘‘Abatement’’ can never be less than zero, which rules out explicit representation of ‘‘no regrets’’ options.⁵

⁵ As previously noted, a \$1/MtCe is assigned to the base level of emissions because all inputs are necessary inputs in a CES, so that their use can only approach (but not equal) zero as the price becomes very low. Viewed as an inverse demand for abatement, zero is the base level of emissions, and this occurs at \$1/mtce. Computationally,

Two sample applications of this approach are shown in **Figure 2**, which presents the underlying engineering estimate of the MACs for the abatement of CH₄ emissions from the agriculture sectors of China and the U.S., along with the σ_{GHG} approximation.

The first part of the engineering estimate shows that some negative cost (beneficial) or no-regrets options are estimated to be available: the cost of abatement is more than covered by the sales value of the gas. Bottom-up results of this form present two choices for constructing the

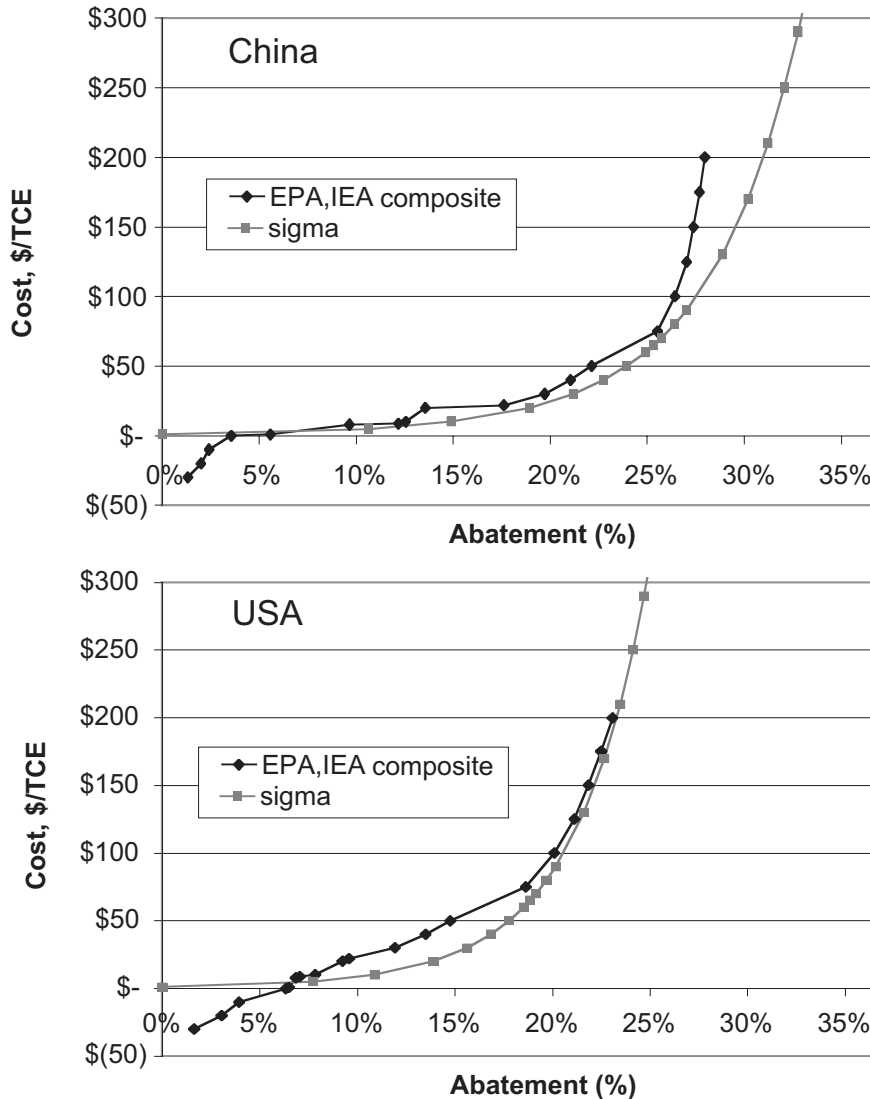


Figure 2. Comparison of EPPA parameterization (squares) with methane marginal abatement curves (diamonds) for China (top panel), and the USA (bottom panel) *Source:* Bottom-up abatement curves were derived by combining data from IEA (1998, 1999) and U.S. EPA (1999); for details, see Hyman (2001).

we include code to provide that, if a policy solution yields an equilibrium price is less than \$1, emissions do not exceed the reference emissions. Such a result can occur, for example, in a situation where there is hot air in the carbon market and there is inter-gas trading but no international trading. Without code to detect and avoid this condition, emissions can be much higher than in the reference, suggesting negative abatement.

approximation. One approach is to accept non-adoption of apparent no-regrets options as evidence that they are not economic, and shift up the MAC so that all portions of the curve are above the horizontal axis, as shown with the dashed line MAC in **Figure 3**. A second approach is to include the no regrets ‘abatement’ in the reference scenario, assuming that it will occur in the absence of a climate policy. The relevant portion of the MAC, then, is only that part that crosses the \$0/tCe axis, the part to the right of the vertical dotted line in Figure 3.

In the simulations discussed below we have adopted the first approach, and chosen an elasticity value that, we argue, overcomes some of the biases that often exist in bottom-up studies. It is often difficult in these types of studies to fully allocate a variety of overhead and transactions costs that are involved in such mitigation efforts (for instance, an agricultural emissions reduction option might require farmer education and government outreach programs to help farmers realize the benefits of methane mitigation). These studies may also underestimate the rate of return a firm requires to undertake a relatively small investment—*e.g.*, when there are other higher-return activities to which scarce management and financial resources will be devoted. And, it can also be difficult to identify all of the various site- or enterprise-specific conditions that may add to abatement costs. Cost evidence from already operating facilities, for example, may reflect the fact that these sites had the most favorable economic conditions. On the other hand, to the extent bottom-up studies focus mostly on existing technologies that seem feasible today, they can under-represent the options available at higher prices.

In the examples shown in Figure 2 the underlying engineering analysis foresaw no way to achieve more than about a 25 to 30% reduction from reference emissions levels. However, if the carbon-equivalent prices actually rises to \$50, \$100 and higher, so that market participants actually faced these prices, there would be strong incentives to search out and develop options not currently foreseen in engineering studies. The US EPA (1999, 2001) estimates, that are in part the basis for our work, are described by their authors as conservative, including only those technological options that have been demonstrated so that the costs can be confidently assessed.

We did not econometrically fit the estimate, but instead chose a value for σ and compared that to the bottom-up MAC, to allow us to judgmentally adjust the fit. The non-negativity

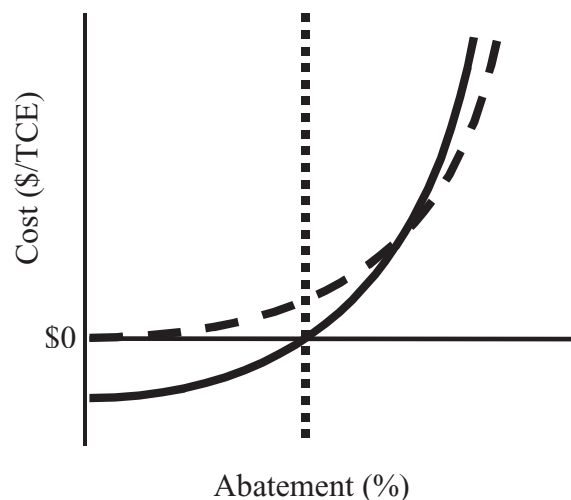


Figure 3. Negative Cost Abatement Opportunities

requirement of the CES meant that our estimates assume that the no regrets portion of the curve is an underestimate of the full cost of abating these emissions, and that there are positive, albeit small costs at these levels of abatement. At higher costs, our estimates allow a somewhat greater potential to abate than in the bottom-up MACs, for the reasons discussed above. Figure 2 illustrates the approximate nature of our fits.

3. IMPLEMENTATION IN THE MIT EPPA MODEL

We apply the method above to the MIT Emissions Prediction and Policy Analysis (EPPA) model (Babiker *et al.*, 2001). This model simulates the world economy in order to produce scenarios of anthropogenic greenhouse gas emissions and to analyze the economic impact of climate change policies. It is part of a larger Integrated Global System Model of human-climate interaction (Prinn *et al.*, 1999). EPPA is a recursive dynamic multi-regional general equilibrium model. It 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 it is solved recursively through time at 5-year intervals. The model has 12 regions, eight commodity groupings, and a consumption sector, as shown in **Table 1**. Nested constant elasticity of substitution (CES) functions are used to describe technologies and preferences, as noted earlier.

A first step in introducing GHGs into the EPPA structure is to identify those sectors responsible for emissions. **Table 2** shows each GHG source and the responsible economic sector in EPPA. A second step is the development of an inventory of GHG emissions by region and sector and determination of the time path of emissions factors. Earlier versions of EPPA (Babiker *et al.*, 2001) included such an inventory and future emissions projections, and the development of these data is described by Mayer *et al.* (2000). Uncertainties in the inventories and in future projections, comparisons with the IPCC's SRES projections (SRES, 2000), and the climatic implications of future emissions uncertainty using the EPPA model have been explored elsewhere (Webster *et al.*, 2002).

The limitation of the version of EPPA described in Babiker *et al.* (2001) was that, because emissions were introduced as Leontief (fixed coefficient) inputs, the model could not be used to

Table 1. Regions and Sectors in EPPA

Regions in EPPA		Sectors in EPPA	
<i>Annex B</i>		<i>Non-Energy Production Sectors</i>	
USA	United States	AGRIC	Agriculture
JPN	Japan	ENINT	Energy-intensive industries
EU	European Union (1995 members)	OTHIND	Other industries and services
OOE	Other OECD	<i>Energy Production Sectors</i>	
FSU	Former Soviet Union	OIL	Crude oil production
EET	Eastern Europe	GAS	Natural gas production
<i>Non-Annex B</i>		COAL	Coal Production
CHN	China	REFOIL	Refined oil production
IND	India	ELEC	Electricity production
EEX	Energy Exporting LDCs	<i>Consumption</i>	
BRA	Brazil	CONS	Household consumption
DAE	Dynamic Asian Economies		
ROW	Rest of World		

Table 2. Non-CO₂ Gas sources and EPPA Activities

Gas and Source	EPPA Representation	
CH₄	Activity	Sector
Coal seams	Coal production	COAL
Petroleum production	Oil production	OIL
Transmissions and distribution losses	Gas consumption	GAS
Landfill, wastewater gas	Household consumption	CONS
Industrial sewage, paper and chemicals	Energy intensive production	ENINT
Industrial sewage, food processing	Other industry production	OTHIND
Rice, enteric fermentation, manure management, agr. waste, savannah, and deforestation burning	Agriculture production	AGRIC
N₂O		
Adipic and nitric acid production	Energy intensive industry	ENINT
Refined oil products combustion	Refined oil consumption in all sectors	REFOIL
Coal combustion	Coal consumption in all sectors	COAL
Agr. soils, manure management, agr. waste, savannah, and deforestation burning	Agriculture production	AGRIC
HFCs		
Air conditioning, foam blowing, other	Other industry production	OTHIND
PFCs		
Semi-conductor production, solvent use, other	Other industry production	OTHIND
Aluminum smelting	Energy intensive industry production	ENINT
SF₆		
Electrical switchgear	Electricity production	ELEC
Magnesium production	Energy intensive industry production	ENINT

accurately cost abatement opportunities of these gases. The critical new element introduced here is implementation of the cost function approach shown above, which was developed first by Hyman (2001) in application to CH₄. To develop estimates for all the non-CO₂ gases, we draw on earlier work that developed exogenous marginal abatement curves for CH₄, N₂O, SF₆, PFCs, and HFCs. The underlying sources of information are the US EPA (2001), the IEA (1999), and engineering estimates developed in consultation with industry as described in Reilly, Mayer and Harnisch (2002). The earlier work constructed a single aggregate MAC for each country/region but we are now able to make use of the disaggregated sectoral detail. Thus, even though we use the same basic technological data for different regions of the world, the actual regional abatement opportunities vary considerably depending on the emissions levels of each gas from each activity.

In addition, the coefficients for CH₄ and N₂O vary by region for agriculture (**Table 3**). While the EPPA model includes only an aggregate agriculture sector, we are able to reflect differences in the make-up of the agriculture sector as it affects abatement costs by choice of the elasticity of substitution for CH₄. In particular, the underlying data provide different abatement opportunities for rice production, manure disposal, and enteric fermentation by livestock. In general, CH₄ is produced from manure only when it is kept under anaerobic conditions in manure pits. This manure handling practice occurs mainly in the United States and other developed countries. The relatively higher elasticity of substitution for these regions thus reflects the fact that a share of the methane emitted from these regions is from manure handling and there are technologies to collect this methane. On the other hand, the technological data we used did not present practical

Table 3. Elasticities of Substitution for CH₄ and N₂O with other inputs

Sector	Region	σ_{CH_4}	$\sigma_{\text{N}_2\text{O}}$
AGRIC	USA	0.05	0.04
	JPN	0.08	0.04
	EU	0.07	0.04
	OOE	0.04	0.04
	FSU	0.05	0.04
	EET	0.08	0.04
	CHN	0.07	0.02
	IND	0.04	0.02
	EEX	0.02	0.02
	BRA	0.02	0.02
	DAE	0.07	0.02
	ROW	0.03	0.02
	ENINT	All regions	0.11
OTHIND	All regions	0.11	--
REFOIL	All regions	0.15	0.0
GAS	All regions	0.15	--
COAL	All regions	0.30	0.0
Final Demand	All regions	0.11	--

means for abating methane from enteric fermentation. As this is a particularly large share of CH₄ emissions from agriculture in developing countries, the low elasticity of substitution reflects the inability to abate these, at least as represented in the analyses on which we based our estimates.

Abatement opportunities for N₂O are based on earlier work (Reilly, Mayer, and Harnisch, 2002). The underlying estimates were from econometrically estimated elasticities of demand for nitrogen fertilizer, which tend to show relatively limited price response. For developed regions, an initial low-cost abatement opportunity was identified to reflect evidence that, through soil testing and better crediting of nitrogen from manure and other organic sources, the amount of inorganic nitrogen applied could be reduced without a substantial yield penalty. Developing countries tend not to apply excess nitrogen, and in many developing country areas nitrogen may be a limiting nutrient so that soil testing would likely indicate that more rather than less nitrogen should be applied. Elasticities of substitution for PFCs, HFCs, and SF₆ with other inputs are given in **Table 4**.

3.1 National Cost Curves for the U.S. and China

The economic results of including other gases in the EPPA model can be illustrated by deriving a national cost curve from the model. Such a relation can be estimated by simulating the model numerous times with progressively tighter emissions constraints. The simulations were derived assuming a cap and trade system, with trading among gases, using 100-year Global Warming Potential (GWP) indices. The results for the USA and China are plotted in **Figure 4**.

Table 4. Elasticities of Substitution for PFCs, HFCs, and SF₆ with other inputs

Sector	Region	σ_{PFC}	σ_{HFC}	σ_{SF_6}
ENINT	All regions	0.30	--	0.3
OTHIND	All regions	0.30	0.15	--
ELEC	All regions	--	--	0.3

-- Not applicable

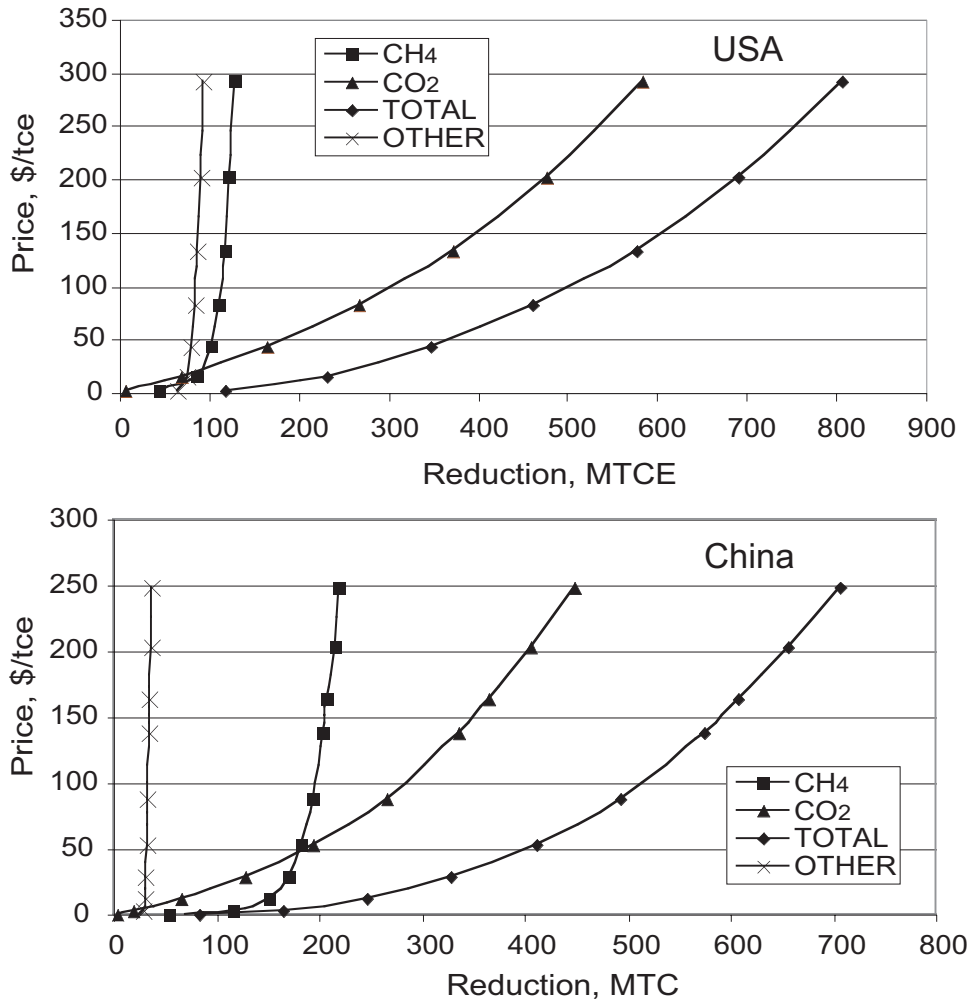


Figure 4. National Cost Curves for the USA (top panel), and China (bottom panel)

The “All-Gas” curve is, in effect, a MAC for the nation assuming an efficient policy, which is the horizontal sum of the reductions achieved for each contributing gas: CO₂, CH₄, and a single curve aggregating all of the others. Such a national MAC derived from the EPPA model represents the underlying bottom-up technology studies as captured by the choice of σ for each sector and each gas, as well as all of the economic interactions among sectors.

These summary MACs allow a direct comparison of the relative contribution of different gases at different carbon prices. Taking the U.S. as an example, at low prices a large percentage of any reduction is achieved from the non-CO₂ gases. Even though CO₂ accounts for about 80% of U.S. total GHG emissions when weighted using 100-year GWPs, economically efficient levels of abatement of CH₄ alone, and separately the combination of the other gases (N₂O, SF₆, PFCs, and HFCs), are greater than the abatement potential of CO₂ when carbon prices are less than about \$25/tCe. At about \$25/tCe, the CH₄ and other non-CO₂ gas curves cross the CO₂ abatement curve, indicating that at higher prices the contribution of CO₂ abatement becomes more important.

Two phenomena are responsible for the disproportionate contribution of non-CO₂ abatement at low prices. First, in carbon-equivalent terms many of these gases see much larger incentives for reduction of emissions at low carbon-equivalent prices than does CO₂ because of the

differences in radiative forcing (and lifetime) as represented in Global Warming Potentials (GWP). Consider methane that is vented from a coal mine, for example. It could be captured and sold to a natural gas pipeline, say at a price of \$3 per thousand cubic feet (MCF). In the absence of any charge on emissions, the \$3 price would be the firm's incentive to abate the methane. Now assume an emissions penalty of \$50 per ton of carbon-equivalent. If the mine-owner is charged only for the carbon dioxide that will be released when the methane is ultimately burned, the incentive to abate rises by about \$0.70 per MCF, for a total incentive of \$3.70. If, however, the methane is penalized for its carbon-equivalent radiative effect, as defined by its GWP, the incentive rises to over \$8.00 per MCF. The incentives for controlling emissions of the industrial gases and nitrous oxide are still stronger, because their radiative potency is so much greater than either methane or carbon dioxide. For example, sulfur hexafluoride sells for around \$10 per pound but with a GWP of 23,900 a carbon-equivalent price of \$50 per ton would translate into a penalty for emitting the gas of \$150 per pound, 15 times the product's selling price. The \$50 carbon charge equals \$0.17/gallon of gasoline given the carbon contained in it. At a price of \$1.50 per gallon this is only an 11% increase.

The second factor is that some reduction of these gases is realized as a byproduct of CO₂ reduction, as noted earlier. Other interactions, such as feedbacks of CH₄ reduction on CO₂-emitting activities, are present but are orders-of-magnitude smaller. So, for example, at a price of \$50 per ton carbon-equivalent (tCe) the non-CO₂ gases would be responsible for over half of the total reduction, as can be determined from Figure 4 by noting where a \$50 per tCe price would cross the CO₂ and non-CO₂ abatement curves.

At higher prices, the CO₂ abatement comes to dominate other gases. In part this shift reflects the simple fact that for the U.S., non-CO₂ gases are less than 20% of GWP-weighted emissions, so even if all emissions were abated there is only so much they can contribute. It also reflects the underlying technological estimates as reflected in Figure 2, that show limits on non-CO₂ abatement potential, particularly from agricultural sources.

A similar pattern holds for China. There, CH₄ is a larger component of emissions, and the other non-CO₂ gases are considerably less important. The industrial gases (HFCs, PFCs, and SF₆) are not big contributors to China's emissions, so there is little abatement potential. Emissions of N₂O come mainly from fertilizer and manure management, where our estimates show very limited abatement potential. On the other hand, CH₄ from coal mines is an important emissions source that can be abated at low cost. And, we included IEA estimates of abatement costs from paddy rice, another important source of CH₄ emissions from China. Together, however, all non-CO₂ gases account for somewhat more than 50% of abatement at a price of \$50 per tCe.

4. A SAMPLE APPLICATION

To demonstrate the application of this all-gas analysis we construct a simple policy, applied uniformly across all countries. It is assumed that reductions in all gas emissions, weighted by the IPCC GWPs, are reduced by either 10% or 20% below year-2000 levels, and maintained at these levels through 2040. No emissions permit trading is allowed among countries. Within countries, however, two cases are constructed. One assumes policies that will yield a common marginal cost across the gases by imposing a total GWP-weighted GHG cap with inter-gas trading. The other does not adopt this efficient pricing approach, but imposes proportional reductions on each gas.

Table 5. Percentage of Stated Reduction from Non-CO₂ Gases

Country	% Reduction	Time Period			
		2010	2020	2030	2040
USA	10	36	31	28	24
	20	29	26	26	24
China	10	43	34	31	30
	20	38	32	30	29

4.1 The Relative Role of the Non-CO₂ Gases

Table 5 shows the percentage of the carbon-equivalent reduction that is realized from the non-CO₂ gases, assuming that intergas trading is allowed. Again taking the U.S. as the first example, two aspects of the results are worth special note. First, the less stringent the constraint, the greater the relative role of the non-CO₂ gases. So, in 2010 they account for 36% of reductions under a national cut of 10% below the 2000 level, but only 29% of a 20% cut. This result could be anticipated from the shape of the U.S. cost function in Figure 4. By the same token, as the U.S. economy grows over time the stringency of any target reduction increases, so at a 10% target the relative role of the non-CO₂ gases falls from 36% in 2010 to 24% in 2040. With a tightening target rather than a constant one, the reduction in relative role would be still greater. Put another way, these gases (some with very high GWPs) are a crucial part of a cost-effective policy in the near term, but over time (and with tightening targets) they are driven out of the economy, so the burden of control falls ever more heavily on CO₂.

Results for China show a similar pattern, with the total contribution of non-CO₂ gases somewhat higher than in the U.S. With a 10% reduction below 2000, non-CO₂ gases account for 43% of an efficient abatement policy in China in 2010, falling to 30% by 2040.

4.2 The Importance of Multi-Gas Coordination

Up to this point in the discussion, and particularly in Figure 4 and Table 5, we have assumed a cost-efficient reduction in all gases in each country. The assumption can be thought of as implying an all-gas constraint with free trading across gases within a domestic economy. How great a difference does it make whether such a cost-effective policy is pursued? One way to consider the economic importance of this flexibility is to compare the cost-effective (equal marginal cost) approach with a policy that applies the agreed national percentage reduction individually to each of the gases, allowing no trade among them. This analysis is meant to be indicative only and should not be interpreted as the value of a trading system versus a command and control system, which involves far greater complexities.⁶

⁶ For example, our analysis assumes that marginal cost is equalized across the various sources of each gas (*e.g.* equalization of the marginal cost of CH₄ reduction in agriculture with CH₄ reduction from landfills and coal mining, and for that matter, equalization of costs across every coal mine and every livestock producer). The advantages to trading would be much greater if we set the target sector-by-sector and gas-by-gas, or if we compared it to a command and control system where targets were set for each producing source with no explicit mechanism by which marginal costs were equalized. Of course proportional reduction in all gases is just one particular constraint. If a country really wished to pursue gas-by-gas, sector-by-sector or source-by-source targets it might hope to set those targets based on an assessment of the comparative ease of abating among

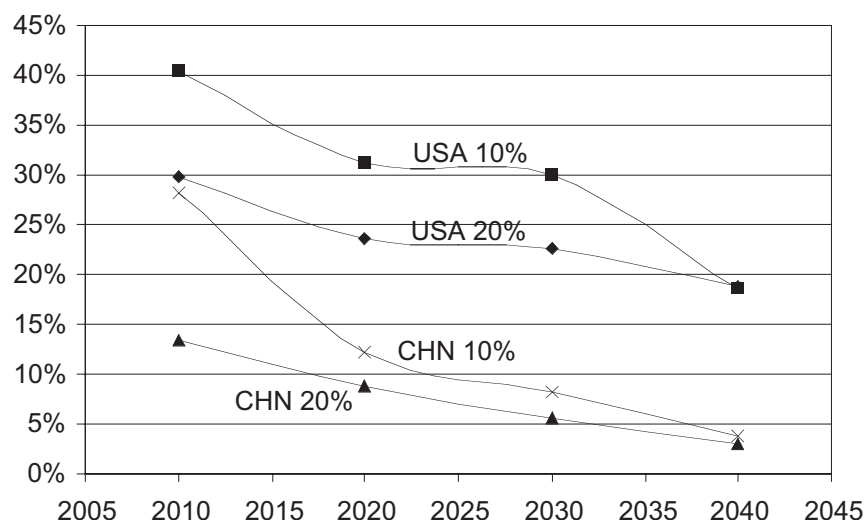


Figure 5. Percentage Reduction in GDP Loss with Shift to Trading

The result is shown in **Figure 5**. Starting with a counterfactual of no trading among gases, the figure shows the percent reduction in GDP loss achieved by a change to the efficient policy. Again the 10% and 20% reduction targets are shown, using the U.S. and China as examples. Several insights may be drawn from these results. First, for both countries, and over all periods, the gain from trading is greater under the less restrictive target. This result is simply a reflection of the fact that the non-CO₂ gases play a greater role under a looser constraint, so handling them in an efficient manner makes a greater difference. Similarly, as the constraints tighten with time and economic growth, and the relative role of the non-CO₂ gases diminishes, the saving from an efficient policy, in relation to the proportional reductions, is diminished.

The implication of these results is that, in a climate regime where the stringency of control is expected to increase with time, efficient handling of the non-CO₂ gases is of particular importance in the first few decades of control, essentially because their control allows postponement of the more expensive reductions in CO₂ emissions.⁷ The difference between the U.S. and China reflects the fact that a proportional reduction in gases is closer to the cost-effective solution in China than in the U.S. While this is the simple explanation, it reflects many factors and so it is not possible to generalize this result, for example, as a difference between developed and developing countries. Among the reasons for the difference between the U.S. and

different sources, and therefore avoid truly costly mistakes in setting caps. The value of trading then depends on how well a country is able to make such an assessment, its willingness to make reduction assignments on that basis, and its ability to adjust those assignments as conditions change. The comparison here is thus indicative of the differential abatement potential across gases, in economic terms, rather than the value of trading *per se*, which depends on how close one is able to set caps to the solution a trading system would generate. Existence of other economic distortions can also affect the economic benefits of a trading system. One can often do better than placing economically ideal policies, like a cap and trade system, on top of markets that are heavily distorted (see Babiker, Metcalf, and Reilly, 2002; Babiker *et al.*, 2002).

⁷ This decline in importance over time may be less than estimated here if the non-CO₂ abatement curves are unduly pessimistic about evolving technologies to abate some sources of GHGs. Agricultural CH₄ abatement is particularly limited by the assumption that ruminant livestock emissions cannot be abated.

China is the fact that a larger share of CH₄ emissions in the U.S. is from easier-to-abate sources like landfills, concentrated livestock manure, and coal mines—whereas a significant share of China’s CH₄ emissions is from harder-to-abate sources like ruminant animals and rice production. And, the easier-to-abate industrial gases are important in the U.S. but not in China. On the other side, however, non-CO₂ GHGs are just 17% of total U.S. GHG emissions but, by our estimate in 2010, they are 30% of China’s emissions. More generally, differential growth in total GHGs among regions, and differential growth among gases and sectors will interact with the comparative ease of abatement of different gases from different sectors to determine just how much gain there is in moving from a proportional reduction to cost-effective trading.

4.3 Regional Contributions of Non-CO₂ Gases to a Cost Effective Climate Policy

While we focused on the U.S. and China as an example to illustrate some key results, the policy of a 10% reduction below 2000 was enforced in all regions in the EPPA model. We plot the percentage contribution of the non-CO₂ gases to a cost effective policy implemented in each region for Annex B countries and the developing country regions (**Figure 6**). As before, there is trading among gases so that the GWP-weighted marginal cost of abatement is equal across gases but there is no trading across regions. We make no claims to the likelihood,

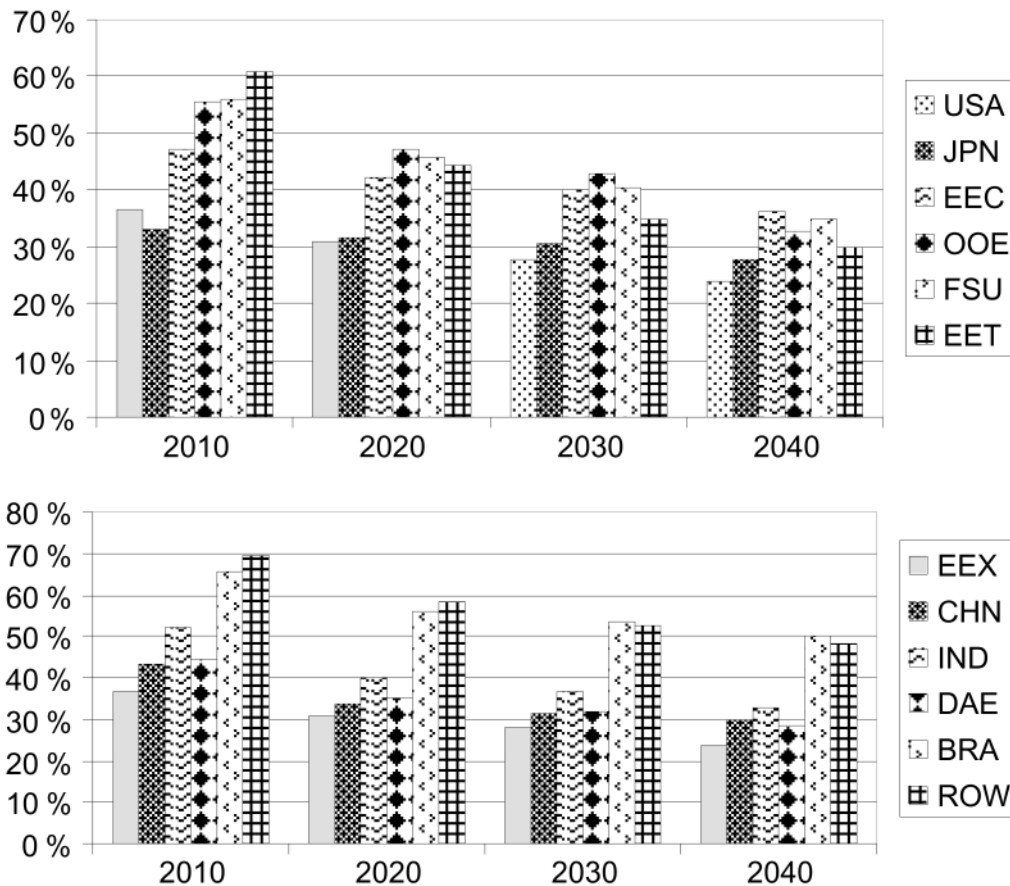


Figure 6. Percent Reduction from Non-CO₂ Gases for a 10% Total GHG Reduction from 2000 for Annex B (top panel), and Non-Annex 1 (bottom panel) Countries

reasonableness, or equity of this policy. While it is a cost-effective solution within a country/region, the fact that marginal costs are not equated across regions means that it is not globally cost-effective. The policy represented here, with identical constraints in each region, was chosen to show the importance of the non-CO₂ gases without the confounding effects of widely varying constraints.

As can be seen from Figures 6, reductions in the non-CO₂ GHGs contribute at least 34% to a cost-effective policy in all regions in 2010, if the goal of such a policy is to achieve total GHG reductions of 10% below 2000. For some regions, the contribution of non-CO₂ GHGs is as much as 65 to 70% (*e.g.*, Brazil and the ROW region). As for China and the U.S., the contribution declines over time, again reflecting gradual tightening of the constraint with growth, and the general shape of the abatement curves for non-CO₂ GHGs. The different contributions across regions in **Table 6** reflect underlying differences in the relative contributions of different GHGs. Countries with higher contributions from the non-CO₂ GHGs in the reference forecasts also tend to have a higher contribution of them in a cost-effective abatement strategy. This is not strictly the case, however, because it depends on the sources of non-CO₂ gases, and the abatement potential of fossil emissions as well. For many of the non-Annex B countries a much greater share of the non-CO₂ gases come from hard-to-abate agricultural sources whereas in developed countries more of the non-CO₂ gases come from easier to abate landfill or coal mining, or from industrial gases.

For example, EPPA’s EEX region contains most of Africa and most of its non-CO₂ gases are CH₄ from ruminant livestock or N₂O from soils. Both of these sources are represented as having limited abatement potential (see the low elasticities of substitution in Table 3). Thus, in contrast to many other regions where the non-CO₂ gas contribution to a cost-effective policy is more than proportional to their contribution to emission, the 40% abatement contribution of non-CO₂ gases is just about proportional to their contribution to total emissions in EEX. This is similarly the case for India. On the other hand, the 35% contribution of non-CO₂ gases to Japanese abatement is 3.5 times their contribution to reference emissions because a disproportionate share are from easier to control industrial sources rather than agriculture.

Table 6. Percentage of Reference GHG Emissions from Non-CO₂ Gases

	USA	JPN	EU	OOE	EEX	CHN	FSU	IND	EET	DAE	BRA	ROW
2000	17	10	20	36	39	31	32	56	39	30	61	58
2010	17	12	20	35	39	30	29	50	36	29	59	57
2020	18	13	21	34	40	29	28	45	34	29	58	55
2030	18	14	22	34	41	29	27	40	32	28	58	53
2040	17	15	22	31	41	30	26	37	30	27	57	51

5. HOW IMPORTANT IS ENDOGENOUS REPRESENTATION OF GHGS?

As discussed in Section 1, there are several reasons for including all GHGs in a single model rather than running separate models. We consider three issues where we are able to quantify the benefits of endogenous representation of abatement as compared with the use of exogenous abatement curves. These are: (1) market equilibrium effects in GHG permit markets—*i.e.*,

changes in the carbon price because of abatement of other GHGs, (2) interaction effects among policies directed at GHGs—for example, a policy directed toward CO₂ might indirectly affect emissions of CH₄, N₂O or SF₆ through their effects on coal mining, fossil fuel combustion, or electricity production, and (3) consistent cost accounting—how the integrated area under an exogenous abatement curve compares with the standard welfare concept applied in CGE modeling. We consider these issues, again with US and China as examples.

To consider the first two issues above we construct two new marginal abatement curves (MACs), one for the non-CO₂ GHGs and one for CO₂. In contrast to the curves represented in Figure 4 that were derived by jointly constraining all gases at the same time, the new set of MACs were constructed by separately constraining the model to control first only the non-CO₂ gases, and then only CO₂, so that any interaction effect is eliminated.⁸ We then add these together to create a total “Summed MAC”. These are shown in **Figure 7** along with the GHG MAC from Figure 4 now labeled as the “True Total MAC”.

Our first concern, with the permit market equilibrium, arises because non-CO₂ GHGs have been a secondary consideration in climate policy. Thus one way that analysis of abatement potential has proceeded is to use a carbon price estimate from energy models that consider only CO₂ abatement, on the assumption that the abatement contribution of any one of these non-CO₂

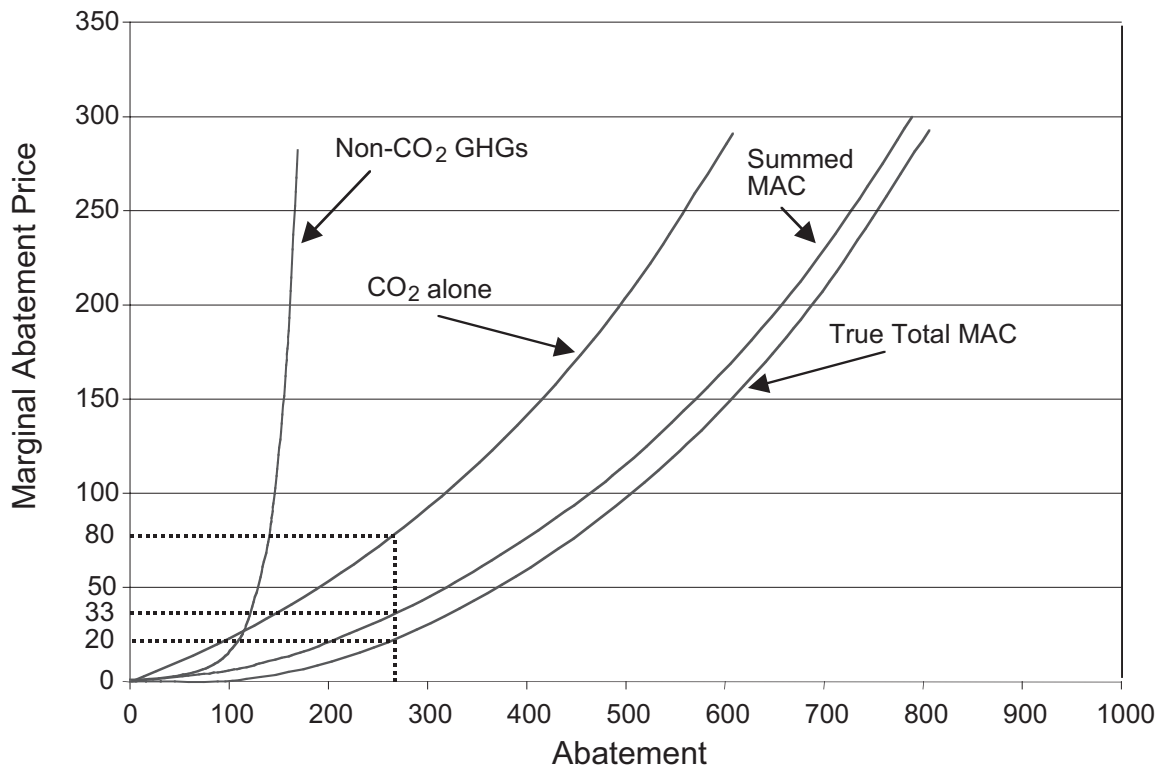


Figure 7. Effects of Endogenizing GHG Abatement

⁸ Hyman (2001) showed that constraints on the non-CO₂ gases by themselves had virtually no economy-wide interaction effect, so this method of deriving a total non-CO₂ abatement curve is essentially equivalent to summing together individual abatement curves for each gas and sector without running the model at all.

sources was too small to have a measurable effect on the market clearing price of GHGs. To illustrate, consider a 275 MtCe GHG constraint that, when evaluated using a CO₂-only MAC from EPPA, results in a market price for permits of \$80/tCe. This is shown in Figure 7 by following the vertical dashed line that starts at 275 MtCe to the CO₂ MAC and then horizontally to the price axis. However, we can determine from Figure 7 that, for a total constraint of 275 MtCe, and using the True total MAC, that the market price would fall to \$20.

To date the common method of avoiding this error and bringing the non-CO₂ gases into a CGE analysis has been to construct an exogenous MAC for these sources, and then sum with a CGE-generated MAC for CO₂. This procedure yields the Summed MAC in Figure 7, and it falls afoul of our second concern above: omissions of interaction effects. Comparison of the Summed MAC, with the True Total MAC in Figure 7 reveals that the policies have a synergistic effect—more total abatement is achieved at every price when the policies are implemented together than if each is imposed separately. Rather than the true \$20 marginal cost for a 275 MtCe constraint, the Summed MAC procedure would yield \$33/tCe, a 65% overestimate.

The third benefit of endogenous abatement is consistent costing of abatement options. The cost concept most commonly derived from CGE models is lost welfare measured as equivalent variation—the amount of income that would be needed to make consumers just as well off as without the abatement. Using exogenous MACs the cost is approximated by integrating underneath the MAC up to the equilibrium price. This latter procedure is familiar in partial equilibrium analyses. In such studies all of the inputs are assumed to have fixed prices—unaffected by demand and supply changes caused by the abatement activity. In an economy without distortions, and assuming that the abatement activity was small relative to the economy (so that prices were not affected) these costs would represent the real resource cost. Such MACs can also be constructed from complex partial or general equilibrium models, as we have done, in which case the feedbacks in the model are incorporated, although the integrated area under an abatement curve does not have an immediate interpretation in terms of the standard equivalent variation measure of welfare.

To consider what difference the cost accounting makes, we evaluated costs in three ways. Again we use the U.S. and China as examples, applying our constraints at 10 and 20 percent below 2000 with a focus on 2010 (**Table 7**). The three are: (1) welfare measured as equivalent variation, (2) integrated costs under the Summed MAC in Figure 7, and (3) integrated costs under the True Total MAC in Figure 7. As shown in Table 7, the cost estimates using the Summed MAC exceed the cost derived from the True Total MAC by about 30% for the U.S. and about 25% for China. We take this as our measure of the possible error of not endogenously treating non-CO₂ GHG abatement.⁹ Neither of these is a good approximation of the preferred measure, welfare loss. Even the True Total MAC overstates the U.S. cost by greater than a factor of two, and China's cost by about 30%.

The reason for the difference among these estimates is to be found in the price changes that the integrated MAC cannot reflect. Since the welfare loss concept measures the income that

⁹ Reilly *et al.* (1999) iterated between a CGE model and exogenous MAC for non-CO₂ GHGs to approximate this interaction effect.

Table 7. Alternative Cost Measures, Billions of 1995 \$US

Cost Measure	USA	CHN
Welfare Loss	9.7	12.5
Summed MAC	28.6	20.4
True MAC	21.9	16.4

would be required to make consumers as well off as before the policy change, it includes consideration of consumers' willingness to substitute among goods given new prices, whereas the MAC measures do not take this substitution into account. This factor alone suggests that the welfare cost will be less than that from an integrated MAC. In addition, one of the price effects that has proven to be important in the welfare estimates is the shift in the terms of trade (the price of domestic versus international goods). As has been shown elsewhere (Babiker *et al.*, 2000), one effect of carbon policy is to depress the producer prices of fossil energy. Large energy importers like the U.S. gain from these depressed prices and this effect is fully reflected in the welfare measure. Since China relies to a greater extent than the U.S. on its domestic energy resources it is not surprising that the welfare cost measure in China is larger, in relation to the integrated MAC measure, than in the U.S. China has less offsetting gain from lower fuel import costs.

Another issue shown to be of importance in CGE cost estimation is the extent of existing distortions in the economy (Babiker *et al.*, 2003b). When distortions exist the market prices of inputs may not reflect their true resource cost. For example, subsidies lead to production above the efficient level whereas taxes depress production of a sector below the efficient level. The true resource cost of inputs drawn from subsidized sectors is less than the market price because drawing resources from those sectors has the benefit of bringing the level of production closer to the efficient level. The price of resources drawn from a taxed sector will under represent their true resource cost because the production level of the sector is falling further below the efficient level. Depending, then, on where resources are drawn from, their market prices may be above or below the true resource cost.

6. SUMMARY AND CONCLUSIONS

A growing body of work has shown for developed countries that non-CO₂ GHG abatement can make a contribution to a cost effective policy that is disproportionate to their contribution to emissions. We find similar results. For the U.S., Japan, and the EU non-CO₂ GHGs contribute less than 20% of GWP-weighted emissions in our 2010 reference forecast, but their contribution toward a cost-effective emissions control policy is on the order of twice that percentage. We find that this is not generally the case for developing country regions. For these regions, the non-CO₂ GHG gases are a larger share of emissions, but they are often emitted from hard-to-abate sources such as ruminant livestock and rice production. They turn out to contribute a large share to a cost effective combination of GHG reductions but that contribution is closer in proportion to their contribution to emissions.

We also find that the contribution of non-CO₂ GHG abatement falls as policies become more stringent, and that this trend holds for all regions. It reflects the relative shape of the CO₂ and non-CO₂ abatement cost curves and the obvious fact that, with an ever-tightening total GHG

constraint, CO₂ emissions must eventually be cut more deeply. The non-CO₂ GHGs can, however, serve a crucial role in a cost-effective transition.

A key objective of this paper is methodological—to develop and demonstrate a method for incorporating non-CO₂ GHG abatement endogenously within a CGE model. The benefits of endogenous treatment of the non-CO₂ GHGs are several. These include accounting for permit market equilibrium, synergisms between CO₂ and non-CO₂ GHG policies, and consistent cost accounting. Because non-CO₂ GHGs can make a big contribution to reductions it is not analytically defensible to take a partial equilibrium approach to estimating their contribution—*i.e.*, taking as given a carbon price from an energy model. In the example we considered, the market equilibrium price fell by 75% and the estimated non-CO₂ GHG contribution fell by 25% compared with the partial equilibrium estimate. We also found that there are strong synergisms between CO₂ and non-CO₂ GHG abatement efforts. In the cases we examined, failure to account for these effects leads to a significant overestimate of the CO₂ price. Finally, we showed that integrated costs under exogenous marginal abatement curves, even when constructed from a CGE model, are not directly comparable to the welfare concepts usually drawn from CGE models and widely used to measure the cost of CO₂ policies

Given these differences, analysts seeking to compare various costs that might exist in the literature must avoid comparing apples and oranges—numbers described as GHG policy costs but measuring very dissimilar cost concepts. Because much of the CO₂ abatement cost literature has relied on CGE model-based estimates of costs, it is important to compare non-CO₂ GHGs on the same footing. It is thus an important step forward to be able to include all GHGs within CGE modeling frameworks.

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