MIT Joint Program on the Science and Policy of Global Change

The Role of Non-CO_2 Greenhouse Gases in Climate Policy: *Analysis Using the MIT IGSM*

John Reilly, Marcus Sarofim, Sergey Paltsev and Ronald G. Prinn

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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

First steps toward a broad climate agreement, such as the Kyoto Protocol, have focused attention on agreement with less than global geographic coverage. We consider instead a policy that is less comprehensive in term of greenhouse gases (GHGs), including only the non-CO_2 GHGs, but is geographically comprehensive. Abating non-CO_2 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 who have thus far resisted limits on CO_2 emissions. The policy we consider involves a GHG price of about $15 per ton carbon-equivalent (tce) levied only on the non-CO_2 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 0.57 ^oC; application of this policy to methane alone would achieve a reduction of 0.3 to 0.4 ^oC. We estimate the Kyoto Protocol in its current form would achieve a 0.30 ^oC reduction in 2100 if all Annex B Parties except the US maintained it as is through the century. Furthermore, we estimate the costs of the non-CO_2 policies to be a small fraction of the Kyoto restriction. Whether as a next step to expand the Kyoto Protocol, or as a separate initiative running parallel to it, the world could make substantial progress on limiting climate change by pursuing an agreement to abate the non-CO_2 GHGs. The results suggest that it would be useful to proceed on global abatement of non-CO_2 GHGs so that lack of progress on negotiations to limit CO_2 does not allow these abatement opportunities to slip away.

Contents

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 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, leaving CO_2 out of a global cap, but consider that it may be possible to achieve global geographic coverage. 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 result to the effect of a comprehensive cap including CO_2 at

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that same price, and to the climate benefits of the Kyoto Protocol in its current form, assuming its current participants would hold to the first commitment period caps through 2100. The simulation experiments are not meant to suggest that the non-CO_2 gas strategy is all that should be done to reduce emissions over the next century, or that CO_2 from fossil energy should be ignored. Our intent is to show what can be achieved in terms of climate change mitigation benefit if it is possible to attain nearly global coverage of the non-CO_2 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-CO_2 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-CO_2 GHGs. In Section 3 we discuss briefly the case for a non-comprehensive GHG cap, and why there may be more room for global agreement on non-CO_2 GHGs than on CO_2. Section 4 describes the MIT IGSM that we use to simulate these scenarios, focusing our attention on the Emissions Prediction and Policy Analysis (EPPA) model component as it is key to the economic policy results we present. Section 5 describes the specific scenarios and results, and Section 6 offers our overall conclusions.

2. PAST AND FUTURE CONTRIBUTIONS OF NON-CO_2 GREENHOUSE GASES

After CO_2, methane (CH_4) is the most important direct anthropogenic source of increased radiative forcing. The Intergovernmental Panel on Climate Change (IPCC) estimated its contribution to increased radiative forcing between 1750 and 2000 to be 0.48 watts per square meter (Wm^{-2}), nearly one third the contribution from CO_2 (Ramaswamy *et al.*, 2001). These calculations do not include the full contribution of CH_4. One product of CH_4 oxidation in the atmosphere is CO_2, and so part of the CO_2 increase, albeit a small part, is the result of oxidation of methane. CH_4 is also a contributor to tropospheric ozone (O_3) formation, which also is a warming gas. The IPCC estimated that increases in tropospheric O_3 between 1750 and 2000 contributed 0.35 ± 0.15 Wm^{-2}. CH_4 is likely not the most important contributor to past increases in O_3 because emissions of other precursors have increased substantially over that time. Clearly identifying the CH_4 contribution to the increase is difficult because the chemistry of O_3 formation in the troposphere is complex and non-linear in its precursor emissions.

Existing projections suggest that the relative contribution of CH_4 to radiative forcing may decrease in the future. Webster *et al.* (2003) estimated that CH_4 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 CO_2 of 4.2 (2.1 to 7.5) Wm^{-2}. At the median values the additional CH_4 contribution drops to about 15% of CO_2, from the historical share of one third. CO_2 and CH_4 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 CH_4 emissions from both fossil and non-fossil sources are subject to uncertainties independent from those affecting CO_2 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 CH_4 and low levels of CO_2. Based on the Webster *et al.* (2002) study it is thus not possible to rule out cases where the CH_4 contribution remains high or even increases relative to CO_2.

The historical contribution of nitrous oxide (N_2O), hydrofluorocarbons (HFCs), sulfur hexafluoride (SF_6), and perfluorocarbons (PFCs) together are on the order of CH_4 (Ramaswamy *et al.*, 2001). Much of the historical forcing is due to the chlorofluorocarbons (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 their sources, have 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 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 their release, to recycle them, or to switch to others 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 justified if a climate agreement might require early phase 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 N_2O by 2100 to be 0.50 (0.16 to 1.0) Wm^{-2} and the combined additional forcing from PFCs, SF_6, 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 the resulting 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. If it enters into force, greatly expanded geographic coverage in a second commitment period currently appears to face many obstacles. The Protocol has many features that in principle make it desirable from a cost-effectiveness standpoint. It starts with more or less comprehensive inclusion of GHGs[1] and it allows emissions trading (UNFCC, 1997), which under some

[1] It does not include tropospheric ozone or aerosols that also have important effects on the radiative balance of the atmosphere, and it also limits the contribution from sinks. Including these specifically within the GWP weighted caps presents difficult problems, see Reilly *et al.* (2003).

conditions can lead to efficient reductions among different substances and different regions.[2] But the fact that it does not include all regions means that, at best, emissions trading could equalize marginal cost among the participating countries but not between developed and developing countries, unless the Clean Development Mechanism (CDM) worked very effectively. Experience has shown that the inclusion of crediting features within cap and trade systems, of which CDM is an example, are usually not very effective at getting reductions. These credit systems get bogged down in the bureaucracy of defining the baseline against which a credit is allowed, and many of the abatement actions that would be encouraged under a cap are not easily brought under a project-based credit system. Problems of leakage can also be more severe with project-based credit systems.

So while there was much effort at including flexibility mechanisms in the Protocol with the aim of reducing the cost of achieving its targets, the problem it could not overcome was limited regional coverage. The agreement started with relatively deep cuts in developed countries and no cuts in developing countries, and so the potential for cost-effectiveness was compromised by the lack of geographical comprehensiveness. Now that the US has withdrawn from Kyoto, the cap is far less restrictive if all of the flexibility mechanisms are used. Indeed, 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-CO_2 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 of course decrease if more regions gradually joined as planned.

If the Kyoto Protocol does not enter into force, or it proves difficult to expand geographical coverage in succeeding commitment periods, is there another way to further climate policy rather than gradual regional expansion? Cost effectiveness would go for the least costly reductions first, and only tackle the more costly reductions as needed. One of the most important results of analyses of the non-CO_2 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-CO_2 GHGs. For example, Hyman *et al.*, 2003 show that with a cap of 10% below a 2010 reference for all GHGs including CO_2, the non-CO_2 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,

[2] Babiker *et al.* (2004) and Paltsev *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.

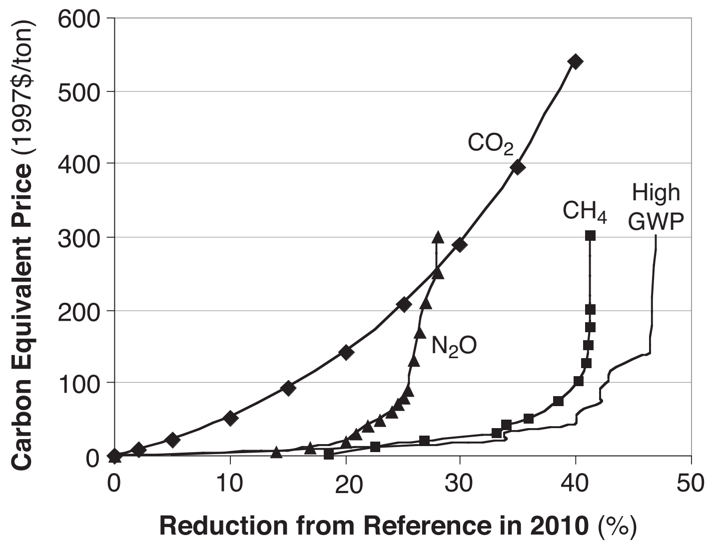

Figure 1. Marginal Abatement Curves (MACs) for the high-GWP industrial gases (hydrofluorocarbons, perfluorocarbons, sulfur hexafluoride), methane (CH_4), nitrous oxide (N_2O), and carbon dioxide. *Sources*: Figure adapted from Reilly *et al.* (2003). Original data: Methane: U.S. EPA, 1999; High-GWP Industrial gases: U.S. EPA, 2001b; nitrous oxide: Jochen Harnisch, 2001, personal communication; CO_2 calculations based on EPPA model simulations.

that if we could get agreement on the non-CO_2 gases we would get the majority of the most cost effective reductions that a modest comprehensive cap would get. As a next step it may be reasonable to consider policies to control non-CO_2 GHGs with broader regional coverage while the difficult negotiations on CO_2 limits continue. Why might it be possible to get global agreement on the non-CO_2 GHGs when it has been impossible to get such agreement on CO_2? The simple answer is that there are a lot of abatement opportunities that are not very expensive. Given that CO_2 emissions are closely 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 that 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-CO_2 GHGs as a means of disposing of them is unpriced and little attention has been paid to preventing this release. To be sure, many venting disposals have some price: CH_4 is an energy source and venting it means the opportunity value of the energy is lost; the produced chemicals (SF_6, 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-CO_2 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 CH_4. 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, SF_6, 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 N_2O and CH_4, tied as they are to food production, are potentially as big a threat as limits on CO_2 and energy use. The good news is that it appears that substantial mitigation of CH_4 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 CH_4 emissions. CH_4 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 CH_4. 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 O_3 has a highly non-linear dependence on levels of NO_x, volatile organic compounds (VOCs) including CH_4, 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 CH_4. 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 CH_4. In turn, production of OH is driven by O_3 and NO_x (which also produces O_3). Too much NO_x however, will deplete OH through HNO_3 formation. Correctly resolving the atmospheric chemistry is thus important both for estimating the concentrations of CH_4 (as its lifetime endogenously changes with changes in OH) and levels of tropospheric O_3 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 & McDugall, 2002; Hertel, 1997) and additional data for the greenhouse gases (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6) and urban gas emissions (CO, VOC, NO_x, SO_2, black carbon (BC), organic carbon (OC), and ammonia (NH_3)) (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/multi-gas interactions (Reilly *et al.*, 1999; Felzer *et al.*, 2004), 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-CO_2 GHGs Hyman *et al.* (2003).

Inventories for non-CO_2 GHGs were updated for this study to be consistent with US EPA data made available for the Energy Modeling Forum (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, CH_4 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

Table 1. Countries, Regions, and Sectors in the EPPA Model

Country or Region	Sectors	Factors
Developed	***Non-Energy***	Capital
United States (USA)	Services (SERV)	Labor
Canada (CAN)	Energy-Intensive Products (EIT)	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
India (IND)	Refined Oil (ROIL)	Wind/Solar Resources
China (CHN)	Natural Gas (GAS)	
Indonesia (IDZ)	Electric: Fossil (ELEC)	
Higher Income East Asia[c] (ASI)	Electric: Hydro (HYDR)	
Mexico (MEX)	Electric: Nuclear (NUCL)	
Central & South America (LAM)	Electric: Solar and Wind (SOLW)	
Middle East (MES)	Electric: Biomass (BIOM)	
Africa (AFR)	Electric: Natural Gas Combined Cycle (NGCC)	
Rest of World[d] (ROW)	Electric: NGCC with Sequestration (GGCAP)	
	Electric: Integrated Gasification with Combined Cycle and Sequestration (IGCAP)	
	Oil from Shale (SYNO)	
	Synthetic Gas (SYNG)	

Emissions of Climate Relevant Substances

Substances	***Sources***
CO_2, CH_4, N_2O, HFCs, SF_6, PFCs, CFCs, CO, NO_x, SO_x, VOCs, black carbon (BC), organic carbon (OC), NH_3	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 and 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.

chemical industries); household consumption (land fills); coal production (coal seam gas); oil production (venting from production); and gas consumption (leakage from pipelines). Similar modeling detail is provided for each of the substances. This approach allows us to specify separate abatement opportunities for each sector, and to distinguish between emissions that come from production of oil and coal from those that result from consumption/transmission (as in the case of CH_4 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 based on a technology-by-technology assessment, as in EPA (2001a,b,c). Agriculture is relatively aggregated, with bottom-up abatement curves for different agricultural sources being summed into a single abatement curve for the sector. We have made these region-specific based on the shares of various agricultural sources. We assume no feasible abatement possibilities for ruminant emissions, and very restrictive opportunities for abatement of N_2O from agriculture in developing countries. In developed countries we include somewhat more abatement of N_2O 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 CH_4 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 CH_4 emissions in developing countries comes from livestock operations of this type. There are consequently much lower emissions per head from livestock in developing countries compared to the US. Nearly all of what is emitted in developing countries is from ruminants, and there is no abatement possibility for these regions that we represent as feasible in the model.

If we imagined the development of manure handling operations in developing countries of the type that are common in the US, our baseline emissions of CH_4 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 would create large amounts of CH_4. As modeled, 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 for this practice. Recent observations that mid-season drainage may actually increase yields could mean it would in some places be, on net, economically beneficial even 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 there remains a small 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 seven cases:

1. *Ref*: A reference case with no explicit climate policy.
2. *CH_4-only*: All abatement options for CH_4 below \$15/tce (100-yr GWPs).
3. *All Non-CO_2*: As (2) expanded to include 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 include CO_2, but total GWP-weighted emissions reductions are set equal to the GWP-weighted emissions reduction resulting from the $15/tce in (3).
6. *Kyoto*: Kyoto with current participants (assuming Russia ratifies and without the US) with sink allowances agreed at Marrakesh, and full trading among Parties including non-CO_2 GHG emissions of the participating parties and no Clean Development Mechanism (CDM) credits.
7. *Kyoto-CO_2*: 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 lower 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 through 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 coverage to the non-CO_2 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-CO_2 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-CO_2 GHG approach. Finally, the last two cases are Kyoto targets, but Case 7 (excluding the non-CO_2 GHGs) is designed to separately identify the non-CO_2 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 7 because it is nearly indistinguishable from Case 6. The climate results show that the *CH_4-only* policy has a substantial effect on temperature, particularly in the nearer term. The reduction in the temperature increase reaches about 0.3 to 0.4 ^{o}C by 2050-2060, and varies in this range through 2100. The average over these 5 decades is 0.33 ^{o}C. In comparison the *Kyoto* warming reduction only approaches this level by 2100 (the temperature reduction in 2050 is 0.07 ^{o}C, rising to about 0.30 ^{o}C by 2100). This result reflects mostly the fact that the effective lifetime of CH_4 is quite short (on the order of 12 years allowing for OH effects) whereas the *Kyoto* reductions include abatement of the longer-lived CO_2.

[3] However, as shown elsewhere (Reilly *et al.*, 1999, Sarofim *et al.*, 2004) GWPs 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.

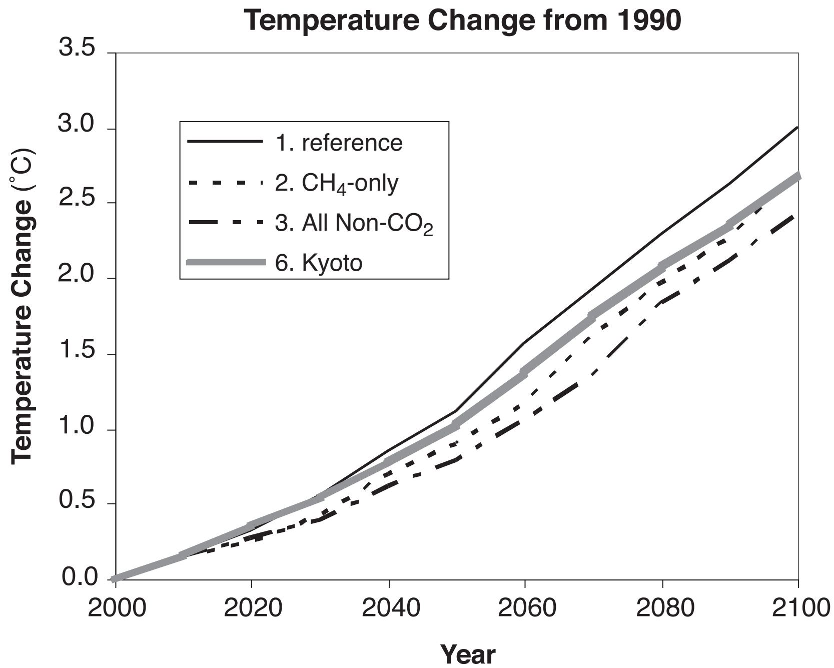

Figure 2. Climate change results expressed as decadal average mean surface temperature change from year 2000 for the reference and for policy scenarios.

The climate benefits of reductions in CH_4 are seen mostly within the time horizon of the simulation, whereas the lifetime of CO_2 is on the order of 100 years, and thus the climate benefits of CO_2 reductions in the latter half of the century are mostly not realized until after 2100.[4] Sarofim *et al.* (2004) 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 CO_2 and other GWP-weighted GHGs to show similar temperature reductions. Similar to this paper, they show greater near term benefits of CH_4 abatement, compared to CO_2.

The *All Non-CO_2* case shows, of course, greater climate mitigation benefit than the *CH_4-only* case. The benefit rises to about a 0.57 °C reduction in warming by 2100. These gases include N_2O with a lifetime similar to that of CO_2, HFCs, which have on average a shorter lifetime (~30 to 50 years), and the very long-lived PFCs and SF_6, which have lifetimes of thousands 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 N_2O reductions and the shorter-lived HFCs. The *All GHGs* case, where we further extend the \$15/tce policy to CO_2, has small additional climate benefits, somewhat under a 0.1°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 7 (*Kyoto-CO_2)* climate results, not plotted because they are indistinguishable from

[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 CH_4 in the MIT IGSM is endogenous but it is not straightforward to extract its lifetime as it changes over time.

Kyoto case when graphed, show somewhat less reduction in warming (about 0.05 ºC) compared with Case 6. *Kyoto-CO_2* actually shows very slight warming compared to the reference in the 2020-2040 decades because the CO_2 constraints reduce coal use and associated emissions of sulfates. This offsetting sulfate effect is greatly reduced in the *Kyoto* case because more of the reductions come from the non-CO_2 GHGs (and less from reductions in fossil energy use), and in addition it includes CH_4 abatement, which has a more immediate effect on climate.

It is of interest given the high costs often associated with the Kyoto Protocol, where projections quickly rise to hundreds of dollars per ton carbon-equivalent, that a global policy focused particularly on the non-CO_2 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 CO_2-only version of the Kyoto Protocol extended to 2100. If we failed to deal with CO_2 the accumulating atmospheric concentrations would, of course, become a greater burden over time. But, if we could make progress on these inexpensive abatement options, these results show substantial climate benefits.

Economic Costs. We have standardized the non-CO_2 scenarios around a $15/tce price, but the coverage varies yielding different macroeconomic cost in terms of lost consumption. Climate policy can also interact with 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, and the climate mitigation benefit in terms of reduced temperature change for the 2090-2100 decade. The time paths of climate change over the century are shown in Figure 2. The NPV welfare cost of the *CH_4-only* case is $58 billion (1997$), or about 0.005% of the NPV of total consumption over the century. The cost of the *All Non-CO_2* case is $182 billion, and if we expand this policy to CO_2 the costs more than double to $430 billion. The *$CH_4$-only* policy cost is about 13% of the *All GHG* case ($58 billion/$430 billion) but it achieves slightly more than half the temperature reduction benefits in 2100 (0.33 ºC/0.65 ºC). The increased cost from adding N_2O, HFCs, PFCs,

Table 2. Economic costs (net present value today of the policy through 2100) and temperature reduction benefits (2090-2100 decade) of mitigation policies.

Scenario	**2** **CH_4-only**	**3** **All Non-CO_2**	**4** **All GHGs**	**5** **All GHGs = cap**	**6** **Kyoto**	**7** **Kyoto-CO_2**
Net Present Value welfare loss (billions 1997$)	58	182	430	96	6663	8941
Welfare loss (% of NPV of total consumption)	0.005	0.017	0.039	0.009	0.606	0.813
Temperature reduction (°C) from reference for 2090- 2100 decade	0.33*	0.57	0.65	—	0.30	0.26

* Mean for 2050-2100; climate benefit by decade in this case is variable, ranging from 0.29 to 0.39 °C. The mean for the longer period is more representative than a single decade. See Fig. 2 for the full time path of temperature for these cases.

— GWP weighted reduction same as Case 3.

and SF_6 to the policy is nearly 30% of the *All GHG* case costs, and it contributes about 30% of the climate mitigation benefit. The cost of expanding the $15 tax to CO_2 is 58% of the *All GHG* case, ($430 billion – $182 billion)/$430 billion, 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 CO_2, costs about half as much as the *All Non-CO_2* case. Hence even these marginal reductions from a low carbon price reduce 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 CO_2 polices reduce coal use, they can also reduce sulfate aerosols, and this reduction has a warming effect that offsets the cooling from CO_2 reductions, as noted earlier. CO_2 also enhances growth of vegetation and carbon storage, and thus policies that reduce CO_2 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 O_3 precursors. Specifically, CH_4 and NO_x and CO produced in combustion of fossil fuels are all O_3 precursors. We find that Cases 2 through 4, with larger reductions in CH_4, reduce tropospheric O_3 levels about 5% on average by the end of the century compared to the reference. In comparison, the Kyoto scenarios reduce O_3 by about 3% due to reduced NO_x and CO only. While a small effect, O_3 is a warming substance and thus this makes the CH_4 policies somewhat more effective than CO_2 policies in reducing temperature. A further effect of methane abatement is a lower CO_2 concentration because the CH_4 would have been oxidized. If the CH_4 emissions reductions from fossil energy sources (coal mining, petroleum production, and leakages from natural gas transmission and distribution) that we estimated for Cases 2 to 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 to 3 years of current annual fossil carbon emissions. So abating these emissions also reduces atmospheric CO_2.

In the above calculation we do not include oxidation of the CH_4 involved in abatement from biogenic sources because we assume the biomass material that produced this CH_4 was atmospheric CO_2 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 CH_4 under anaerobic conditions leaves this vegetation to instead decay directly into CO_2. This would be the case for paddy rice for example.[5] On the cost side, many countries have existing fuel

[5] If CH_4 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.

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 CO_2 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 CO_2 reduction source has been included in climate policies. Aerosols have important radiative effects; sulfates cool the surface whereas other aerosols like black carbon have more complex warming and cooling effects on climate. Tropospheric O_3 has been a major contributor to historical forcing but the complex and non-linear interactions among its precursors make it difficult to confidently identify reductions in emissions of specific substances that would in all circumstances lead to reductions of O_3. 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 define a simple, scientifically accurate 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.*, 2004). 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 that 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 policies that are global in nature but focused on the non-CO_2 GHGs. The radiative effects of the non-CO_2 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-CO_2 emissions at low cost, or possibly with economic benefit. Whereas reducing CO_2 emissions from energy has been seen as a threat to economic growth among developing countries, the non-CO_2 GHGs are less fundamental to an economy and so reducing them does not pose as large of a threat. We estimate that abatement opportunities for CH_4 that could be achieved at less than $15/tce would over the next century reduce warming by 0.3 to 4 ^{o}C. Expanding this to other non-CO_2 GHGs would reduce warming by another 0.2 ^{o}C, for a total reduction of about 0.56 ^{o}C. This is substantially more than the 0.30 ^{o}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-CO_2 policies to be a fraction of the Kyoto policy extended through 2100. If one were thus forced to choose between (1) extending the Kyoto targets for future commitment periods for just the narrow group of countries that have so far ratified the agreement (and assuming Russia also ratifies), and (2) retaining a lower carbon-equivalent price in these regions but extending mitigation efforts geographically to include just the non-CO_2 GHGs (or to include CO_2 but with the price capped so as to limit concerns about the cost of the policy), the latter approach would have greater climate mitigation benefits and far lower costs. It thus seems worthwhile to see if the latter approach would be more acceptable to countries that have thus far not adopted targets.

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-CO_2 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-CO_2 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 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 then vent SF_6 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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