



The Role of Non-CO₂ GHGs in Climate Policy: Analysis Using the MIT IGSM

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First steps toward a broad climate agreement, such as the Kyoto Protocol, have focused on less than global geographic coverage. We consider instead a policy that is less comprehensive in term of greenhouse gases (GHGs), including only the non-CO₂ GHGs, but is geographically comprehensive. Abating non-CO₂ GHGs may be seen as less of a threat to economic development and therefore it may be possible to involve developing countries in such a policy even though they have resisted limits on CO₂ emissions. The policy we consider involves a GHG price of about \$15 per ton carbon-equivalent (tce) levied only on the non-CO₂ GHGs and held at that level through the century. We estimate that such a policy would reduce the global mean surface temperature in 2100 by about 0.55° C; if only methane is covered that alone would achieve a reduction of 0.3° to 0.4° C. We estimate the Kyoto Protocol in its current form would achieve a 0.25° C reduction in 2100 if Parties to it maintained it as is through the century. Furthermore, we estimate the costs of the non-CO₂ policies to be a small fraction of the Kyoto policy. Whether as a next step to expand the Kyoto Protocol, or as a separate initiative running parallel to it, the world could well make substantial progress on limiting climate change by pursuing an agreement to abate the low cost non-CO₂ GHGs. The results suggest that it would be useful to proceed on global abatement of non-CO₂ GHGs so that lack of progress on negotiations to limit CO₂ does not allow these abatement opportunities to slip away.

1. INTRODUCTION

It seems unlikely that the world will soon negotiate a comprehensive global agreement to abate all greenhouse gases (GHGs). First steps toward a broader agreement, such as the Kyoto Protocol, have focused on less than

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global geographic coverage. A notable exception was a proposal by Hansen et al. (2000) that focused on scenarios of global abatement of methane and black carbon emissions but included no formal economic analysis. In this paper we examine less than comprehensive coverage of the significant GHGs but consider that it may be possible to achieve global geographic coverage. We examine the implications of leaving CO₂ out of a global cap, as CO₂ emissions are arguably the most expensive to reduce substantially of all the major GHGs. We suppose a modest policy with a GHG price of about \$15 per ton carbon-equivalent (tce) throughout the century, and we look at the resulting emissions reductions and their implications for climate change and economic welfare. We compare that to what we would get if we had a comprehensive cap including CO₂, at that same price, and to the climate benefits of the Kyoto Protocol in its current form, assuming its current participants would hold to the Protocol's caps through 2100. The simulation experiments are not meant to suggest that this is all that should be done to reduce GHGs over the next century, or that CO₂ from fossil energy should be ignored. Our intent is to show what we can get in terms of climate change mitigation benefit if it is possible to achieve nearly global coverage of the non-CO₂ gases. Broader negotiations on climate change currently appear stalemated and in the meantime it may be worthwhile to at least pursue an agreement to limit the non-CO₂ GHGs. We use the MIT Integrated Global System Model (IGSM) for this analysis.

The next section provides a brief discussion of the past and future contribution of the non-CO₂ GHGs. In section III we discuss briefly the case for a non-comprehensive GHG cap, and why there may be more room for global agreement on non-CO₂ GHGs than on CO₂. Section IV describes the MIT IGSM that we use to simulate these scenarios, focusing our attention on the Emissions Prediction and Policy Analysis (EPPA) component as it is key to the economic policy results we present. Section V describes the specific scenarios and results, and Section VI offers our overall conclusions.

2. PAST AND FUTURE CONTRIBUTIONS OF NON- CO₂ GHGS

Among the greenhouse gases, methane (CH₄) is the most important direct anthropogenic source of increased radiative forcing after CO₂. The Intergovernmental Panel on Climate Change (IPCC) estimated its contribution to increased radiative forcing between 1750 to 2000 to be 0.48 watts per meter squared (Wm⁻²), nearly 1/3 the contribution from CO₂ (Ramaswamy et al., 2001). These calculations do not include the full contribution of CH₄. One product of CH₄ oxidation in the atmosphere is CO₂, and so part of the CO₂ increase, albeit a small part, is the result of oxidation of methane. CH₄ is also a contributor to tropospheric ozone (O₃) formation, which also is a warming gas. The IPCC estimated that increases in tropospheric O₃ between 1750 and 2000 contributed 0.35± 0.15 Wm⁻². CH₄ is likely not the most important contributor to past increases in O₃, and clearly identifying its contribution is difficult because the chemistry of O₃

formation in the troposphere is complex and non-linear in precursor emissions.

Existing projections suggest that the relative contribution of CH₄ to radiative forcing may decrease somewhat in the future. Webster et al. (2003) estimated that CH₄ might contribute another 0.6 (-0.17 to 1.71) Wm⁻² of radiative forcing by 2100 (95% error bars in parentheses), compared to an additional forcing from CO₂ of 4.2 (2.1 to 7.5) Wm⁻². At the median values the additional CH₄ contribution drops to about 15% of CO₂, from the historical share of 1/3. CO₂ and CH₄ are produced, in part, by the related processes (fossil fuel production) and in part by separate processes (e.g., agriculture, biomass burning, land fills and other waste disposal) and CH₄ emissions from both fossil and non-fossil sources are subject to uncertainties independent from those affecting CO₂ emissions (Webster et al. 2002). Thus, low and high levels of the two gases are correlated to some degree but it is possible to have relatively high levels of CH₄ and low levels of CO₂. This work can thus not rule out cases where the CH₄ contribution remains high or even increases relative to CO₂.

The historical contribution of nitrous oxide (N₂O), hydrofluorocarbons (HFCs), sulfur hexafluoride (SF₆), and perfluorocarbons (PFCs) together are on the order of CH₄ (Ramaswamy et al., 2001). Much of the historical forcing is due to the CFCs, whose emissions have largely been phased out because of their ozone depleting effects. HFCs have been rapidly replacing them. PFC use was growing rapidly because of its use in computer chip manufacture, but more recently has slowed. The mix of these substances, and the source of them, has changed dramatically in the past decade or so, and could change further still in the future (Reilly et al., 1999; US EPA 1999, 2001a,b,c; Reilly et al. 2000; Mayer, et al., 2001; Reilly et al., 2002; Reilly et al. 2003). Forecasts are highly uncertain (Harnisch, et al., 2000; Mayer et al., 2001), in part, because these new chemicals may find new uses. As the automobile fleet continues to grow, particularly in tropical developing countries, HFC use in mobile air conditioning could grow dramatically. As the climate effects of these substances have become more widely known, some firms are already taking actions to prevent the release of the substances, to recycle them, or to switch to those with less powerful effects on climate. In some cases, the potential development of new products and new uses for them is being shelved, recognizing that the investment in development may not be worth it if soon after introduction a climate agreement would mean they would need to be phased out. All of this adds to uncertainty. A true “no-policy” case, ignoring actions that already appear to be built into decisions because of the expectation of climate policy, can lead to very large projections of industrial GHG emissions (US EPA, 2001b). These considerations add further to uncertainty and make it difficult to establish a true no-policy reference. Webster et al. (2003) estimated the additional contribution from N₂O by 2100 to be 0.50 (0.16 to 1.0) Wm⁻² and the combined additional forcing from PFCs, SF₆, and HFC to be 0.34 (0.27 to 0.54) Wm⁻². Even though emissions are more uncertain for these substances than for methane, there is somewhat less uncertainty in their atmospheric concentrations because of their very long lifetimes.

3. POLICY CONSIDERATIONS

Global climate policy is currently at a stalemate. The Kyoto Protocol may or may not enter into force, and in any case the US, the world's largest emitter of GHGs, is not part of it, nor do developing countries such as India and China have commitments under the Protocol. The Protocol had many features that in principle made it desirable from a cost-effectiveness standpoint. It started with more or less comprehensive inclusion of GHGs¹ and it allowed emissions trading (UNFCCC, 1997) which under some conditions can lead to efficient reductions among different substances and different regions.² But the fact that it did not include all regions meant that, at best, emissions trading could equalize marginal cost among the participating countries but not between developed and developing countries, except to the extent the Clean Development Mechanism (CDM) could work. Experience has shown that crediting features of cap and trade systems, of which CDM is an example, are usually not very effective at getting reductions from the creditable sources. These credit systems get bogged down in the bureaucracy of defining the baseline against which a credit is allowed. So while there was much effort at including market mechanisms in the Protocol that would reduce the cost of achieving its targets, the problem it could not overcome was limited regional coverage. It started with relatively deep cuts in developed countries and no cuts in developing countries, and so the cost-effectiveness within the capped countries was destroyed by the lack of geographical comprehensiveness. Now that the US has withdrawn from Kyoto, the cap is far less binding if all of the flexibility mechanisms are used, and in that case the cuts look not deep at all, and if achieved cost effectively most of the reductions in the first commitment period would likely come from reductions of non-CO₂ GHGs (Babiker, et al. 2002). The Protocol was intended to be only a start toward a comprehensive policy, and any inefficiency of narrow regional coverage would decrease if more regions gradually joined as planned.

If Kyoto doesn't get very far, or we look for ways to expand its coverage, is there another way to make a start on climate policy rather than a gradual regional expansion? The Kyoto Protocol approach imagines more countries joining and accepting a comprehensive GHG cap. This is unlikely to be cost effective for many years because it will continue to have a price gap between those under a cap, and those not yet capped. While the Kyoto cap is not a very deep cut in the first commitment period, it likely will gradually become tighter with economic growth in the participating countries. Efficiency of the trading mechanism will be gradually compromised if the Protocol is unable to get other big emitters to join. Cost effectiveness would go for the least costly reductions first, and only tackle the

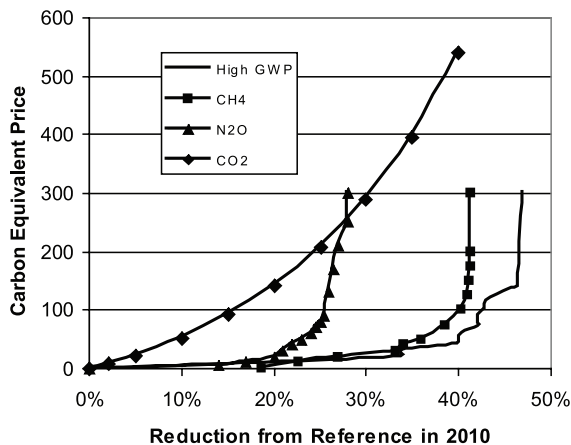
1. Although it did not include tropospheric ozone or aerosols that also have important effects on the radiative balance of the atmosphere, and it also limited the contribution from sinks. Including these specifically within the GWP weighted caps presents some difficult problems, see Reilly et al. 2003.

2. Babiker et al., 2004 show that given existing tax distortions in energy markets, emissions trading can easily increase the economic cost of a policy compared to the case without emissions trading.

more costly reductions as needed. One of the most important results of analyses of the non-CO₂ GHGs abatement possibilities is that considerable reductions can be achieved at a quite low cost per ton of carbon equivalent. Figure 1 illustrates the broad picture for these gases by showing, in percentage terms, the reductions that can be achieved for a given cost/tce (using 100-year Global Warming Potential indices to convert to carbon equivalent). Figure 1 shows abatement curves for the US, but the picture is not vastly different for other countries. The implication of this basic picture is that in the first-step of comprehensive and cap and trade scenarios, a disproportionate amount of the reductions come from the non-CO₂ GHGs. For example, Hyman et al., 2003 show that with a cap of 10% below a 2010 reference for all GHGs including CO₂, the non-CO₂ GHGs make up 30 to 70 percent across countries of the cost effective reduction in 2010 which is far above their share of emissions.

Of course it would be desirable to have a comprehensive cap on all substances set at just the right level, but that has proved politically infeasible. The above reasoning suggests, however, that if we could get agreement on the non-CO₂ gases we would get the majority of the most cost effective reductions that a modest comprehensive cap would get. Therefore, if a comprehensive cap is infeasible, leaving out CO₂ initially might be a reasonable start to a policy that would not lead to excessive cost inefficiency. Why might it be possible to get global agreement on the non-CO₂ GHGs when it has been impossible to get such agreement on CO₂? The simple answer is that there are a lot of abatement opportunities that are not very expensive. Given that CO₂ emissions are closely

Figure 1. Marginal Abatement Curves (MACs) for the High-GWP Industrial Gases (Hydrofluorocarbons, Perfluorocarbons, Sulfur Hexafluoride), Methane, Nitrous Oxide, and Carbon Dioxide



Sources: Figure from Reilly, et al. (2003). Original data: Methane: U.S. EPA, 1999; High-GWP Industrial gases: U.S. EPA, 2001b; nitrous oxide: Jochen Harnisch, 2001, personal communication; CO₂ calculations based on EPPA model simulations.

linked to energy which is quite fundamental to the economy, and given the existing price of fuels, people have already exhausted many of the easy ways to reduce fuel use. A small additional carbon charge which would produce a small increase in the price of fuels would only yield marginal reductions in fuel use and carbon emissions. In contrast, venting of the non-CO₂ GHGs as a means of disposing of them is unpriced and little attention has been paid to preventing this release. To be sure, many have some price: CH₄ is an energy source and venting it means the opportunity value of the energy is lost, and the produced chemicals (SF₆, HFCs) have a production cost, and the cost of venting them is the cost of purchasing replacements. But, because of the high GWPs of these gases, the opportunity costs of venting are on the order of pennies per carbon-equivalent ton when using 100-year GWP or any other reasonable index of their climate effects. Looked at another way, a \$15 per ton carbon-equivalent incentive would be several multiples of the opportunity cost of not venting these substances (e.g. Reilly et al., 2003).

Detailed studies suggest that preventing release of these substances may even be economic in some cases, given the opportunity cost of purchasing the replacements (US EPA, 2002). Such no regrets options have been likened to finding \$50 bills on the sidewalk, and if they existed many argue that most would have been spotted and picked up already. But abatement opportunities for the non-CO₂ GHGs, if they are no regrets, are comparatively nickels, dimes, and quarters on the sidewalk. Yet, if we recognize that in climate terms they are worth several dollars that may make it worthwhile to stoop, pocket the change, and make substantial progress in slowing climate change. Even if the spare change does not fully compensate for the bother of stooping, we still have the climate benefits. Developing countries looking for energy without having to spend hard currency may find it particularly attractive to recover CH₄. Similarly, recycling the industrial gases, if it saves their purchase, may be desirable. A further consideration is that at this point, very little of the industrial gases (PFCs, SF₆, and HFCs) are emitted in developing countries. Therefore agreement here would focus on prevention, establishing best practice in developed countries, and assuring that these practices are used elsewhere when the products and production moves there. This may be easier to agree on than cutting back on something on which a poor country already depends. As noted above, either because reducing emissions of these substances is actually cost-effective or in anticipation of carbon-equivalent penalty for emitting them, many firms are reducing them. Creating a global agreement on these substances would consolidate these actions, and in many cases act as a preventative measure against developing practices that would lead to their release.

Not all is completely without pain, however. Cutting agricultural sources of N₂O and CH₄, tied as they are to food production, are potentially as big a threat as limits on CO₂ and energy use. The good news is that it appears that substantial mitigation of CH₄ from paddy rice is possible with mid-season drainage, and this appears to also increase yield. The practice has thus spread widely in China quite apart from any concern about CH₄ emissions. CH₄ from ruminants is by

comparison not an easily solved problem. Manure handling, however, need not develop into the manure pit operations prevalent in the US that, due to the anaerobic conditions, generate large amounts of CH₄. Alternatively, building in the capacity to collect and use the methane from these pits as an energy source could be cost-effective. We discuss how we deal with these issues below.

4. THE MIT IGSM

The MIT Integrated Global System Model (IGSM) (Prinn et al., 1999) includes the Emissions Prediction and Policy Analysis (EPPA) model, designed to project emissions of greenhouse-relevant gases (Babiker et al., 2001) and the economic consequences of policies to limit them (e.g., Paltsev, et al., 2003, Reilly et al., 1999; Jacoby et al., 1997); a chemistry and climate model that includes a two-dimensional (2D) land-ocean (LO) resolving climate model (Sokolov & Stone, 1998), coupled to a 2D model of atmospheric chemistry (Wang et al., 1998; Wang & Prinn, 1999; Mayer et al., 2000), and a 2D or three-dimensional (3D) model of ocean circulations (Kamenkovich et al., 2002). The TEM model of the Marine Biological Laboratory (Melillo et al., 1993; Tian et al., 1999; Xiao et al., 1997, 1998) simulates carbon and nitrogen dynamics of terrestrial ecosystems. With regard to the simulations reported here, the particularly important aspects of the earth system components of the model are those that represent atmospheric chemistry. Atmospheric chemistry is resolved separately for polluted conditions, i.e., emissions in urban airsheds, and background conditions. Urban conditions are resolved at low, medium and high levels of pollution (Mayer et al., 2001). This is important because the formation of tropospheric O₃ has a highly non-linear dependence on levels of NO_x, volatile organic compounds (VOCs) including CH₄, and CO as they vary from background levels to concentrations observed in different types of urban environments. The hydroxyl radical (OH) is key to the oxidation of CO and CH₄. For example, if levels of CO are high then oxidation of it will use up much of the OH and therefore extend the lifetime of CH₄. In turn, production of OH is driven by O₃ and NO_x (which also produces O₃). Too much NO_x however, will deplete OH through HNO₃ formation. Correctly resolving the atmospheric chemistry is thus important both for estimating the concentrations of CH₄ (as its lifetime endogenously changes with changes in OH) and levels of tropospheric O₃ as they affect warming.

The EPPA component of the IGSM model is a computable general equilibrium (CGE) model. The main advantage of CGE models is their ability to capture the influence of a sector-specific (e.g. energy, fiscal, or agricultural) policy on other industry sectors, on consumption, and also on international trade. EPPA is a recursive-dynamic and multi-regional model covering the entire the world economy (Babiker et al, 2001). It is built on the economic and energy data from the GTAP dataset (Dimaranan and McDugall, 2002; Hertel, 1997) and additional data for the greenhouse gases (CO₂, CH₄, N₂O, HFCs, PFCs and SF₆) and urban gas emissions (CO, VOC, NO_x, SO₂, black carbon (BC), organic

carbon (OC), and ammonia (NH₃) (Mayer et al., 2001; Hyman et al. 2003). GHG inventory data and projections of abatement opportunities are based largely on US EPA data (US EPA 2001a-c; 2002 a-b). It has been used extensively for the study of climate policy. (Jacoby et al, 1997; Babiker, et al, 2000, 2002; Viguier et al, 2001; Bernard et al, 2003; Paltsev et al, 2003; Reilly et al, 2002; McFarland et al, 2003), climate-multigas interactions (Reilly et al, 1999; Felzer et al. 2003), and to study uncertainty in emissions and climate projections for climate models (Webster et al, 2002, 2003). Table 1 provides an overview of the basic elements of the model, with greater details in Babiker et al. (2001) and Paltsev et al. (2003, 2004), and for the non-CO₂ GHGs Hyman et al. (2003).

Inventories for non-CO₂ GHGs were updated for this study to be consistent with US EPA data made available for the EMF study. The approach for inclusion of these gases is detailed in Hyman, et al. (2003) and Webster et al. (2002), with greater details on the methods of developing emissions coefficients that change over time for aggregate EPPA sectors in Mayer et al., (2001). Briefly, the method is to introduce each separate GHG emission as an input into a separate nest of the constant elasticity of substitution (CES) production function of the relevant sectors. For example, CH₄ emissions are modeled as coming from agriculture (paddy rice, ruminant, manure, and biomass combustion related to deforestation); other industry (food processing waste); energy intensive industry (waste from paper and chemical industries); household consumption (land fills); coal production (coal seam gas); oil production (venting from production); and gas consumption (leakage from pipelines). Similar detail for each of the substances is modeled based on the various emissions sources. This allows us to specify separate abatement opportunities for each sector, and, for example, to distinguish between emissions that come from production of oil and coal from those that result from consumption/transmission as in the case of CH₄ from natural gas.

We estimate an elasticity of substitution for each sector's emissions such that the partial equilibrium production function response to changing price of the substance matches bottom-up abatement curves constructed based on a technology-by-technology assessment as in EPA (2001a,b,c). Agriculture is relatively aggregated and here we combine bottom-up abatement curves for different agricultural sources into a single abatement curve for agriculture. We assume no feasible abatement possibilities for ruminant emissions, and very restrictive opportunities for abatement of N₂O from agriculture in developing countries. In developed countries we include somewhat more abatement of N₂O because studies show the potential for reducing nitrogen fertilizer use without reducing yield by, for example, soil testing and better crediting of nitrogen in manure. Similarly, there is more opportunity for CH₄ abatement from agriculture in the US because more of it is emitted from large confined cattle operations where opportunities for abatement have been identified. Little or none of the CH₄ emissions in developing countries comes from livestock operations of this type. There are consequently much lower emissions per head from livestock compared to the US, nearly all of what is emitted is from ruminants, and there is no abatement

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

Country or Regions	Sectors	Factors
Developed	Non-Energy	Capital
United States (USA)	Services (SERV)	Labor
Canada (CAN)	Energy Intensive products (EINT)	Land
Japan (JPN)	Other Industries products (OTHR)	Crude Oil Resources
European Union ^a (EUR)	Transportation (TRAN)	Natural Gas Resources
Australia/New Zealand (ANZ)	Agriculture (AGRI)	Coal Resources
Former Soviet Union ^b (FSU)	Energy	Hydro Resources
Eastern Europe (EET)	Coal (COAL)	Shale Oil Resources
Developing	Crude Oil (OIL)	Nuclear Resources
Africa (AFR)	Refined Oil (ROIL)	Wind/Solar Resources
India (IND)	Natural Gas (GAS)	
China (CHN)	Electric: Fossil (ELEC)	
Indonesia (IDZ)	Electric: Hydro (HYDR)	
Higher Income East Asia ^c (ASI)	Electric: Nuclear (NUCL)	
Mexico (MEX)	Electric: Solar and Wind (SOLW)	
Central and South America (LAM)	Electric: Biomass (BIOM)	
Middle East (MES)	Electric: Natural Gas Combined Cycle (NGCC)	
Rest of World ^d (ROW)	Electric: NGCC with Sequestration (NGCAP)	
	Electric: Integrated Combined Cycle Coal Gasification, Sequestration (IGCAP)	
	Oil from Shale (SYNO)	
	Synthetic Gas (SYNG)	
Emissions of Climate Relevant Substances		
Substances		
CO ₂ , CH ₄ , N ₂ O, HFCs, SF ₆ , PFCs, CFCs, CO, NOx, SOx, VOCs, BC, OC, NH ₃		
Sources		
Combustion of refined oil, coal, gas, biofuels and biomass burning, manure, soils, paddy rice, cement, land fills, and industrial production.		

a. The European Union (EU-15) plus countries of the European Free Trade Area (Norway, Switzerland, Iceland).

b. Russia and Ukraine, Latvia, Lithuania, Estonia, Azerbaijan, Armenia, Belarus, Georgia, Kyrgyzstan, Kazakhstan, Moldova, Tajikistan, Turkmenistan, and Uzbekistan.

c. South Korea, Malaysia, Phillipines, Singapore, Taiwan, Thailand

d. All countries not included elsewhere: Turkey, and mostly Asian countries.

possibility for these regions that we represent as feasible in the model.

If we imagined the development of manure handling operations in the developing countries of the type in the US, our baseline emissions of CH₄ would be higher. In that regard, our simulations may underestimate the importance of focusing on preventative measures. Similarly, we do not simulate in our baseline a large transition to landfills in developing countries that create large amounts of CH₄. Reduction of agricultural methane from livestock production in developing countries would need to come from reduced agricultural production, but that is

negligible because the value of food is high relative to the GHG cost share in production, particularly for the low GHG prices we simulate here. We include abatement from rice paddies based on drainage studies done by International Energy Agency (IEA), as discussed in Hyman et al., 2003. The IEA data estimated a cost to this practice. Recent observations that mid-season drainage may actually increase yields could mean it is, on net, economically beneficial apart from the CH₄ abatement.

By reflecting abatement opportunities as they differ in developing versus developed countries and among different sources, the EPPA model is well-designed to consider the questions we address in this paper. A related aspect of the approach is that, as previously discussed, many of the detailed bottom-up estimates suggest no regrets, or economically beneficial actions that would reduce GHG emissions. As discussed in Hyman et al. (2003) one could treat this information in a model of our type by removing them from abatement opportunities and building the reductions into the reference scenario. Another approach, and the one we use, is to assume that because these abatement activities have not occurred implies that there is some unmeasured cost or barrier that is preventing them from being implemented. We thus include these emissions in the reference, and assume that they require a low carbon-equivalent price in order to be realized.

5. SCENARIOS CONSTRUCTION AND RESULTS

We construct the following cases:

1. *Ref*: A case with no explicit climate policy.
2. *CH₄-only*: All abatement options for CH₄ below \$15/tce(100-yr GWPs)
3. *All Non-CO₂*: As (2) expanded to N₂O, SF₆, PFCs, and HFCs
4. *All GHGs*: As in (3) expanded to include CO₂.
5. *All GHGs=cap*: Cap and trade is expanded to CO₂, but total GWP weighted emissions reductions is equal to the GWP-weighted emissions reduction resulting from the \$15/tce in (3).
6. *Kyoto*: Kyoto with current participants, i.e. without the US, and with sink allowances agreed at Marrakesh, and full trading among Parties (assuming Russia ratifies) including non-CO₂ GHG emissions of the participating Parties with no Clean Development Mechanism (CDM) credits.
7. *Kyoto-CO₂*: As in (6) but excluding non-CO₂ GHGs from the policy. However, reductions in emissions of non-CO₂ gases because of reductions in fossil fuels (e.g. reduced coal bed methane emissions because of reduced coal use) are included in the IGSM runs.

The reference case serves as a basis of comparison to allow us to estimate the net present value of the welfare loss (discounted at 5% per annum)

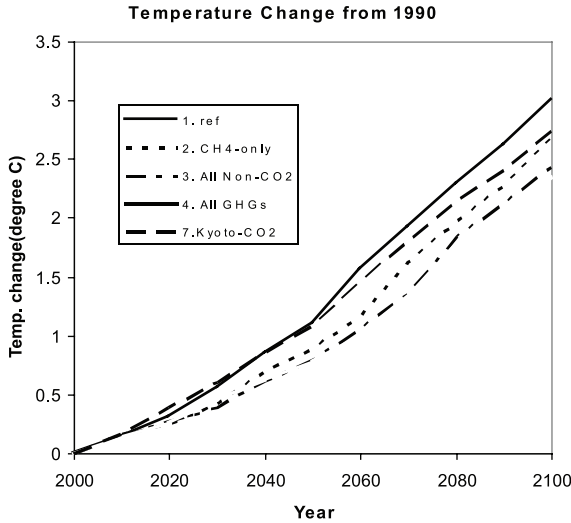
under the different scenarios and to see the climate benefits of the policy cases. Cases 2-4 are normalized on the carbon-equivalent price, and so we expect more climate mitigation benefit as we include more GHGs, but we also expect the cost in terms of welfare loss to increase because of the greater GHG coverage. Case 5 is designed to show the economic cost of limiting ourselves to the non-CO₂ GHGs by contrasting Case 3 with a scenario where the GWP weighted emissions reductions are the same but spread over all gases to equilibrate the carbon-equivalent price. These cases are all done in place of Kyoto; i.e., assuming the Protocol does not enter into force and the Parties that have ratified it abandon that approach and pursue the non-CO₂ GHG approach. This is not meant to represent the realistic intentions of the Parties that have already ratified but to show clearly the difference between the Kyoto approach and non-CO₂ GHG approach for making a start on global climate policy. Finally, the last two cases are Kyoto targets but Case 7, by excluding the non-CO₂ GHGs is designed to separately identify the non-CO₂ GHG contribution to the Kyoto Protocol, and is not meant to suggest that the Kyoto Parties do not intend to control these emissions.

Climate Results. Figure 2 shows the simulated change in global mean surface temperature for five of the seven simulations. We omit case 5, *All GHGs=cap*, because this has the same GWP weighted reduction in emissions as case 4, and we are interested in it solely for the economic comparison.³ We also do not graph Case 6 because it is nearly indistinguishable from Case 7. The climate results show that the *CH₄-only* policy has a substantial effect on temperature, particularly in the nearer term. The reduction in the temperature increase reaches about .3° to .4° C by 2050-2060 and remains at about that level through 2100. In comparison the *Kyoto-CO₂* warming reduction only approaches this level by 2100 (the temperature reduction in 2100 is about .26° C). This reflects mostly the fact that the effective lifetime of CH₄ is quite short (on the order of 12 years allowing for OH effects) compared with CO₂ which remains in the atmosphere much longer. Thus, the climate benefits of reductions in CH₄ are seen mostly within the time horizon of the simulation, whereas the lifetime of CO₂ is on the order of 100 years, and thus the climate benefits of CO₂ reductions in the latter half of the century are mostly not realized until after 2100.⁴ Sarofim et al. (2005) conduct very long run model integrations with the MIT IGSM and show that it can take more than 200 years for similar reductions in emissions of CO₂ and other GWP-weighted GHGs to show similar temperature reductions. Similar to this paper,

3. However, as shown elsewhere (Reilly et al. 1999, Sarofim et al. 2005) the GWP weights do not correctly weight the GHGs and so the temperature effects are different depending on which gases are reduced. This issue has been explored thoroughly in the above papers and elsewhere. Here we want to focus on the economic differences of policies that would be viewed as identical given the agreement to use GWPs.

4. Here we use lifetimes frequently used in the literature only to provide an order-of-magnitude idea of the difference. Because carbon is partitioned in different reservoirs, a single lifetime is not truly appropriate, and as noted, the calculation of the lifetime of CH₄ in the MIT IGSM is endogenous but it is not straightforward to extract its lifetime as it changes over time.

Figure 2. Climate Change Results Expressed as Decadal Average Mean Surface Temperature Change from Year 200 for the Reference and for Policy Scenarios



they show greater near term benefits of CH₄ abatement, compared to CO₂. The *All Non-CO₂* case shows, of course, greater climate mitigation benefit than the *CH₄-only* case. The benefit rises to over .5° C reduction in warming by 2100. These gases include N₂O with a similar lifetime as CO₂, HFCs which have on average a shorter lifetime (~30-50 years) and the very long-lived PFCs and SF₆ which have lifetimes of 1000's of years. So this is a mixed group of gases, but much of the additional benefit we see through the year 2100 simulation horizon likely comes from N₂O reductions and the shorter-lived HFCs. The *All GHGs* case, where we further extend the \$15/tce policy to CO₂, has small additional climate benefits, about .1° C warming reduction. This reflects the fact that the \$15/tce is a marginal increase in fuel prices and spurs on only small reductions in energy use. The case 6 (*Kyoto*) climate results, not plotted because they are indistinguishable when graphed from *Kyoto-CO₂*, show a small (.05° C) reduction in warming compared with case 7. This warming reduction also starts much earlier and the difference with *Kyoto-CO₂* and holds steady for most of the century, reflecting the effects of including CH₄ abatement and the relatively short lifetime of CH₄.

As discussed at the beginning of the paper, we are not proposing that any of these policies represents a sufficient response to the risks posed by climate change. Rather we are considering possible next steps in what appears to be a stalled global climate negotiation. In that regard, it is of interest given the high costs often associated with the Kyoto Protocol, where projections quickly rise to \$100's/tce, that a global policy focused particularly on the non-CO₂ GHGs

where the price is on the order of \$15/tce could achieve, at least in the 2100 time horizon, greater climate benefits than a CO₂-only version of the Kyoto Protocol extended to 2100. If we failed to deal with CO₂, the accumulating atmospheric concentrations would, of course, become a greater burden over time. But, if we could make progress to make sure that the very inexpensive abatement options are in place to prevent the releases of the non-CO₂ GHGs these results show substantial climate benefits.

Economic Costs. We have standardized the non-CO₂ scenarios around a \$15/tce price, but the coverage varies and so the macroeconomic cost in terms of lost consumption differs. Climate policy can also interact with other pre-existing taxes in the economy and so carbon price is a poor indicator of the cost of a policy (Paltsev, et al, 2004). Table 2 shows the Net Present Value (NPV) cost, using a 5% discount rate, of these policy cases through 2100. The NPV welfare cost of the CH₄-only case is \$57.6 billion (1997\$), or about .005% of the NPV of total consumption over the century. The cost of the All Non-CO₂ case is \$181.6 billion, and if we expand this policy to CO₂ the costs more than double to \$430 billion. The CH₄-only policy cost is about 13% of the All GHG case but it achieves more than 1/2 the climate mitigation benefits. The increased cost from adding N₂O, HFCs, PFCs, and SF₆ to the policy is nearly 30% of the All GHG case costs, and it contributes about 30% of the climate benefit. The cost increase of expanding the \$15 tax to CO₂ is 58%, but this addition contributes only 15% of the climate mitigation benefit realized in 2100. Of course these less comprehensive policies are more expensive than a comprehensive global policy covering all gases designed to achieve the same GWP-weighted reduction. The All GHGs=cap case with a cap on all gases including CO₂ costs about 1/2 as much as the All Non-CO₂ case. The amount of CO₂ reductions that result from a \$15 price are small but adding this flexibility further reduces the policy cost. The problem is that the negotiations to put policies in place to achieve this appears stalemated because countries are concerned that current policy approaches using a fixed cap would become too costly. We see this in the Kyoto scenarios (6 and 7) which are measured in trillions of dollars rather than billions (Table 2). And, with narrow regional coverage they achieve less climate benefit.

Interactions. There are a number of interactions that come into play in the estimate of cost and climate mitigation benefit. To the extent that CO₂ polices reduce coal use, they can also reduce sulfate aerosols, and this reduction has a

Table 2. Economic Costs of Mitigation Policies

Scenario	2	3	4	5	6	7
	CH ₄ -only	All Non-CO ₂	All GHGs	All GHGs=cap	Kyoto	Kyoto-CO ₂
NPV welfare loss (billions of 1997\$)	57.6	181.6	429.9	95.5	6663.1	8941.5
Welfare loss (% of NPV of total consumption)	0.005	0.017	0.039	0.009	0.606	0.813

warming effect that offsets the cooling from CO₂ reductions. CO₂ also enhances growth of vegetation and carbon storage, and thus policies that reduce CO₂ also reduce uptake by vegetation in the IGSM runs, and as a result the reductions in emissions are not quite as effective as if this did not occur. Changes in energy use also affect emissions of many O₃ precursors. Specifically, CH₄ and NO_x and CO produced in combustion of fossil fuels are all O₃ precursors. We find that scenarios 2-4 with larger reductions in CH₄ reduce tropospheric O₃ levels about 5% on average by the end of the century compared to the reference. In comparison, the Kyoto scenarios reduce O₃ by about 3% due to reduced NO_x and CO only. While a small effect, O₃ is a warming substance and thus this makes the CH₄ policies somewhat more effective than CO₂ policies in reducing temperature. A further effect of methane abatement is a lower CO₂ concentration because the CH₄ would have been oxidized. If the CH₄ emissions reductions from fossil energy sources (coal mining, petroleum production, and leakages from natural gas transmission and distribution) that we estimated for cases 2-4 are used for fuel in order to displace other natural gas use, the displaced natural gas would have oxidized into about 14 GtC, or about 2-3 years of current annual fossil carbon emissions. So abating these emissions also reduces atmospheric CO₂.

We do not include in the above calculation oxidation of the CH₄ involved in abatement from biogenic sources because we assume the biomass material that produced this CH₄ was atmospheric CO₂ before it was taken up by the vegetation. The agricultural activities leading to these emissions are cycling the carbon on fairly rapid timescales, and so we assume that avoiding the formation of CH₄ under anaerobic conditions leaves this vegetation to instead decay directly into CO₂. This would be the case for paddy rice for example.⁵ On the cost side, many countries have existing fuel taxes, and climate policy directed toward fuels interacts with these existing taxes to raise the cost of the climate policy. Paltsev et al. (2004) show that the extra cost due to this tax interaction effect can be several times the direct cost of the carbon policy itself. This fact likely explains why expanding the \$15/tce policy to CO₂ increases the costs as much as it does (Table 2).

6. CONCLUSIONS

The current policy challenge is to make a start toward stabilizing greenhouse gases in the atmosphere. An idealized policy would be comprehensive geographically, and would include all substances that affect the radiative balance of the atmosphere. There are technical, scientific, and policy-related reasons why it has not been possible to jump-start a fully comprehensive policy. Issues of measuring carbon sinks have limited how this potential CO₂ reduction source has been included in climate policies. Aerosols have important radiative effects; sulfates cool the surface whereas other aerosols like BC have more complex

5. If CH₄ from manure is collected and used as an energy source to offset a fossil source this would through the offset lead to a reduction in carbon.

warming and cooling effects on climate. Tropospheric O₃ has been a major contributor to historical forcing but the complex and non-linear interactions among its precursors makes it difficult to confidently identify reductions in emissions of specific substances that would in all circumstances lead to reductions of O₃. Moreover, aerosols and ozone are short-lived and not well-mixed in the atmosphere and so their climate effects display a different geographic pattern, and may differentially affect cooling, warming, and precipitation compared with the longer-lived GHGs (Reilly, et al., 2003). Even among the GHGs, their differing nature has made it impossible to find the correct index by which to compare them, and so policies that use 100-year GWPs poorly represent the relative climatic effects (Reilly et al., 1999; Sarofim, et al., 2005). On the policy side, developing countries have resisted joining the group of countries in the Kyoto Protocol that have taken on caps, at least for the present. Recognizing these many difficulties, to get started one would like to find the less than comprehensive set of policies that would be effective, have a chance of broad acceptance among most countries, and would not be highly inefficient. Fortunately, these last two conditions, cheap and acceptable, often go hand in hand.

We have considered here policies that are global in nature but focused on the non-CO₂ GHGs. The radiative effects of the non-CO₂ GHGs are well-known, and so there is no scientific doubt that reducing them will lead to climate mitigation benefit. On the cost side, it has become ever clearer with more study and attention that there are many ways to abate these non-CO₂ emissions at low cost, or possibly with economic benefit. Whereas reducing CO₂ emissions from energy has been seen as a threat to economic growth among developing countries, the non-CO₂ GHGs are less fundamental to an economy and so reducing them does not pose that large a threat. We estimate that abatement opportunities for CH₄ that could be achieved at less than \$15/tce would over the next century reduce warming by .3° to .4° C. Expanding this to other non-CO₂ GHGs would reduce warming by another .2° C, for a total reduction of about 0.55° C. This is substantially more than the .25° C reduction we estimate the Kyoto Protocol in its current form would achieve if Parties to it maintained it as is through 2100. Furthermore, we estimate the costs of the non-CO₂ policies to be a fraction of the Kyoto policy.

Stabilization of greenhouse gases in the atmosphere will require that carbon emissions from fossil energy be reduced. Unfortunately, we are stuck in a policy stalemate of how to proceed on carbon dioxide. Non-CO₂ GHG abatement would occur through the Kyoto Protocol and even abatement in developing countries could be achieved under it through the CDM. However, the opportunities to avoid these emissions may slip away as we wait for ratification of the Kyoto Protocol. Even if ratified the CDM itself may be ineffective at getting the reductions in developing countries. Whether as a next step to expand Kyoto, or as a separate initiative running parallel to it, the world could well make substantial progress on limiting climate change by pursuing an agreement to abate the low cost non-CO₂ GHGs.

While we simulated control with an emissions tax and/or cap and trade system, other policy approaches may be equally effective. Abatement of these substances may be easily controlled by establishing best practice measures, or through regulatory standards without being highly inefficient. Policies might simply be established to not use landfills as a waste disposal method, or to create them such that methane would be collected and used as an energy source. Methods that capture rather than vent SF₆ from electrical switchgear testing, already used by many companies, could simply be mandated. As long as we are focused on methods that are relatively low cost, it is not obvious that great inefficiencies arise from less than ideal market incentive mechanisms. And given the existence of other pre-existing distortions in the economy and the inability to establish accurate indices by which to establish equivalent multi-substance taxes (or the rate at which different substances would trade) the idealized instruments may not work ideally. The bottom line is that there appear to be low cost abatement options that we should act on as soon as we can, and through whatever policies or measures different countries find acceptable to their circumstances, and thus hopefully make it possible to get broad country participation.

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